Static verification of dynamically detected program invariants: Integrating Daikon and ESC/Java

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Abstract
This paper shows how to integrate two complementary techniques for manipulating program invariants: dynamic detection and static verification. Dynamic detection can propose likely invariants based on program executions, but the resulting properties are not guaranteed to be true over all possible executions. Static verification can check that properties are always true, but it can be difficult and tedious for people or programs to select a goal and to annotate programs for input to a static checker. Combining these techniques overcomes the weaknesses of each: dynamically detected invariants can annotate a program or provide goals for static verification, and static verification can confirm properties proposed by a dynamic tool.

We have integrated a tool for dynamically detecting likely program invariants, Daikon, with a tool for statically verifying program properties, ESC/Java. Daikon examines runtime values of program variables; it looks for patterns and relationships in those values, and it reports properties that are never falsified during test runs and that satisfy certain other conditions, such as being statistically justified. ESC/Java takes as input a Java program annotated with preconditions, postconditions, and other assertions, and it reports which annotations cannot be statically verified and also warns of potential runtime errors, such as null dereferences and out-of-bounds array indices.

Our system runs Daikon, inserts its output into code as ESC/Java annotations, and then runs ESC/Java, which reports unverifiable annotations. The entire process is completely automatic. In our experiments, ESC/Java verified all or most of the invariants proposed by Daikon, and few additional annotations were required.

1 Introduction

Static and dynamic analyses have complementary strengths and weaknesses, so combining them has great promise. Static analysis operates by examining program source code and reasoning about possible executions. It builds a model of the state of the program, such as values for variables and other expressions. Static analysis can be conservative and sound; however, it can be inefficient, can produce weak results, and can require explicit goals or annotations. Dynamic analysis obtains information from program executions; examples include profiling and testing. Rather than modeling the state of the program, dynamic analysis uses actual values computed during program executions. Dynamic analysis can be efficient and precise, but the results may not generalize to future program executions. Our research integrates static and dynamic analysis to take advantage of their complementary strengths: dynamic analysis can propose program properties to be verified by static analysis.

This paper focuses on analyses over program invariants. A program invariant is a property that is true at a particular program point or points, such as might appear in an `assert` statement or formal specification. Invariants include procedure preconditions and postconditions, loop invariants, and object (representation) invariants. Examples include $y = 4 * x + 3$; $x > \mathsf{abs}(y)$; array a contains no duplicates; n = n.child.parent (for all nodes n); $\mathsf{size}(\mathsf{keys}) = \mathsf{size}(\mathsf{contents})$; and graph g is acyclic. Invariants explicate data structures and algorithms and are helpful for programming tasks from design to maintenance. Invariants assist in creation of better programs [Gri81, LG86, HHJ+87b, HHJ+87a], document program operation [LCKS90, KL86], assist testing and enable correct modification [OC89, GKMS00], assist in test-case generation [TCMM98] and validation [CR99], form a program spectrum [AFMS96, RBDL97, HRWY98], and can enable optimizations [CFE99], among other uses. Despite their advantages, invariants are usually missing from programs.

Dynamic invariant detection is a technique for postulating likely invariants from program runs: a dynamic invariant detector runs the target program, examines the values that it computes, and looks for patterns and relationships over those values, reporting the ones that are always true over an entire test suite and that satisfy certain other conditions (see Section 3.1). The outputs are likely invariants: they are not guaranteed to be universally true, because the test suite might not characterize all possible executions of the program.

Static invariant verification is a technique for checking program properties. Given a program and a set of properties over that program, the verifier reports which properties are guaranteed to be true for all executions. Other (unverified) properties might or might not be universally true. Static verifiers can operate by dataflow analysis, theorem proving, model checking, or other techniques. Users of static verifiers must annotate their programs with the properties to be proved (and any other properties on which those might depend).

Combining dynamic invariant detection with static verification has benefits for the user of the invariant detector. Because its output is not guaranteed to be sound, programmers may be reluctant to use it, and its output cannot be fed into other tools that require sound input. A static verifier can indicate which proposed invariants are guaranteed to be true. Users can filter out unverified invariants so that the results are sound or can use the verifications as a first approximation when determining which dynamically detected properties are functional invariants and which are usage properties — both of which are useful, but for different tasks.

Combining dynamic invariant detection with static verification also has benefits for the user of the verifier. Static verification often requires extensive annotations or intermediate assertions and goals. Automatic annotation will relieve users of the burden of annotating programs from scratch — a task few enjoy or are good at. Dynamically detected invariants can also indicate properties programmers might otherwise have overlooked.

