2LS: Heap Analysis and Memory Safety
(Competition Contribution)⋆

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Abstract 2LS is a framework for analysis of sequential C programs that can verify and refute program assertions and termination. The 2LS framework is built upon the CPROVER infrastructure and implements template-based synthesis techniques, e.g. to find invariants and ranking functions, and incremental loop unwinding techniques to find counterexamples and k-induction proofs. The main improvements in this year’s version are the ability of 2LS to analyse programs requiring combined reasoning about shape and content of dynamic data structures, and an instrumentation for memory safety properties.

1 Overview

2LS is a static analysis and verification tool for sequential C programs. At its core, it uses the kI\(I\) algorithm (k-invariants and k-induction) [1], which integrates bounded model checking, k-induction, and abstract interpretation into a single, scalable framework. kI\(I\) relies on incremental SAT solving in order to find proofs and refutations of assertions, as well as to perform termination analysis [2].

This year’s competition version introduces new product and power domain combinations to support invariant inference for programs that manipulate shape and content of dynamic data structures [4]. Moreover, there is an improved encoding of memory safety properties.

Architecture. The architecture of 2LS has been described in previous competition contributions [6,5]. In brief, 2LS is built upon the CPROVER infrastructure [3] and thus uses GOTO programs as the internal program representation. The analysed program is translated into an acyclic, over-approximate single static assignment (SSA) form, in which loops are cut at the edges returning to the loop head. Subsequently, 2LS refines this over-approximation by computing inductive invariants in various abstract domains represented by parametrised logical formulae, so-called templates [1]. The competition version uses the zones domain for numerical variables in combination with our shape domain for pointer-typed variables and the symbolic paths domain described below. The SSA form is bit-blasted into a propositional formula and given to a SAT solver. The kI\(I\) algorithm then incrementally amends the formula to perform loop unwindings and invariant inference based on template-based synthesis [1].

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2 New Features

The major improvements for SV-COMP’20 are all related to analysis of heap-manipulating programs. We build on the shape domain presented last year [5] and introduce abstract domain combinations that allow us to analyse both shape and content of dynamic data structures. Furthermore, we present encoding of assertions that are used for verifying memory safety properties.

2.1 Combinations of Abstract Domains

The new capability of 2LS to jointly analyse shape and content of dynamic data structures takes advantage of the template-based synthesis engine of 2LS. Invariants are computed in various abstract domains where each domain has the form of a template while relying on the analysis engine to handle the domain combinators.

Memory model In our memory model, we represent dynamically allocated objects by so-called abstract dynamic objects. Each such object is an abstraction of a number of concrete dynamic objects allocated by the same malloc call (i.e. at the same program location) [4].

Shape Domain For analysing the shape of the heap, we use an improved version of the shape domain that we introduced last year [5]. The domain over-approximates the points-to relation between pointers and symbolic addresses of memory objects in the analysed program: for each pointer-typed variable and each pointer-typed field of an abstract dynamic object \( p \), we compute the set of all addresses that \( p \) may point to [4].

Template Polyhedra Domain For analysing numerical values, we use the template polyhedra abstract domains, particularly the interval and the zones domains [1].

Shape and Polyhedra Domain Combination Since both domains have the form of a template formula, we simply use them side-by-side in a product domain combination—the resulting formula is a conjunction of the two template formulae [4].

This combination allows 2LS to infer, e.g., invariants describing an unbounded singly-linked list whose nodes contain values between 1 and 10. We show an example of such a list in Figure 1. Here, all list nodes are abstracted by a single abstract dynamic object \( ao_1 \) (i.e. we assume that they are all allocated at the same program location). The invariant inferred by 2LS for such a list might look as follows:

\[
(ao_1.next = \& ao_1 \lor ao_1.next = \text{NULL}) \land ao_1.val \in [1, 10] \tag{1}
\]

The first disjunction describes the shape of the list—the next field of each node points to some node of the list or to NULL. The second part of the conjunct is then an invariant

\[1\]

Here, \( ao_1.f \) is an abstraction of the \( f \) fields of all concrete objects represented by \( ao_1 \). Analogously, \( \& ao_1 \) is an abstraction of symbolic addresses of all represented objects.
in the interval domain over all values stored in the list—it expresses the fact that the value of each node lies in the interval between 1 and 10.

