Cooperative Verification via Collective Invariant Generation

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ABSTRACT
Software verification has recently made enormous progress due to the development of novel verification methods and the speed-up of supporting technologies like SMT solving. To keep software verification tools up to date with these advances, tool developers keep on integrating newly designed methods into their tools, almost exclusively by re-implementing the method within their own framework. While this allows for a conceptual re-use of methods, it requires novel implementations for every new technique.

In this paper, we employ cooperative verification in order to avoid re-implementation and enable usage of novel tools as black-box components in verification. Specifically, cooperation is employed for the core ingredient of software verification which is invariant generation. Finding an adequate loop invariant is key to the success of a verification run. Our framework named CoVerCIG allows a master verification tool to delegate the task of invariant generation to one or several specialized helper invariant generators. Their results are then utilized within the verification run of the master verifier, allowing in particular for crosschecking the validity of the invariant. We experimentally evaluate our framework on an instance with two masters and three different invariant generators using a number of benchmarks from SV-COMP 2020. The experiments show that the use of CoVerCIG can increase the number of correctly verified tasks without increasing the used resources.

CCS CONCEPTS
• Software and its engineering → Formal software verification.

KEYWORDS
Cooperation, Software Verification, Invariant Generation

1 INTRODUCTION
Recent years have seen a major progress in software verification as for instance witnessed by the annual competition on software verification SV-COMP [2]. This success is on the one hand due to advances in SAT and SMT solving and on the other hand due to novel verification methods like interpolation in model checking [37], automata-based software verification [31] or property-directed reachability [16]. Still, automatic verification remains a complex and error-prone task. In particular, it is often the case that one tool can verify a particular class of programs, but fails to verify other classes (or even gives incorrect answers), whereas it is the reverse situation for another tool. Moreover, to keep their tools up to date with novel techniques, tool developers keep on integrating them by re-implementation within their framework.

An approach for changing this unsatisfactory situation is cooperative verification (for an overview see [13]). Cooperative verification builds on the idea of letting tools (and thus techniques) cooperate on verification tasks, thereby leveraging the tool’s individual strengths. In particular, cooperative verification aims at black box combinations of tools, using existing tools off-the-shelf without re-implementation. While this sounds like a natural idea, its realization poses a number of challenges, the major one being the exchange and usage of analysis information. For cooperation, tools are required to produce (partial) results which other tools can understand and employ in their verification run. With conditional model checking [7], the first proposal of an exchange format for verification results was made. A conditional model checker outputs its (potentially partial) result in the form of a condition which can be read by other conditional model checkers in order to complete the verification task. Since verification tools normally do not understand conditions, reducers [9, 23] have been proposed to bring conditions back into a form understandable by verifiers, namely into (residual) programs describing the so far unverified program part. This allows the result of a conditional model checker to be made usable by arbitrary other verifiers. A second type of existing result usage is the validation of tool’s results [4, 34], similar to proof-carrying code [38]. Both of these types are sequential forms of cooperation: a first verifier starts and a second verifier continues, either by completing or by validating a first result.

In this paper, we propose CoVerCIG, a cooperation framework which complements these existing approaches by a new type of cooperation. Conceptually, this framework (depicted in Figure 1) consists of a master verifier and a number of helper invariant generators. The master verifier has the overall control on the verification process and can delegate tasks to helpers as well as continue its own verification process with (partial) results provided by helpers. The helpers run in parallel as black boxes without cooperation. The task to be delegated is an integral part of software verification, namely invariant generation. The framework allows cooperation via outsourcing the task of invariant generation, leveraging the strength of specialized invariant generation tools.
We have experimentally evaluated 14 different combinations without incurring significant overhead. In some cases, the verification time is even decreased in cooperative verification.

Like for other types of cooperation, the question of the exchange format for results comes up. Here, we have chosen correctness witnesses [3] for this purpose. Correctness witnesses are employed in witness validation and certify a verifier's result stating the correctness of a program. These witnesses are particularly well suited for our intended usage, because their format is standardized and a number of verifiers already produce correctness witnesses. To account for the incooperation of helper verifiers not producing witnesses, our framework also foresees the inclusion of adapters transforming invariants into correctness witnesses. We provide an implementation of such two adapters. Witnesses are then injected into the verification run of the master. For stating the task to be solved by invariant generators we furthermore require mappers transforming program and property to be proven into a task format understandable by the helper tools. Figure 1 depicts our framework for collective invariant generation. The framework can be arbitrarily configured with different masters and helpers, provided that suitable adapters and mappers are given.

We have implemented our framework within the CPACHECKER framework [10] and have employed different configurations of it as master verifier. As helper verifiers we have chosen publicly available frameworks [10] and have employed different configurations of it as suitable adapters and mappers are given.

We aim at the cooperative verification of programs written in GNU C, focusing on the validation of safety properties. To be able to define safety properties, a formal representation of programs as well as their semantics is needed. Thus we next briefly introduce the syntax and semantics of programs which we consider here.

We follow the notation of Beyer et al. [6] describing programs as control-flow automata (CFAs). A CFA is basically a control-flow graph with edges annotated with program statements. More formally, a program is represented as a control-flow automaton $C = (L, l_0, G)$, consisting of a set of program locations $L$, an initial location $l_0 \in L$ and the control-flow edges $G \subseteq L \times Op \times L$. The set $Op$ contains all possible operations on integer variables present in the program, namely conditions (as of conditionals and loops), assignments, method calls and return statements. Figure 2(a) shows a C-program taken from the SV-COMP benchmarks and Figure 2(b) its corresponding CFA. The program also contains a special error label, used for encoding the property to be verified. The verification task for this program is to show the non-reachability of the error label at location 9, i.e., for our example program the verifier has to prove that $y$ equals $n$ after the loop which is true (since $n$ is unsigned).