We have demonstrated these benefits by integrating a dynamic invariant detector, Daikon [Ern00, ECGN01], with a static verifier, ESC/Java [DLNS98, LNS00]. Our system operates in three steps. First, it runs Daikon, which outputs a list of likely invariants obtained from running the target program over its test suite. Second, it inserts those invariants into the target program as annotations. Third, it runs ESC/Java on the annotated target program to report which of the likely invariants can be statically verified and which cannot. Section 4 gives more details about this process. All three steps are completely automatic, though users may provide guidance in order to obtain better results if desired.

The remainder of this paper is organized as follows. Section 2 presents results from several experiments. Section 3 provides background on the dynamic invariant detector and static verifier used by our system, and Section 4 describes how we integrated these tools. Section 5 discusses problems that arose while building and running our system. Finally, Section 6 relates our results to other research, Section 7 proposes followon research, and Section 8 concludes.

2 Experiments

This section gives both quantitative and qualitative results from several experiments with statically verifying dynamically detected invariants. Sections 2.1 and 2.2 discuss in detail two classes taken from a data structures textbook [Wei99]; Section 2.3 overviews other experiments.

2.1 StackAr: array-based stack

The `StackAr` example is an array-based stack implementation [Wei99]. Code comments specify the behavior of the class but do not mention its representation invariant. Our system determined the representation invariant, method preconditions, modification targets, and postconditions, and statically proved that these properties hold.

Figure 1 shows part of the automatically-annotated source code for `StackAr`. The first six annotations describe the representation invariant. The array is never null, and its runtime type is `Object[]`. The `topOfStack` index is at least -1 and is less than the length of the array. Finally, the elements of the array are non-null if their index is no more than `topOfStack` and are null otherwise.

The next four annotations describe the specification for the constructor. If the capacity is non-negative on entry, then on exit the array length matches the given capacity, the `topOfStack` index indicates an empty stack, and all elements of the array are null. (The final assertion is implied by the representation invariant.)

The `StackAr` class has the constructor and six methods: `isEmpty`, `isFull`, `push`, `top`, `topAndPop`, and `makeEmpty`. The Daikon invariant detector finds 108 invariants: 6 object invariants, 4 requires clauses, 3 modifies clauses, and 95 ensures clauses. However, 17 of the ensures clauses were inexpressible by ESC (see Section 4.2). Also, of the 108 invariants, 75 were redundant and could have been removed by improved redundancy checks in Daikon (see Section 7). Finally, our system heuristically added 2 annotations involving the owner of the array (see Section 4.3).

Without these annotations, ESC issues warnings about many potential runtime errors. With the addition of the detected invariants, ESC successfully checks that the `StackAr` class avoids runtime errors, meets its specification, and maintains important properties during execution.

The invariants guarantee that certain runtime errors are impossible as long as callers meet requires clauses; ESC can be used to check that those preconditions are met in calling code. Errors guaranteed to be absent include null dereferencing, negative array sizes, and array bounds errors.

In addition to proving the absence of errors, our system generated specifications for all operations of the class, and verified that the implementation met the specification. For example, two postconditions for the `topAndPop` method were:

```
(\old(topOfStack) == -1) == (\result == null)
(\old(topOfStack) >= 0) == (\result != null)
```

These invariants state that `topAndPop` returns `null` if and only if the stack is empty upon entry. These invariants were detected by Daikon, proved by ESC, and could be used by ESC while checking code which called the method.

Taken together, the set of assertions for a given method provide a specification by describing its behavior in ways which are useful for reasoning, checking, and program understand-

```
/**
 * Array-based implementation of the stack.
 * @author Mark Allen Weiss
 */
public class StackAr
{
/*@ invariant this.theArray != null */
/*@ invariant \typeof(this.theArray) == \type(java.lang.Object[]) */
/*@ invariant this.topOfStack >= -1 */
/*@ invariant this.topOfStack <= this.theArray.length-1 */
/*@ invariant (\forall int i; (0 <= i & i <= this.topOfStack) ==> (this.theArray[i] != null)) */
/*@ invariant (\forall int i; (this.topOfStack+1 <= i & i <= this.theArray.length-1)
                               ==> (this.theArray[i] == null)) */

    /**
     * Construct the stack.
     * @param capacity the capacity.
     */
    public StackAr( int capacity )
/*@ requires capacity >= 0 */
/*@ ensures capacity == this.theArray.length */
/*@ ensures this.topOfStack == -1 */
/*@ ensures (\forall int i; (0 <= i & i <= this.theArray.length-1) ==> (this.theArray[i] == null)) */
    {
        theArray = new Object[ capacity ];
        topOfStack = -1;
/*@ set theArray.owner = this */
    }

    ...

    /*@ spec_public */ private Object [ ] theArray;
/*@ invariant theArray.owner == this */
    /*@ spec_public */ private int        topOfStack;

    ...

}
```

Figure 1: The object invariants, first method, and field declarations of the annotated `StackAr.java` file [Wei99]. The JML annotations (comments starting with "`/*@`") are produced automatically by Daikon, are automatically inserted into the source code by our system, and are automatically verified by ESC/Java.

ing. The assertions do not necessarily give a full input-output relation, however.