2.2 Symbolic Paths

To improve precision of the analysis, we let 2LS compute different invariants for different symbolic paths taken by the analysed program. We require a symbolic path to express which loops were executed at least once. This allows us to distinguish situations when an abstract dynamic object does not represent any really allocated object and hence the invariant for such abstract dynamic object is not valid [4].

The symbolic path domain allows us to iteratively compute a set of symbolic paths $p_1, \ldots, p_n$ (represented by guard variables in the SSA) with associated shape and data invariants $I_1, \ldots, I_n$. The aggregated invariant is then $p_1 \Rightarrow I_1 \land \cdots \land p_n \Rightarrow I_n$, which corresponds to a power domain combination.

2.3 Memory Safety

To verify memory safety, appropriate assertions are inserted into the program. We now describe the structure of these assertions for different types of memory errors.

**Dereferencing/Freeing a NULL Pointer** To check for this kind of errors, we add an assertion $p \neq \text{NULL}$ to each location where $*p$ or $\text{free}(p)$ occurs [4]. Since the shape domain over-approximates the set of all addresses that $p$ may point to, absence of such errors can be proven. If an error is found, we use BMC to check its reachability.

**Dereferencing/Freeing a Freed Pointer** Using a single abstract dynamic object to represent multiple concrete objects poses problems when trying to determine if a particular concrete object (within the abstract one) has already been freed or not. To resolve this, for each abstract dynamic object $ao_i$, we non-deterministically select a single concrete object represented by $ao_i$ and materialize it as $ao_i^{co}$. After that, every time $ao_i^{co}$ is freed, we non-deterministically set a special variable $fr$ to $true$. This allows us to generate an assertion $p \neq fr$ for each location containing $*p$ or $\text{free}(p)$ [4].

**Memory Leaks** To find a memory leak, we check whether, at the end of the program, there is an object $ao_i^{co}$ such that $fr \neq &ao_i^{co}$. If such $ao_i^{co}$ exists, there is a memory leak present (some object represented by the corresponding $ao_i$ has has not been freed). On the other hand, absence from memory leaks can only be proven for programs without loops (or with loops that can be fully unwound). This is because checking that $fr$ may be equal to a materialized object $ao_i^{co}$ is not sufficient to prove that all objects represented by the corresponding abstract object $ao_i$ were freed [4].

3 Strengths and Weaknesses

This year’s improvements mostly influenced results in the MemSafety category where 2LS narrowly missed the podium in 4th place. There were many new benchmarks and a new sub-category (MemCleanup) whose benchmarks were handled well by 2LS.
One of the main strengths of 2LS is verification of programs requiring joint reasoning about shape and content of dynamic data structures. There were no such benchmarks in previous SV-COMP editions, thus, we contributed 10 of our own benchmarks. Combining our shape domain with the zones domain for value analysis allows 2LS to successfully verify 9 out of 10 of these benchmarks (the last one has timed out). None of the other tools was able to verify more than 3 of these benchmarks.

Still, there remain a lot of challenges and limitations. The heap domain is quite simple and over-approximates the heap too much to allow us to analyse complicated properties of dynamic data structures. Moreover, reasoning about array contents is still lacking, and the 2LS' algorithm \texttt{klkl} does not yet support recursion. Moreover, there is a large number of unconfirmed witnesses, especially in the termination analysis (500 points lost).

4 Tool Setup

The competition submission is based on 2LS version 0.7. The archive contains the binaries needed to run 2LS (\texttt{2ls-binary, goto-cc}), and so no further installation is needed. There is also a wrapper script \texttt{2ls} which is used by Benchexec to run the tools over the verification benchmarks. See the wrapper script also for the relevant command line options given to 2LS. The further information about the contents of the archive could be find in the \texttt{README} file. The tool info module for 2LS is called \texttt{two\_ls.py} and the benchmark definition file \texttt{2ls.xml}. As a back end, the competition submission of 2LS uses Glucose 4.0. 2LS competes in all categories except Concurrency and Java.

5 Software Project

2LS is maintained by Peter Schrammel with pull requests contributed by the community. It is publicly available under a BSD-style license. The source code is available at \texttt{http://www.github.com/diffblue/2ls}.

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\footnote{Executable available at \texttt{https://gitlab.com/sosy-lab/sv-comp/archives-2020}}
\footnote{\texttt{https://github.com/diffblue/2ls/graphs/contributors}}