For the semantics, we start by defining program states. Let $Var$ denote the set of all integer variables occurring in programs, $BExp$ the set of boolean expressions and $AExp$ the set of arithmetic expressions over $Var$. Then a state $\sigma$ of the program is a mapping from the variables to the integers, i.e., $\sigma : Var \rightarrow \mathbb{Z}$. We lift the mapping to also contain the evaluation of arithmetic and boolean expressions so that $\sigma$ maps $AExp$ to $\mathbb{Z}$ and $BExp$ to $\mathbb{Z}$. A finite program path $\pi$ is a sequence of transitions $\langle \sigma_0, l_0 \rangle \xrightarrow{g_0} \langle \sigma_1, l_1 \rangle \cdots \xrightarrow{g_{n-1}} \langle \sigma_n, l_n \rangle$, such that $\sigma_0$ assigns 0 to all variables, $l_n$ is a leaf in the CFA and $(l_i, g_i, l_{i+1}) \in G$ holds for each transition $\langle \sigma_i, l_i \rangle \xrightarrow{g_i} \langle \sigma_{i+1}, l_{i+1} \rangle$ in $\pi$. Infinite program paths are defined analogously. As for state changes in paths: If $g_i$ is a boolean expression, method call or return statement, then $\sigma_i = \sigma_{i+1}$ holds. If $g_i$ is an assignment $x = a$, where $a \in AExp$, then $\sigma_{i+1} = \sigma_i[x \mapsto \sigma_i(a)]$. Finally, we denote all paths of a program represented by a CFA $C$ by $paths(C)$.

Here, we are interested in verifying safety properties of programs given as CFAs. For the purpose of this paper, we define a safety property $P$ as a pair of a location $\ell \in L$ and a boolean condition $\varphi \in BExp$. There can be multiple safety properties required to hold in a program. For our example program of Figure 2 the property is $(8, n = y)$. For the verifier this is encoded in the form

8:  if $(! (n = y))$
9:    Error: return 1;

Later, we will see that different verifiers require different encodings of the property to be checked, and hence mappers need to be applied to translate property encodings.

1 In our formalization, we use integer variables only, the implementation covers C programs.
2 https://llvm.org/docs/LangRef.html
3 https://github.com/sosy-lab/sv-benchmarks
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1 int main() {
2   unsigned int n = nondet();
3   unsigned int x = n, y = 0;
4   while(x > 0){
5       x--;
6       y++;
7     } // Safety property
8   if (!n == y) {
9       Error: return 1;
10   }
11   return 0;
12 }

(a) C code example

(b) The corresponding CFA

Figure 2: An example program, its control flow automaton and one witness

Figure 3: Excerpt of a correctness witness for the example

A CFA (or program) $C$ violates a safety property $P = (\ell, \varphi)$ when the program reaches location $\ell$ in a state which does not satisfy $\varphi$. More formally, $P$ is violated by $C$, if there is some path $\pi \in \text{paths}(C)$, $\pi = (\sigma_0, l_0) \rightarrow (\sigma_1, l_1) \cdots \rightarrow (\sigma_n, l_n)$ and some $i, 0 \leq i \leq n$, such that $\ell_i = \ell$ and $\sigma_i(\varphi) = false$.

Cooperatively verifying safety of programs is achieved in our framework via collective (loop) invariant generation. Syntactically, a loop invariant is a boolean expression associated to a loop head. A loop invariant needs to hold (1) before the first loop execution and (2) after each loop execution. The expression $n = x + y$, for instance, is a loop invariant for the program in Figure 2(a), associated to the loop head at location 4. This loop invariant facilitates verification of the safety property, because in conjunction with the negated loop condition and information about initial variable values it ensures $n$ to be equal to $y$ after the loop. Other valid loop invariants would be $x \geq 0, n = 3 \Rightarrow y \leq 5$ or true, which however all do not help in proving the safety property. Especially the loop invariant true does not provide any information, as it always is a valid loop invariant. Thus, we call it a trivial invariant.

As stated before, we chose witnesses (more specifically, correctness witnesses) as exchange format during collective invariant generation. Formally, a witness is a finite state automaton in which transitions are labelled with so called source code guards and states can be equipped with boolean expressions. When all these boolean expressions are either true or false, we call the witness trivial. Source code guards are of the form location, type where type can be then, else, enterFunc and enterLoopHead. The guard o/w (otherwise) is used if a source code line does not match the other guards present. Via these labels we can match transitions of the automaton with edges in the CFA.

In Figure 2(c), we see a correctness witness for our example program. State $q_3$ is reached by transitions labelled 3, enterLoopHead or 6, enterLoopHead and thus corresponds to the loop head at program location 4. Associated with this state is the invariant $n = x + y$.

Syntactically, correctness witnesses are stored in an XML format and consist of two parts: (1) general information like the producer of the witness or the program associated with the witness, and (2) a GraphML representation of the witness automaton. Figure 3 shows an excerpt of this format for the witness in Figure 2(c). More information and a formal specification of correctness witnesses can be found in [3].

3 CONCEPT

In this section, we introduce our novel concept of Cooperative Verification via Collective Invariant Generation (CoVerCIG), shown in Figure 1. The framework contains two sorts of main components: Master verifiers (one) and helper invariant generators (several). Next, we state some requirements on and explain the functionality of these components as well as their cooperation.

3.1 Components of the CoVerCIG-Framework

The most important component of the framework is the master verifier, which we build out of an existing verifier. The master is responsible for coordinating the verification process and can, if needed, request support from the second type of components, the helpers, in the form of invariants as described by correctness witnesses. Hence, the master is also steering the cooperation.