The specifications derived from detected invariants are useful for several reasons. First, specifications have the general benefit that users can read the specification to understand behavior, instead of reasoning about the implementation. Additionally, static tools can check the assertions, and can use the (checked) assertions to perform reasoning about calling code. Also, programmers modifying existing code may be aided by knowledge of existing invariants which the code preserves.

In general, these generated specifications inform users about the abstraction in terms of the implementation. In one sense, this is a deficiency because abstract datatypes (ADTs) should hide the implementation through the use of specification. On the other hand, certain invariants are useful without describing the implementation (such as a result being non-null), and invariants which refer to implementation details are still more useful than no specifications at all.

Finally, the invariants contain potentially important properties of the implementation. For example, the representation invariant on `StackAr` guarantees that unused array elements are set to null. This guarantees that objects popped from the stack will not be prevented from being garbage collected.

2.2 DisjSets: union-find disjoint sets

A second example illustrates the usefulness of our approach, even when necessary invariants are not automatically detected.

The `DisjSets` class is an array-based implementation of disjoint sets, a partition of some range of integers into disjoint subsets that support the `union` and `find` operations [Wei99]. Code comments specify the behavior of the class but do not mention its representation invariant. Our system determined part of the representation invariant, method preconditions, modification targets, and postconditions, and statically proved that most of these properties hold.

Our system found 259 invariants over the class. Of these, 62 were not expressible in JML, 11 were object invariants, 56 were requires clauses, 2 were modifies clauses, 126 were ensures clauses, and 2 were test suite artifacts which could not be proven true in general. Again, 2 annotations involving the owner of the array were added by a heuristic. Of the 197 invariants expressible in JML, 155 were redundant (given our additions to the representation invariant, described immediately below).

ESC could not initially prove some of the detected invariants because two components of the representation invariant were missing:

```
(\forall int i; (0 <= i & i <= this.s.length-1)
                 ==> (this.s[i] >= -1))
(\forall int i; (0 <= i & i <= this.s.length-1)
                 ==> (this.s[i] != i))
```

Once these two invariants were added by hand, ESC was able to prove 195 of the 197 expressible invariants, and it warned about the two (unprovable) test suite artifacts. Because ESC assumes rather than proves preconditions, test suite artifacts in preconditions would not be a problem (as long as the class did not call its own methods in its implementation).

Even though the `DisjSets` class could not pass through the system without user assistance, the annotations provided are still extremely helpful. The addition of two object invariants by hand is certainly easier than fully annotating a program from scratch.

Adding a test for the lower bound of the elements of an array to the Daikon invariant detector would provide one of the missing invariants. This would be both simple and generally useful.

Daikon could also compare array elements to their indices to detect the $a[i] \neq i$ invariant. However, it is not clear that this invariant would make sense in general contexts, as few programs may use such an invariant. In this example, the invariant is helpful and informative, but is not strictly necessary; many useful properties can be detected and proved without it. The invariant is needed to prove certain other detected invariants, such as $a[0] \neq 0$. However, these other invariants could be removed without impairing the usefulness of the specifications [FL, FJL00].

2.3 Other experiments

We have run our system on approximately ten other examples, primarily chosen from textbooks and from staff solutions to problem sets in a programming course at MIT. We selected these particular programs because they contain representation invariants that are interesting and nontrivial but are not obviously beyond the capabilities of ESC. Given ESC's intended use as a lightweight technology for detecting a restricted class of runtime errors, this choice may be questionable. However, we wished to explore the limits of what invariants can be dynamically detected and statically verified, and good object invariants are usually required in any event to determine that array accesses are within bounds and variables are non-null.

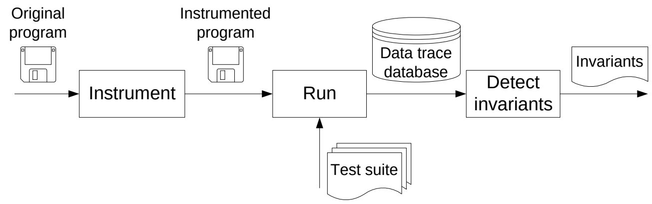

Figure 2: An overview of dynamic detection of invariants as implemented by Daikon.

We were not able to verify all the detected invariants for these other programs. We found there were three general classes of problems with these other examples. First and foremost were artifacts of the test suites, which initially resulted in many irrelevant invariants. The initial test suites were unit tests that came from the textbooks or were used for grading. We speculate that unit tests, which tend to be smaller and more stylized than typical usage, throw off Daikon's statistical justification tests (see Section 3.1), which seem to work well when running system tests [ECGN01].

The second class of problem involved invariants that Daikon could not detect — generally missing classes of invariants, as discussed in Section 2.2. For instance, we would have liked to prove the equality of the denominators of the argument and result of the `RatNum.negate` method. However, that would require detecting that the numerator and denominator of the argument are in reduced form and that the `gcd` operation called by the constructor therefore has no effect. We had previously rejected such invariants as of insufficiently general applicability.

The third class of problems involved ESC's inability to prove certain invariants. We found that discovering the source of the second and third class of problems was easy and quick, and we had little trouble convincing ourselves of the correctness or incorrectness of the invariant or the code. By comparison, extending the unit test suites to find the interesting invariants in Daikon's output was time-consuming and tedious. In the future we will avoid starting with unit tests.

3 Background

3.1 Daikon: Invariant Discovery

Dynamic invariant detection [Ern00, ECGN01] discovers likely invariants from program executions by instrumenting the target program to trace the variables of interest, running the instrumented program over a test suite, and inferring invariants over the instrumented values (Figure 2). The inference step tests a set of possible invariants against the values captured from the instrumented variables; those invariants that are tested to a sufficient degree without falsification are reported to the programmer. As with other dynamic approaches such as testing and profiling, the accuracy of the inferred invariants depends in part on the quality and completeness of the test cases. The Daikon invariant detector is language independent, currently supporting instrumenters for C, Java, and Lisp.

Daikon detects invariants at specific program points such as loop heads and procedure entries and exits; each program point is treated independently. The invariant detector is provided with a variable trace that contains, for each execution of a program point, the values of all variables in scope at that point. Each of a set of possible invariants is tested against various combinations of one, two, or three traced variables.

For variables x, y, and z, and computed constants a, b, and c, some examples are: equality with a constant ($\mathsf{x = a}$) or a small set of constants ($\mathsf{x \in \{a, b, c\}}$), lying in a range ($\mathsf{a \leq x \leq b}$), non-zero, modulus ($\mathsf{x \equiv a \pmod b}$), linear relationships like $\mathsf{z = ax + by + c}$, ordering ($\mathsf{x \leq y}$), a range of functions ($\mathsf{x = fn(y)}$), and invariant combinations ($\mathsf{x + y \equiv a \pmod b}$). Also sought are invariants over a sequence variable such as minimum and maximum sequence values, lexicographical ordering, element ordering, invariants holding for all elements in the sequence, or membership ($\mathsf{x \in y}$). Given two sequences, some example invariants are elementwise linear relationship, lexicographic comparison, and subsequence relationship.

In addition to local invariants such as $\mathsf{node = node.child.parent}$ (for all nodes), Daikon detects global invariants over pointer-directed data structures, such as mytree is sorted by $\leq$. Finally, Daikon can detect conditional invariants that are not universally true, such as "if $\mathsf{p \neq null}$ then $\mathsf{p.value > x}$" and "$\mathsf{p.value > limit}$ or $\mathsf{p.left \in mytree}$". Pointer-based invariants are obtained by linearizing graph-like data structures. Conditional invariants result from splitting data into parts based on the condition and comparing the resulting invariants; if the invariants in the two halves differ, they are composed into a conditional invariant [EGKN99].

For each variable or tuple of variables, each potential invariant is tested. Each potential unary invariant is checked for all variables, each potential binary invariant is checked over all pairs of variables, and so forth. A potential invariant is checked by examining each sample (i.e., tuple of values for the variables being tested) in turn. As soon as a sample not satisfying the invariant is encountered, that invariant is known not to hold and is not checked for any subsequent samples. Because false invariants tend to be falsified quickly, the cost of computing invariants tends to be proportional to the number of invariants discovered. All the invariants are inexpensive to test and do not require full-fledged theorem-proving.

To enable reporting of invariants regarding components, properties of aggregates, and other values not stored in program variables, Daikon represents such entities as additional derived variables available for inference. For instance, if array `a` and integer `lasti` are both in scope, then properties over `a[lasti]` may be of interest, even though it is not a variable and may not even appear in the program text. Derived variables are treated just like other variables by the invariant detector, permitting it to infer invariants that are not hardcoded into its list. For instance, if `size(A)` is derived from sequence `A`, then the system can report the invariant $\mathsf{i < size(A)}$ without hardcoding a less-than comparison check for the case of a scalar and the length of a sequence. For performance reasons, derived variables are introduced only when known to be sensible. For instance, for sequence `A`, the derived variable `size(A)` is introduced and invariants are computed over it before `A[i]` is introduced, to ensure that `i` is in the range of `A`.