In the following, we explain the two sorts of main components in more detail:
We cannot expect existing verification tools which we wish to use to be constructable from the CFA. For this, many compilers offer debug flags, adding this information inside the program into the desired input format of the CFA and a safety property \( P \). It computes as output a boolean answer \( b \), stating whether the property holds, and possibly (but not necessarily) provides an overall witness \( \omega \). To be able to process the provided support in form of invariants stored inside of correctness witnesses, a master is required to implement an internal function called \( \text{injWit}\)ness. The function loads a witness, extracts the invariants present in it and injects them into the analysis of the master verifier. The witness injection can either happen before (re-)starting the analysis or during runtime. We exemplify the realization of witness injection later.

**Helper Invariant Generator** A helper invariant generator gets as input the program \( C \) as CFA and a safety property \( P \). It computes as output a set of invariants, stored in a verification witness \( \omega' \). The generated invariants are neither required to be helpful for the master verifier nor to be correct. Thus, helper invariant generators are also allowed to generate trivial invariants or invariant candidates which might turn out to be wrong.

We cannot expect existing verification tools which we wish to use as helpers to be able to work on CFAs, to understand the safety property or to produce witnesses. Hence, we foresee two further sorts of components in our framework:

**Mapper** A mapper transforms the safety property specification inside the program into the desired input format of the helper. A mapper basically conducts some simple syntactic code replacements. For instance, for our running example some helpers might instead require the safety property to be written as \( \text{if}(n=y)\{\text{verifier\_error}();\} \) or \( \text{assert}(n=y); \)

**Adapter** An adapter generates a correctness witness out of the computed loop invariants of a helper. Furthermore, some helper invariant generators work on intermediate representations (IR) of the C-language (e.g. LLVM) or intermediate verification languages (e.g. Boogie). In this case, the computed invariants (formulated in terms of IR-variables) first of all need to be translated back to the namespace of the C-program.

The latter transformations happening inside an adapter are shown in Figure 4. Initially, the IR-language variables present in the invariants are translated to variables present in the C-program. After that, we transform their IR-code locations back to C-code locations. For this, many compilers offer debug flags, adding this information to the IR. Otherwise, building and matching the CFAs of the C-program and the IR-program is required. Finally, the pairs of mapped location and invariant are stored in the form of a witness, constructable from the CFA.

### Table 1: Overview of the configuration options available

| Name             | Description                                      | Values          |
|------------------|--------------------------------------------------|-----------------|
| restartMaster    | restart the master after invariant generation    | boolean         |
| termAfterFirstInv| use first witness only                           | boolean         |
| timerM           | maximum time for master                         | time in s       |
| requestsForHelp  | until requestsForHelp is send                    |                 |
| timeoutH         | maximum time for helpers to generate an invariant| time in s       |

### 3.2 Cooperation within CoVerCIG

After having explained the individual components, we define their interaction in the framework. In this paper, we focus on the parallel execution of several helpers which implement complementary approaches so that we can leverage their individual strengths. Algorithm 1 describes the form of cooperation. It is steered by several user configurable options which fix aspects like time and resource limits of master and helpers. Table 1 summarizes the configuration options. We next describe them in detail.

**Master options** The following aspects of the master’s behavior need to be fixed: First, when to delegate tasks to helpers, and second, how to continue the verification process after invariant generation. For the delegation, we let the master verifier run until it requests support, which can be checked by inspecting the master’s flag \( \text{requestsForHelp} \). The master gets a configurable timelimit (called \( \text{timerM} \)) after which it is expected to send this request. By adding such an explicit request for help, we allow the master to send a request for other reasons (besides the timer) in the future. Then, after invariant generation, the master can either be freshly restarted or continued (option \( \text{restartMaster} \)).

**Helper option** When at least two helpers run in parallel, eventually one of them first computes a witness. We can then either (1) directly stop the other helpers, or (2) wait for all to complete before injecting witnesses into the master. This option is called \( \text{termAfterFirstInv} \).

**Timeouts** Finally, similar to the master, we can set a specific timeout for the helpers which fixes how long they are allowed to try to generate invariants. The timeout option is called \( \text{timeoutH} \).

Next, we explain the CoVerCIG algorithm shown in Algorithm 1 in detail. We assume that master and helpers run as threads and can be started and stopped. We furthermore employ methods \( \text{wait} \) for waiting until some condition is achieved and \( \text{join} \) for waiting for a specific thread to complete.

Initially, the master verifier is started without any helper invariant generators running in parallel (line 1), providing the opportunity to verify programs on its own. It runs standalone until it requests for help (either due to not being able to solve the problem alone or due to hitting its timer) or it computes a result which is subsequently returned (line 3). Afterwards all helpers are started in parallel (lines 5 and 6). They also run until they reach their timeout,
CoVerCIG-algorithm

Input: C \[\rightarrow\] CFA
P \[\rightarrow\] safety property
M \[\rightarrow\] master
Helpers \[\rightarrow\] set of helpers
conf \[\rightarrow\] configuration
Output: \[\omega\] invariant

Initially, the master verifier runs standalone and after 50 seconds configure the framework as follows:

1. M.start(C, P, conf.timerM);
2. wait until (M.requestsForHelp \lor M.hasSolution());
3. if (M.hasSolution()) then
   return M.getSolution();
5. for each \( H \in \text{Helpers} \) do parallel \( \rightarrow \) run helpers in parallel
   6. H.start(C, P, conf.timeoutH);
   7. wait until (H.timedout() \lor H.hasSolution() \lor H.stopped());
   8. if (H.hasSolution() \land \text{nonTrivial}(H.getSolution())) then
      witnesses := witnesses \cup H.getSolution();
   10. if (conf.termAfterFirstInv) then
      for each \( H' \in \text{helpers} \setminus \{H\} \) do parallel
         H'.stop(); \( \rightarrow \) stop other helpers
11. if (M.hasSolution()) then
    return M.getSolution();
15. if (witnesses \neq \emptyset) then \( \rightarrow \) invariants found
16. if (conf.restartMaster) then
   M.stop();
18. M.inject(witnesses); \( \rightarrow \) inject witnesses into master
19. if (conf.restartMaster) then
   M.start(C,P,\infty);
20. join(M); \( \rightarrow \) wait for M to finish
22. return M.getSolution();

Algorithm 1

A solution is found or they are stopped. Their solutions (invariants) are inserted into the witness set (line 9). Depending on option termAfterFirstInv, either all but the first finished helper are stopped or it is waited until all helpers either computed a solution or ran into their timeout. If invariants (witnesses) have been computed, these are injected into the master (line 18). If the restartMaster option is set, the master needs to be stopped before injection and restarted afterwards. Then the master continues and completes its verification (without any further request for help) and the result is finally returned.