An invariant is reported only if there is adequate evidence of its plausibility. In particular, if there are an inadequate number of samples of a particular variable, patterns observed over it may be mere coincidence. Consequently, for each detected invariant, Daikon computes the probability that such a property would appear by chance in a random input. The property is reported only if its probability is smaller than a user-defined confidence parameter [ECGN00].

The Daikon invariant detector is available for download from `http://sdg.lcs.mit.edu/~mernst/daikon/`.

3.2 ESC: static checking

ESC [Det96, DLNS98, LN98] is an Extended Static Checker that has been implemented for Modula-3 [Nel91, Har92] and Java [JSGB00]. It statically detects common errors that are usually not detected until run time, such as null dereference errors, array bounds errors, and type cast errors.

ESC is intermediate in both power and ease of use between typecheckers and theorem-provers, but it aims to be more like the former and is lightweight by comparison with the latter. Rather than proving complete program correctness, ESC detects only certain types of errors. Programmers must write program annotations, many of which are similar in flavor to `assert` statements, but they need not interact with the checker as it runs over the annotated program. ESC issues warnings about annotations that cannot be proven and about potential run-time errors.

ESC performs modular checking: it checks different parts of a program independently and can check partial programs or modules. It assumes that specifications for missing or unchecked components are correct. We will not discuss ESC's checking strategy in more detail because this research treats ESC as a black box (it is distributed in binary form). We did have to add specifications for some library functions, which was an easy task.

ESC/Java is a successor to the previous ESC/Modula-3. ESC/Java's annotation language (a variant of JML; see Section 4.2) is simpler, because it is slightly weaker. This is in keeping with the philosophy of a tool that is easy to use and useful to programmers rather than one that is extraordinarily powerful but so difficult to use that programmers shy away from it.

Both versions of ESC are publicly available from `http://research.compaq.com/SRC/esc/`.

4 Implementation

This section discusses our implementation. We enhanced Daikon's invariant detection capabilities to permit it to report certain invariants (Section 4.1). To permit ESC to verify the detected invariants, they must be converted into ESC's input language, JML (Section 4.2). Finally, some annotations are added heuristically (Section 4.3).

4.1 Daikon additions

We made several enhancements to Daikon to make its output easier for ESC to prove.

We added some invariants over sequence elements, such as that all elements are greater than another variable. Such invariants were present in a previous implementation of dynamic invariant detection [ECGN01] but had not been added to the current implementation.

We suppressed object invariants from all preconditions and postconditions of non-private methods. This greatly reduces the number of reported invariants, making them more manageable without removing any information.

We listed which variables are modified by the routine. This output can sometimes be misleading. For instance, the disjoint set union routine modifies `s[set2]`; but `set2` might be 0, so `s[0]` is also listed as possibly modified, even though it is never modified unless `set2` is 0. We plan to eliminate this extraneous listing by a combination of statically analyzing the method text and heuristically omitting from the modification list sometimes-modified variables that overlap with always-modified variables.

Finally, we added to Daikon's list of splitting criteria which it uses to produce implications [EGKN99]. Daikon uses splitting criteria to split data into two parts; if different invariants are true in the parts of the data, they can be combined into implications or disjunctions. The new splitting criteria split boolean functions based on their return value and split functions with multiple exit points based on which return statement (or fallthrough) was executed.

4.2 JML notation

ESC's input language is a variant of JML, the Java Modeling Language [LBR99, LBR00]. JML is an interface specification language that can specify the behavior of Java modules. Most relevant to this research are its ability to specify object representation invariants and method preconditions and postconditions. JML expressions are written in a syntax closely resembling Java. In the sequel, "JML" refers to the JML variant accepted as input by ESC.

Daikon's default output language is also similar to Java, with extensions that permit certain varieties of invariant to be expressed more concisely or clearly than would be possible in Java. As a user option, Daikon can produce output in JML. The differences between these formats fall into two categories. When the semantics differ because JML is less convenient or concise but the languages are equally expressive, we usually convert Daikon's output to JML. In cases where JML cannot express concepts that Daikon discovers and expresses in its own language, we omit those invariants when attempting verification with ESC.

Semantic differences

Daikon's default output format supports array comprehensions such as `a[i..j]` to represent the subarray of `a` from indices `i` to `j` inclusive. Daikon also permits quantification via the expression "*`array`* `elements`"; for instance, this.s elements $\leq$ this.s.length. Daikon represents accesses to arrays, vectors, and linked lists uniformly and succinctly with subscripting notation, `a[i]`. Field accesses may be applied to sequences, indicating a sequence of the specified fields. By contrast, JML expresses expressions over arrays via an explicit `\forall` quantifier and cannot access vector or linked list elements.

By default, expressions in Daikon's output are assumed to hold only when their subexpressions are sensible. For instance, foo.bar $= 22$ means "foo $=$ null or foo.bar $= 22$", and a[i] $>$ x means "i < 0 or i $\geq$ a.length or a[i] $>$ x". A Daikon switch makes these guards explicit in the output or eliminates invariants over expressions that are sometimes nonsensical. In ESC, use of an expression like `a[i]` when `i` may not be a legal index can result in failure to verify and uninformative error messages.

Daikon's object invariants are specified to hold at entry and exit of non-private methods, whereas ESC's are required to hold at entry and exit of all methods. However, private helper methods need not require or maintain object invariants. We do not rewrite Daikon's object invariants by repeating them at all appropriate method entries and exits, because we judged that to be too verbose and confusing; this prevents some true (public) object invariants from being proved by ESC.

Invariants inexpressible in JML

Daikon and JML method postconditions can indicate that expressions should be evaluated in the prestate. Daikon's `orig()` can apply to array objects, array contents, and array elements/subsequences: `orig(a)[i]`, `orig(a[])[i]`, and `orig(a[i])` may be different (if `a` or `a[i]` are assigned by the method body); furthermore, `orig(a)[orig(i)]` and `orig(a[])[orig(i)]` may differ from any of the above. All of these expressions have come up in realistic and useful invariants we have encountered in programs. JML's `\old()` cannot apply to array contents or to method parameters of primitive type. Furthermore, it cannot be nested, and there is no \new() notation that can be placed inside an \old() expression. (Some of these limitations can be worked around by tricks such as existential quantifiers, but the resulting invariants are not particularly readable.)

JML annotations cannot include method calls, even ones that are side-effect-free. Daikon uses these for obtaining `Vector` elements and as predicates in implications.

Unlike Daikon, JML cannot express closure operations, such as all the elements in a linked list. Properties over such collections are often the most interesting and important invariants over recursively defined data structures.

4.3 Other annotations

When adding invariants to the source code preparatory to verification by ESC, we make private variables accessible to the specification with the `spec_public` annotation. Additionally, in each constructor we set the `owner` ghost field of each field to the object itself. This states that the contents of the field are not aliased by other objects. Without this annotation, ESC reasons that the field can be arbitrarily modified at any time by another method, and very little whatsoever can be proved. Adding this annotation without examining the source code is unsafe, but this discipline is very frequently followed, so it has been acceptable in practice.

5 Challenges

This section discusses challenges to static verification of dynamically detected program invariants. These challenges fall into three general categories: problems with the tools, problems with the target programs, and problems with the test suites for the target programs. In some cases we have largely solved the problems, and in other cases difficulties remain to be overcome.

5.1 Tools

Section 4.1 listed enhancements made to the Daikon invariant detector as a part of this research. As Daikon is still a prototype, we anticipate that additional changes may be required in the future, particularly as it is extended to new varieties of invariant. In particular, as noted in Section 2.2, Daikon is missing some invariants over array elements. Also, strengthening its checks for redundant invariants will reduce the size of its output and improve comprehensibility without removing any information.

Section 4.2 noted problems with ESC's input language, a variant of JML that cannot express certain important invariants and cannot concisely and clearly express others. In some cases ESC does not appear to be strong enough to verify certain true invariants, and its error messages are occasionally cryptic. However, in general we have been pleased with ESC: it has operated effectively and efficiently. For instance, though we have not run ESC on Daikon's source code, ESC has detected at least two bugs in Daikon by failing to verify reported invariants that, upon closer inspection, were not true. (Both bugs were cut-and-paste errors: in one case, the invariant formatting routine was incorrect, and in another case, the first element of an array was not being examined.)

JML cannot express invariants over strings, and Daikon reports few such invariants in any event. As a result, it is difficult for ESC to prove that object invariants hold at the exit from a constructor or other method that interprets a string argument, even though it can show that the invariant is maintained by other methods.

In some cases, ESC cannot prove properties Daikon reports (such as that two variables happen to have the same value in a special circumstance), because the property depends on an object invariant that is beyond Daikon's scope. Users can either add such invariants by hand or delete the properties that depend on them (see Sections 2.2 and 6.1).