Example 3.1. To explain the framework’s functionality, we demonstrate the CoVerCIG algorithm on the example presented in Figure 2(a). Assume that we instantiate the framework with a master verifier and four helper invariant generators\(^4\). Moreover, we configure the framework as follows:

- restartMaster = true,
- termAfterFirstInv = false,
- timerM = 50s, timeoutH = 300s.

Initially, the master verifier runs standalone and after 50 seconds runtime it requests help. This means that it cannot generate the invariant \( n = x + y \), for example because it rather proves single

program traces safe. The master verifier would then run in parallel with the four helper invariant generators being called. Let us assume that the first helper returns only trivial invariants (after 10s), the second one an invariant \( n \geq y \) (after 50s), the third one the invariant \( n = x + y \) (after 100s) and the fourth the invariant \( n = x - y = 0 \) (after 500s). The trivial invariant is ignored (see check in line 8) and when the second helper returns a solution, the third and fourth helper are still not stopped, due to the chosen configuration. The algorithm waits until the third helper computes the invariant and the fourth (only being able to compute an invariant after 500s) hits the timeout. Then the master is stopped, the invariants \( n \geq y \) and \( n = x + y \) are injected and the master is restarted. The master verifier can use both invariants and might now compute the correct result.

4 IMPLEMENTATION

To be able to evaluate the performance of our framework CoVerCIG, we instantiated it with two different master verifiers and three helpers, using existing off-the-shelf invariant generation tools. As verifiers need to be extended with witness injection for being able to act as a master, we used the open-source configurable program analysis framework CPAchecker [10] for this purpose and employed two of its standard instantiations (predicate abstraction and k-induction). We also decided to implement Algorithm 1 within CPAchecker. For the helper invariant generators – which can be used off-the-shelf – we looked at current and past participants of the annual competition of software verification SV-COMP [2]. Our intention was to find tools which provide complementary techniques for invariant generation. To this end, we chose the tools SeaHorn [28], UltimateAutomizer [29] and VeriAbs [1]. All helper invariant generators are used as black-boxes. An overview of the techniques employed in these tools is given in Table 2. The table also states whether the helpers require mappers and adapters. A more detailed explanation is given next.

4.1 Master Verifiers

Predicate Abstraction. The first analysis used as master is a predicate abstraction technique [11], conducting predicate refinement using a CEGAR (counter example guided abstraction refinement) scheme [20] with lazy-abstraction [33] and Craig interpolation [32]. Loop heads and error locations are used as locations where abstractions are computed; the computation of the abstraction itself is done using an SMT solver.

Witness Injection: For using this technique as master, we extended it with witness injection. The purpose of witness injection is the use of the invariants as given in the witnesses in the running analysis of the master. It is realized by extracting predicates from the invariants and inserting them into the set of available predicates as maintained by the analysis. If these predicates contain conjunctions of clauses, these are furthermore split up and inserted individually. Splitting predicates increases the performance due to the fact that SMT solvers perform better on many small predicates than on few larger ones\(^5\).

k-Induction. The basic idea of k-induction [25] is to generalize bounded model checking (BMC) [14] via induction. After proving k-bounded program executions safe using BMC, a generalization

\(^4\)Later, we will see that more than two helpers does not practically make sense.

\(^5\)This has been reported by tool developers and has also shown in our experiments.
We have chosen the existing verification tools whether new witnesses are available before each induction step. If no verification witnesses, hence we had to implement an adapter for our evaluation. Unfortunately, it only returns a boolean answer and thus, neither currently participating in the SV-COMP nor producing witnesses. The three helper invariant generators employ verification techniques complementary to those of both the other helpers and the two masters. 

SeaHorn, SeaHorn [28] is a verification tool using Constrained Horn Clauses (CHCs) to solve the verification tasks. SeaHorn constructs CHCs for each statement, encoding both data and control dependencies as well as the safety property. The (recursive) system of CHC is solved using the solver Spacer [36]. Spacer tries to prove the unsatisfiability of the CHCs, being equivalent to proving the program safe, by searching for interpretations of the predicates present in the CHCs. SeaHorn operates on the LLVM intermediate representation. We choose SeaHorn to extend the stack of helpers by a tool being conceptually complementary to the others. 

Adapter for SeaHorn. SeaHorn participated in the SV-COMP 2015, thus it can process the encoding of safety properties used in our evaluation. Unfortunately, it only returns a boolean answer and no verification witnesses, hence we had to implement an adapter for it. Our adapter follows the general construction explained in Figure 4 and we exemplify its translation in Example 4.1.

| Tool             | Techniques                                      | Mapper | Adapter |
|------------------|-------------------------------------------------|--------|---------|
| SeaHorn          | generation and solving of constrained horn clauses | ✔️     | ✗       |
| UltimateAutomizer| predicate abstraction, automata, path-based refinement | ✗      | ✔️      |
| VeriAbs          | portfolio of 4 different sequential compositions | ✗      | ✗       |

### Example 4.1. SeaHorn associates invariants to LLVM basic blocks.

A basic block is a code fragment having a single entry location (the first) and a single exit location (in general the last location of the block). We obtain the computed invariants in LLVM and the corresponding basic blocks by using the launch parameter --show-invars. To construct a witness containing them, we need to translate the invariants and find the matching C-code location for the basic block. For both, we use the LLVM-IR equipped with debug information, using SeaHorn with launch parameter -g. Thereby, we obtain the IR-code fragment of the program in Figure 2(a), shown in simplified form and containing the most important debug information as comments. The example contains two Basic Blocks, entry and _bb. 

```c
1   entry:
2   v1 = bitcast i32 (...) * @nondet to i32 ()* ▷n
3   v2 = icmp eq i32 v1, 0 ▷y
4   br i1 v2, label %error, label %bb
5
6   _bb:
7   v3 = phi i32 [0, %entry], [v6, %_bb] ▷y
8   v4 = phi i32 [v1, %entry], [v5, %_bb] ▷x
9   v5 = add i32 v4, -1 ▷x
10  v6 = add i32 v3, 1 ▷x
11  v7 = icmp eq i32 v5, 0 ▷x
12  br i1 v7, label %error, label %_bb ▷line 4
13  ...
```

SeaHorn computes the invariant $v1 - v4 = v3 = 0$ for the example and associates it with the basic block _bb. At first, we need to transform the variables from the IR to C-variables occurring in the program. In this example we can use the debug information, as shown in comments in the code. In general, a more sophisticated procedure is needed since LLVM-IR uses a three address code. Therein, complex expressions are split into separate statements using intermediate variables which are resolved to C-expressions.

Afterwards, the transformed invariant needs to be associated with the correct location in the C-code. We analyze the LLVM IR program structure to map the basic blocks back to C-locations. In the example, the block _bb is identified as being the loop of the program, thus the invariant is mapped to the loop head. For this, we employed some basic functions provided by PHASAR [42] in our adapter. Finally, we construct the CFA of the C-program, store the invariants at the nodes and convert the equipped CFA to a verification witness.

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6[https://releases.llvm.org/5.0.0/docs/LangRef.html#functions]
We focus on both effectiveness and efficiency, generally aiming at (2) techniques to abstract arrays and apply BMC afterwards, (3) tomizer search questions. induction as master verifier and using three off-the-shelf helper of the framework, using instances of predicate abstraction and k-induction techniques or (4) a fixed sequence of different verification generation can be constructed using existing tools by building equivalent to proving safety of the program. Although technique is based on predicate abstraction and on automata constructions [29–31]. The program is represented as finite automaton and error labels are final states. UltimateAutomizer then aims at proving emptiness of the accepted language of the automaton which is equivalent to proving safety of the program. Although UltimateAutomizer produces verification witnesses, we added an adapter for the witnesses due to currently existing technical incompatibilities.

VeriAbs. VeriAbs is using a portfolio of four different verification techniques, each containing several sequentially composed components [1]. The selection of strategies (techniques) from the portfolio is performed by analyzing the loop structure and intervals for variables used in the loop. Depending on the analysis result, one of the following four techniques is applied: (1) random fuzz testing, (2) techniques to abstract arrays and apply BMC afterwards, (3) explicit state model checking followed by standalone invariant generation techniques or (4) a fixed sequence of different verification approaches.

5 EVALUATION

In the following, we evaluate different instantiations of CoVerCIG. We focus on both effectiveness and efficiency, generally aiming at checking whether the use of CoVerCIG can increase the number of correctly solved verification tasks within the same resource limits.

5.1 Research Questions

We start with the feasibility of the approach in general.

Feasibility hypothesis: A framework for collective invariant generation can be constructed using existing tools by building adapters when needed. Evaluation plan: We construct instances of the framework, using instances of predicate abstraction and k-induction as master verifier and using three off-the-shelf helper invariant generator. As a result, we obtain 14 different combinations. Besides feasibility, we were interested in the following four research questions.

RQ1. Can collective invariant generation increase the effectiveness of the master verifier? Evaluation plan: We let the framework run with a single invariant generator and compare the results to a run where the master verifier runs standalone.

RQ2. Does cooperation impact the overall efficiency of the verification? Evaluation plan: We compare the run time of CoVerCIG with one helper against the two master verifiers running standalone.

RQ3. What is an appropriate time for the master to run before requesting for help? Evaluation plan: We run CoVerCIG in combination with one helper, evaluating the effectiveness of requesting for help after 50, 100 and 200 seconds.

RQ4. Does it pay off to run two invariant generators in parallel? Evaluation plan: We let the framework run with two invariant generators and compare the results to a run, where only a single invariant generator is used. Moreover, we compare the two configurations for termAfterFirstInv and evaluate timeouts for helpers using 100s and 200s.

5.2 Experimental Setup

Tools. We based the implemented of our CoVerCIG algorithm on the CPAchecker\textsuperscript{7} 1.9.1 (8646a85) using MathSat5\textsuperscript{8} as solver within CPAchecker. For the helper VeriAbs and UltimateAutomizer we used the versions as used in the SV-COMP 2020\textsuperscript{9}. Due to the fact that there is no precompiled binary of SeaHorn, we employ the docker container of the latest version\textsuperscript{10}. All three helper invariant generators are used in their default configuration.

During evaluation, we used the following default configurations for our framework: We set \texttt{termAfterFirstInv} and \texttt{restartMaster} to true, setting the \texttt{timerM} to 50s and the \texttt{timeoutH} to 300s. The master and helper used in a specific configuration as well as changes made to the default configurations are denoted as follows: The configuration \texttt{kInd-ua-va-100-wait-200} denotes a configuration using k-induction as master and the helpers UltimateAutomizer and VeriAbs. The \texttt{timerM} is set to 100s, \texttt{termAfterFirstInv} to false and \texttt{timeoutH} to 200s. In general, we will use the abbreviations SH for SeaHorn, UA for UltimateAutomizer and VA for VeriAbs.