5.2 Target programs

Another challenge to static verification of invariants is the fact that programs are likely to contain errors that prevent the desired invariant from being true. (Although it was never our goal, we have previously identified such errors in textbooks [Gri81, Wei99] and in programs used in testing research [HFGO94, RH98].) As an example of a likely error that we detected in the course of this project, one of the object invariants for `StackAr` states that unused elements of the stack are null; this permits objects to be garbage-collected after the stack is popped and permits earlier detection of certain types of error. The `topAndPop` operation maintains this invariant (which approximately doubles the size of its code), but the `makeEmpty` routine fails to do so — a nonobvious oversight which the implementor and clients should be appraised of.

5.3 Test suites

The largest problem with our technique is that dynamic invariant detection can produce properties that are true for the test suite over which the target program was run, but which are not true for arbitrary runs of the program. However, that problem is solved by integrating dynamic invariant detection with static verification. The static verifier indicates that some invariants are universally true; the others might be true but beyond the capabilities of the verifier, might be true of the context in which the program is always run, or might be accidental usage properties of the test suite. In the latter case, the reported invariants specify the unintended property of the test suite that makes it less general than it should be, so a programmer knows exactly what is wrong with the test suite and exactly how to fix it.

Because static verification partly solves the question of which invariants are necessarily true in all contexts, the remainder of this section only treats this problem in the absence of static verification: how difficult is it to eliminate all properties that are not universally true from the output, so that it verifies with no warnings whatsoever?

In some cases the "bad" invariants gave valuable hints about test cases that needed to be added to the test suite. For instance, certain stack operations were not performed on a completely full stack, and a queue implemented via an array was not forced to wrap around by adding and deleting more elements than its capacity. As another example of a serious oversight, a safe stack pop operation happened to always be protected by a check whether the array was empty. The resulting invariants stated that the result was always non-null, indicating that the full functionality of the method was not being tested.

In other cases, the tests exercised situations that were not special cases in the particular implementations we examined, but which might easily have been in implementations that used other representations or were heavily optimized; we judged these additions, too, to be worthwhile.

In yet other cases, however, eliminating the undesirable invariants was a tedious chore. It required finding a test case that falsified a particular special case that had little to do with the abstraction (it was relevant to the data structures, but not the logic, of the particular implementation). The largest problems were undesirable upper and lower bounds for variables. We speculate that Daikon's statistical tests for whether such invariants should be reported are faulty and need to be overhauled. It is also possible that, since those statistical tests strive to be time- and space-efficient, they make too many approximations and do not produce an accurate result.

6 Related work

This is the first research we are aware of that has dynamically generated, then statically proved, program properties.

Dynamic analysis has been used for a variety of tasks; for instance, inductive logic programming (ILP) [Qui90, Coh94] produces a set of Horn clauses (first-order if-then rules) and can be run over program traces [BG93], though with limited success. Programming by example [CHK+93] is similar but requires close human guidance, and version spaces can compactly represent sets of hypotheses [Mit78, Hir91, LDW00]. Value profiling [CFE97, SS98, CFE99] can efficiently detect certain simple properties at runtime. Event traces can generate finite state machines that explicate potential system organization or behavior [CW98a, CW98b]. Program spectra [AFMS96, RBDL97, HRWY98, Bal99] also capture aspects of system runtime behavior. None of these other techniques have been as successful as Daikon in detecting invariants in programs, though many have been valuable in other domains. Many static inference techniques also exist, but space prohibits discussing them here.

There are many other techniques and tools besides ESC for statically checking formal specifications; for example, [Pfe92, DC94, EGHT94, Det96, Eva96, NCOD97, LN98]. These other systems have different strengths and weaknesses than ESC, but few have the polish of its integration with a real programming language.

6.1 Houdini

The research most closely related to ours is Houdini, an annotation assistant for ESC/Java [FL, FJL00]. Houdini is motivated by the observation that users are reluctant to annotate their programs with invariants; it attempts to lessen the burden by providing an initial set. Houdini takes a candidate annotation set as input and computes the greatest subset of it that is valid for a particular program. It repeatedly invokes the checker and removes refuted annotations, until no more annotations are refuted. The candidate invariants are all possible arithmetic comparisons among fields (and "interesting constants" such as -1, 0, 1, array lengths, and `null`); many elements of this initial set are mutually contradictory.

Daikon's candidate invariants are richer than those of Houdini; Daikon outputs implications and disjunctions, and its base invariants are also richer, including more complicated arithmetic and sequence operations. If even one required invariant is missing, then Houdini will eliminate all other true invariants that depend on it. Houdini makes no attempt to eliminate implied (redundant) invariants, as Daikon does (reducing its output size by an order of magnitude [ECGN00]), so it is difficult to interpret numbers of invariants produced by Houdini. Finally, Houdini is not publicly available, so we cannot perform a direct comparison.