Verification Tasks. The verification tasks used are taken from the set of SV-COMP 2020 benchmarks\textsuperscript{11}. As we are interested in finding suitable loop invariants, we selected all tasks from the category Reach/Safety-Loops. To obtain a more broad distribution of tasks, we randomly selected 55 additional tasks from the categories ProductLines, Recursive, Sequentialized, ECA, Floats and Heap, yielding in total 342 tasks.

Computing Resources. We conducted the evaluation on three virtual machines, each having an Intel Xeon E5-2695 v4 CPU with eight cores and a frequency of 2.10 GHz and 16GB memory, running an Ubuntu 18.04 LTS with Linux Kernel 4.15. We run our experiments using the same setting as in the SV-COMP, giving each task 15 minutes of CPU-time on 8 cores and 15GB or memory. We employed Benchexec thereby guaranteeing the resource-limitations [12]. All experimental data are available\textsuperscript{12}.

5.3 Experimental Results

Feasibility hypothesis. We implemented the CoVerCIG-framework as proof-of-concept in the CPAchecker-framework. For this, we had to extend the existing implementations of k-induction and predicate abstraction with witness injection. For the helper invariant generators we did not change a single line of code, only adding adapters for SeaHorn and UltimateAutomizer. Integrating helpers like VeriAbs, not requiring an adapter or a mapper, can be done within a few lines of code. Although the implementation is a proof-of-concept, this shows that the presented framework works in practice and is applicable to all kinds of off-the-shelf helper invariant generators, those producing verification witnesses and those generating invariants in IR.

RQ1 (Effectiveness). To evaluate whether a master verifier benefits from the support of a helper, we execute a combination of a master and a helper in the default configuration and compare

\textsuperscript{7}https://github.com/sosy-lab/cpachecker
\textsuperscript{8}https://mathsat.fbk.eu/
\textsuperscript{9}https://github.com/sosy-lab/sv-comp-archives-2020/tree/master/2020
\textsuperscript{10}suggested by the developers; used docker seahorn/seahorn-llvm5 (4cf1c1d)
\textsuperscript{11}https://github.com/sosy-lab/sv-benchmarks/releases/tag/svcomp20
\textsuperscript{12}https://covercig.github.io/
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(a) CoVerCIG using k-induction as master

(b) CoVerCIG using predicate abstraction as master

Figure 5: Quantile plots for CoVerCIG using both masters and different single helpers.

Table 3: Comparison of the two master verifiers running standalone and using a single helper.

| Tool-Combination | correct | additional |
|------------------|---------|------------|
|                 | overall | true  | false | true  | false |
| k-induction      | 146     | 102   | 44    | -     | -     |
| kInd-SH-50       | 148     | 104   | 44    | +3    | 0     |
| kInd-UA-50       | 158     | 114   | 44    | +13   | 0     |
| kInd-VA-50       | 163     | 119   | 44    | +19   | 0     |
| pred abstr.      | 116     | 78    | 38    | -     | -     |
| pred-SH-50       | 122     | 84    | 38    | +6    | 0     |
| pred-UA-50       | 132     | 94    | 38    | +16   | 0     |
| pred-VA-50       | 125     | 87    | 38    | +9    | 0     |

Table 3 gives the results of this experiment. In the table we see the number of correct results, the number of correct true and correct false results plus the the number of tasks additionally solved when using a helper. Through the cooperative invariant generation, the performance of both masters is increased. As expected, this applies to verification tasks with fulfilled safety property only, i.e., the master does not generate invariants in these cases. Besides the additionally solved tasks, there is also one for SH and UA and two for VA tasks, respectively, which cannot be correctly solved anymore. In these cases, the master alone consumes nearly all of the CPU time available, hence sharing resources in cooperation with the helpers results in a timeout.

On our data set, the total number of correctly solved tasks increases using CoVerCIG by 12% for k-induction and 14% for predicate abstraction used as master.

RQ2 (Efficiency). Next, we evaluate the efficiency of CoVerCIG, analyzing the CPU-time spend solving the verification tasks. As CoVerCIG eventually shares the CPU time between master and helpers, we expect that more time is needed to compute a correct result after the helper is started.

Figure 5 shows two quantile plots of the verification runs, the left with k-induction and the right with predicate abstraction as master. A datapoint (x, y) in the plot means that the verifier computes the x fastest correct results (for a task) in at maximal y seconds. As CoVerCIG instances behave like masters standalone in the first 50 seconds, we only show results not solved within these 50 seconds. We see that for tasks requiring a low amount of time, all instances (including the master alone) require a similar amount of CPU time. For tasks requiring more time, CoVerCIG is actually often faster, the extreme being predicate abstraction as master which alone is unable to solve more difficult tasks in the given time.

We exemplarily also compared the CPU time of k-induction standalone with CoVerCIG using VeriAbs as helper per task. It turns out that sharing does only slightly impact the runtime, as shown in Figure 6. The scatter plot compares the CPU time of k-induction standalone as master and k-induction supported by VeriAbs, in case both tools solved the task correctly. A datapoint (x, y) means that k-induction standalone takes x seconds to solve the task and in combination with VeriAbs y seconds. The red dashed box contains all tasks solved within 50 seconds, where both tools behave equally, since the master does not request for help in these cases. We see some tasks for which helping increased the runtime, but also some for which it decreased it. In most of the cases, the CPU time used by CoVerCIG is not significantly higher.

Finally, we compare the average CPU time needed to correctly solve a task. Table 4 shows the average time needed for all tasks and – in brackets – for the correctly solved tasks only. We observe that the runtime increases when only looking at correctly solved tasks (in particular for VeriAbs), however, when considering all tasks the CPU time is even decreased. The latter effect is due to the number of timeouts of the master decreasing when cooperating with helpers. Concluding, we can make the following observation.

13Due to possible imprecisely measured CPU time of BENCHEXEC, we computed an upper bound on the runtime.
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Figure 6: Scatter plot comparing kInd and kInd-VeriAbs-50

Table 4: Total CPU time for all tasks and average CPU time taken for a correct answer in brackets, both in seconds.

| Master standalone | +SH | +UA | +VA |
|-------------------|-----|-----|-----|
| kInd              | 491 (50) | 489 (63) | 477 (68) | 482 (107) |
| Pred              | 479 (30) | 468 (39) | 454 (51) | 470 (49) |

Table 5: Number of correctly verified tasks for different parameters of timerM

| Value of timerM | k-induction | predicate abstraction |
|-----------------|-------------|-----------------------|
|                 | -SH | -UA | -VA | -SH | -UA | -VA |
| 50s             | 148 | 158 | 163 | 122 | 132 | 125 |
| 100s            | 148 | 157 | 161 | 122 | 132 | 125 |
| 200s            | 148 | 157 | 156 | 122 | 132 | 125 |

On our dataset, collaborative invariant generation does not negatively impact the effectiveness; in some cases we even see small improvements.

RQ3 (Time for the Master to request for help). To determine a preferable time for the master to run alone, we evaluated CoVerCIG using 50, 100 or 200 seconds for timerM. A summary of the results is given in Table 5, showing the number of correctly solved tasks for each instantiation. Both masters achieve their best result running alone for 50 seconds. For k-induction, a good choice for timerM plays an important role for its performance. In contrast, the results of predicate abstraction are not influenced by different values for timerM at all, because predicate abstraction computes its correctly given answers on average in 19 seconds after obtaining the invariants by the helpers. When using k-induction, we observe cases where the correct solution is computed only if the master sends the request early. Asking later sometimes leads to a situation where the invariant is obtained too late to be helpful. Hence, we employed 50 seconds in our default configuration which we used to evaluate RQ1 and RQ2.

RQ4 (Combination of helpers). In RQ4, we were interested in finding out (a) whether it is beneficial to run two invariant generators in parallel, and (b) if yes, which pair is best for this.

To this end, we first of all determined which helper is able to solve which of the additionally solved tasks. The result is shown in the Venn diagrams of Figure 7. Surprisingly, SeaHorn – although employing a technique conceptually different to UltimateAutomizer and VeriAbs – is not able to solve a single task which not at least one of the others can.

Next, we thus studied the number of correctly solved tasks using the three possible pairs of helpers, running the two helpers in a pair in parallel. Table 6 in the first row shows the results. It in addition also contains results evaluating two values (100 and 200 seconds) for parameter timeoutH in a setting when the master waits for all helpers to complete (not just the first one). A first observation is that – except for the case of k-induction with UA-VA – the results show no significant difference when using the default configuration or wait-100 or wait-200.

For checking whether parallel execution of helpers is beneficial, these numbers need to be compared against those for a single helper as given in Table 3. We see that predicate abstraction benefits from using two helpers, especially using UltimateAutomizer and VeriAbs. Using CoVerCIG with these tools perfectly combines their strengths, thereby increasing the number of correctly solved tasks in total by 17%. In contrast, it turns out that for k-induction none of the combinations of two helpers outperforms CoVerCIG using VeriAbs only. For UltimateAutomizer and VeriAbs as helpers, the total number does not change, only the set of solved tasks. For instance, nearly 50% of the additional tasks solved by kind-UA-VA are not solved using kInd-UA and vice versa. This result is based on the fact that they have to share the available CPU time in the combination. Hence, tasks that are solved using one of them as helper alone could not be solved anymore in a combination because of timeouts. This phenomenon is even more an issue when running all three helpers in parallel. The combination of all three helpers

(a) For k-induction  
(b) For predicate abstraction

Figure 7: Tasks additionally solved using single helpers
We have conducted our evaluation using a random sample of tasks with testing approaches [18, 19, 21, 22, 24, 26] and with approaches VeriAbs. Table 6: Number of correctly solved tasks using different forms of cooperation with two helpers running in parallel.

| Config       | k-induction | predicate abstr. |
|--------------|-------------|------------------|
|              | SH-UA       | VA               |
|              | SH-UA       | VA               |
| default      | 153         | 156              |
| wait-100     | 156         | 155              |
| wait-200     | 155         | 156              |

solves only 154 tasks correctly for k-induction and 129 for predicate abstraction.

On our dataset, CoVerCIG can increase the total number of correctly solved tasks using UA and VA in parallel; in general waiting for the other tool to also finish its computation does not pay off.

5.4 Threads to Validity
We have conducted our evaluation using a random sample of tasks as well as those in the category Loops. Although this guarantees some diversity in the chosen tasks, our findings may not completely carry over to arbitrary real-world programs. The experiments are conducted using the reliable framework BENCHEXE on identical machines with same resource limitations, guaranteeing comparable results. As SEA-HORN is used within a docker-container, its CPU usage however cannot be measured by BENCHEXE. We therefore measured its CPU usage externally, rounded it up and added it to the measured CPU time, obtaining a lower bound for the correctly solved tasks. Thereby, all results stay valid, especially of the best performing instantiations of CoVerCIG, as they do not use SEA-HORN.

Our implementation of CoVerCIG relies on the correctness of the used master verifiers and helpers (which are given) as well as on the adapters (which we build). An incorrectly translated invariant may however influence the performance only negatively.

Both master verifiers used as well as ULTIMATEAUTOMIZER and VeriABS are participating in the annual SV-COMP, hence they might be tuned to the tasks employed. This does however not influence the validity of the results since our interest is in the additional number of tasks solved by cooperation, not the solved ones per se.