Merging the two approaches could be very useful. For instance, Daikon's output could form the input to Houdini, permitting Houdini to spend less time eliminating false invariants. (A prototype "dynamic refuter" — essentially a weak dynamic invariant detector — has been built [FL], but no details or results about it are provided.) Houdini has a different intent than Daikon: Houdini does not try to produce complete specification or annotations that are good for people, but only to make up for missing annotations and permit programs to be less cluttered; in that respect, it is similar to type inference. However, Daikon's output could perhaps be used in place of Houdini's. Invariants that are true but depend on missing invariants or are not provable by ESC would not be eliminated, so users might be closer to a completely annotated program, though they might need to eliminate some invariants by hand.

7 Future work

Section 5 listed a number of problems with our system (and with its components Daikon and ESC) that should be corrected.

Another obvious way to extend this work is to use different invariant detectors than Daikon or different verifiers than ESC. Section 6 lists some other invariant detectors. Examples of static verifiers that are connected with real programming languages include LCLint [EGHT94, Eva96, Eva00], LOOP [JvH+98], Java PathFinder [HP00], and Bandera [CDH+00].

We are currently integrating Daikon with IOA [GLV97, GL00], a formal language for describing computational processes that are modeled using I/O automata [Lyn96, LT87, LT89]. The IOA toolset (`http://theory.lcs.mit.edu/tds/ioa.html`) permits IOA programs to be run and also provides an interface to the Larch Prover (LP) [GG90, GG91, SAGG+93], an interactive theorem-proving system for multisorted first-order logic. Daikon will propose goals, lemmas, or intermediate assertions for the theorem prover. Side conditions such as representation invariants can enable proofs that hold in all reachable states/representations (but not in all possible states/representations). It can be tedious and error-prone for people to specify the properties to be proved, and current systems have trouble postulating them; some researchers consider that task harder than performing the proof [Weg74, BLS96].

We are also interested in recovering from failed attempts at static verification. Broadly speaking, verification fails because the goal properties are too strong or are too weak. Properties that are too strong may be true but beyond the capabilities of the verifier, or may not be universally true (for instance, artifacts of the test suite or guaranteed by the program context). Properties that are too weak are true, but cannot be proved by the static verifier or are not useful to it — for instance, loop invariants may need to be strengthened to be proved. We anticipate that dynamic invariant detection will propose more overly strong invariants than overly weak ones. When verification fails, we would like to know how to strengthen and weaken invariants in a principled way, by examining the source code, program executions, patterns of invariants, and verifier output, to increase the likelihood of successful verification.

While dynamic invariant detection has been quite successful, we believe that truly successful program analysis requires both static and dynamic components. What is hard for one variety of analysis is easy for the other. Some of the properties that are difficult to obtain from a dynamic analyses are apparent from an examination of the source code, and properties that are beyond the state of the art in static analysis can be easily checked at runtime. We plan to integrate more static analysis into our system (and particularly into Daikon). The dynamic analysis need not check properties discovered by the static analysis, the dynamic analysis focus on statically indicated code.

8 Conclusion

We have demonstrated the feasibility of dynamically detecting, then statically verifying, program invariants. In particular, we have built a system that takes the output of the Daikon invariant detector and feeds it to the ESC static checker. Experiments demonstrate that Daikon is effective at proposing useful invariants and that ESC is effective at verifying those invariants. Integrating dynamic invariant detection with static verification has benefits for both tools.

Use of a static verifier to augment dynamic invariant detection overcomes a potential objection about possibly unsound output, classifies the output to permit programmers to use it more effectively, permits proven invariants to be used in contexts (such as input to certain programs) that demand correct input, and may improve the performance or output of dynamic invariant detection. As a result, more programmers can take advantage of dynamically detected invariants in a variety of contexts, directly leading to fewer bugs (by introducing fewer and detecting more), better documentation, less time wasted on program understanding, better test suites, more effective validation of program changes, and more efficient programs.

Use of dynamically detected invariants to bootstrap static verification, by annotating programs or by providing goals and intermediate assertions, will speed the adoption of static analysis tools by lessening the user burden, even if some work remains for the user. The direct effect of increased use of these tools will be the detection of more errors earlier in the software development process, statically at compile time rather than dynamically at test time (or, worse, after an application has been fielded). The indirect effect will be the production of more robust, reliable, and correct computer systems. Both visible faults and silent errors will occur less often, and it will be easier to maintain these properties during a program's life because of machine checking of conditions that program correctness depends upon.

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