6 RELATED WORK
In this paper, we presented a framework for cooperative verification via collective invariant generation. The idea of collaboration for verification by combining known techniques has been widely employed before. For instance, there are combinations of verification with testing approaches [18, 19, 21, 22, 24, 26] and with approaches for invariant generation [15, 17, 27, 40, 41]. The latter combinations are conducted in a white box manner using strong coupling between the components, making the addition of a new approach a challenging task. Our framework conceptually decouples the invariant generation from the verification, making it more flexible.

In addition, using a black box integration with defined exchange formats allows us to easily exchange or integrate new approaches. There are also existing concepts for collaboration between different techniques in a black-box manner. Conditional model checking is a technique for sequentially composing different model checkers, sharing information between the tools in form of conditions [7]. Beyer and Jakobs developed a concept for combining model checking with testing [8]. Although both approaches enable cooperation, none combines a verification tool and tools for invariant generation.

We next shortly discuss three approaches which are conceptually closer to our framework. Frama-C is a framework for code analysis, aiming for analyzing industrial size code [35]. The framework contains different plugins, each implementing a verification or testing technique. The plugins can exchange information in form of ASCL source code annotations. Within Frama-C, the analyzers can collaborate by being either sequentially or parallely composed. For this, partial results produced by an analysis can be completed by a second one or several partial results computed in parallel are composed to a complete result. Frama-C offers the general possibility to define cooperation between existing plugins. To the best of our knowledge, Frama-C does however not provide a conceptual collaboration of a verification approach and tools for invariant generation driven by the verification approach’s demand for support.

The approach of using continuously refined invariants for k-induction [5] uses a lightweight dataflow analysis which can be considered to be a helper for verification. Therein, the supporting invariant generator runs in parallel to the k-induction analysis. Compared to our framework, the main difference is the form of cooperation used. Beyer et al. use a white-box integration for the cooperation between k-induction and the invariant generator, building hardly wired connections between both analyses and sharing the information inside the tool. Thus, integrating external tools is hard to achieve. Moreover, the approach is designed to work for k-induction only. Note that an analogous approach is proposed by Brain et al. [17].

Pauck and Wehrheim proposed CoDiDROID, a framework for cooperative taint flow analysis for Android apps [39]. Within their framework, different analysis tools with specialized capabilities are combined as black-boxes. CoDiDROID is however tailored to the needs of Android taint flow analysis, thus the exchanged information differs. Thus CoDiDROID is not able to orchestrate or exchange information on safety analysis with shared invariant generation.

To summarize, there are a lot of existing approaches for cooperative verification, but most of them are white-box combinations, and the only existing black-box combinations are not general enough to allows for collective invariant generation.

7 CONCLUSION
In this paper, we have presented a novel form of black box cooperation for software verification via collective invariant generation. Within the configurable framework named CoVerCIG, the so called master verifier steering the verification process is able to delegate the task of invariant generation to one or several helper invariant generators.
We implemented CoVeriCIG within the CPAchecker framework using k-induction and predicate abstraction as master analysis supported by three existing helpers SeaHorn, UltimateAutomizer, and VeriAbs. Our evaluation on a set of SV-COMP verification tasks shows that CoVeriCIG increases the number of correctly solved tasks without increasing the overall verification time. The best combination of helpers, UltimateAutomizer and VeriAbs in parallel, yields an increase of 12% for k-induction and 17% for predicate abstraction.

Next, we plan to enhance the cooperation by analyzing the behavior of the master in order to identify an optimal point to request help. Moreover, extending CoVeriCIG by additionally taking error traces found by the helper into account is also scheduled. In addition, we intend to investigate whether a selection of helpers on the basis of the given verification task is beneficial.
[36] Anvesh Komuravelli, Arie Gurfinkel, and Sagar Chaki. 2014. SMT-Based Model Checking for Recursive Programs. In CAV (LNCS), Armin Biere and Roderick Bloem (Eds.), Vol. 8559. Springer, 17–34. https://doi.org/10.1007/978-3-319-08867-9_2

[37] Kenneth L. McMillan. 2018. Interpolation and Model Checking. In Handbook of Model Checking, Edmund M. Clarke, Thomas A. Henzinger, Helmut Veith, and Roderick Bloem (Eds.). Springer, 421–446. https://doi.org/10.1007/978-3-319-10575-8_14

[38] George C. Necula. 1997. Proof-Carrying Code. In POPL, Peter Lee, Fritz Henglein, and Neil D. Jones (Eds.). ACM Press, New York, NY, USA, 106–119. https://doi.org/10.1145/263699.263712

[39] Felix Pauck and Heike Wehrheim. 2019. Together strong: cooperative Android app analysis. In ASE, Marlon Dumas, Dietmar Pfahl, Sven Apel, and Alessandra Russo (Eds.). ACM, 374–384. https://doi.org/10.1145/3338906.3338915

[40] Williame Rocha, Herbert Rocha, Hussama Ismail, Lucas C. Cordeiro, and Bernd Fischer. 2017. DepthK: A k-Induction Verifier Based on Invariant Inference for C Programs - (Competition Contribution). In TACAS (LNCS), Axel Legay and Tiziana Margaria (Eds.), Vol. 10286. 360–364. https://doi.org/10.1007/978-3-662-54580-5_23

[41] Sriram Sankaranarayanan, Henny B. Sipma, and Zohar Manna. 2005. Scalable Analysis of Linear Systems Using Mathematical Programming. In VMCAI (LNCS), Radhia Cousot (Ed.), Vol. 3385. Springer, 25–41. https://doi.org/10.1007/978-3-540-30579-8_2

[42] Philipp Dominik Schubert, Ben Hermann, and Eric Bodden. 2019. PhASAR: An Inter-procedural Static Analysis Framework for C/C++. In TACAS (LNCS), Tomáš Vojnar and Lijun Zhang (Eds.), Vol. 11428. Springer, 393–410. https://doi.org/10.1007/978-3-030-17465-1_22