STATIC VERIFICATION OF DYNAMIC PROPERTIES

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ABSTRACT

This paper is a tutorial on the principles and applications of static verification of dynamic properties to development, verification and validation of embedded applications. The topics covered include what static verification of dynamic properties is, how it works, how it can help in verification and validation activities. It will also present an industrial tool for the automatic detection of run-time errors.

KEYWORDS

run-time errors, static verification, software reliability

1. INTRODUCTION

The principles of static verification of dynamic properties are based on a paradigm that is at the heart of other engineering activities. Activities such as designing a bridge, computing the trajectory of a satellite or optimizing the shape of a plane wing are all based on applied mathematics, whose use is facilitated by high-speed processors. If we want to formalize this statement, we would say that all these engineering activities are based on a central paradigm that consists of a three-step method:

- Modeling a physical world system as a set of mathematical equations
- Solving these equations using high-speed processors
- Using the solutions to these equations to predict the behavior of the physical system

However, there is one engineering activity that has not yet fully benefited from this paradigm when it comes to verification and validation: software engineering. Indeed, software validation is still often mostly based on test techniques which consist in enumeratively executing the application a high number of times. If you succeed in running a high enough number of executions without observing any error, then the software is considered validated. Unfortunately this does not imply that the software is free of run-time errors. Indeed, detecting a run-time error during tests requires:

1. Executing the right statement during tests …
2. … with the right combination of values (as mere execution of the statement may not be enough) …
3. …and detect the error if it occurs (as triggering the error may not be enough)

Even achieving 100% statement coverage during tests may not be enough to detect all errors.

We thus propose to adopt a new approach to software validation: the use of methods based on applied mathematics such as static verification of dynamic properties.

2. WHAT IS STATIC VERIFICATION OF DYNAMIC PROPERTIES?

Static verification of dynamic properties is a software analysis technique that is based on data-flow analysis. Data-flow analysis is a branch of computer science which aims to statistically compute program properties. It is basically done in two steps: translating programs into equations over lattices and then solving these equations by fixed-point iterations. It is now widely used in modern compilers for code optimization purposes. It was pioneered by Kildall in 1973 [1].

Here are a few examples of program-point specific properties computable by data-flow analysis used in optimizing compilers:

- A first example is the computation of live variables. The basic idea is to determine a set of variables that will be possibly used in the future so as to be able to allocate the same register to variables that are not simultaneously live.
- A second example is constant propagation. Here the aim is to replace reads of variables which always have the same value at a given point by a constant.
- A third example is computing available expressions. It consists in determining a set of expressions that are always evaluated in the past and so to proceed to Common Subexpression Elimination (CSE). Similarly, determining very busy expressions – a set of expressions which will always be evaluated in the future allows loop invariant elimination and code motion.

Those are all examples of what is currently done through the use of traditional data-flow analysis. On the other hand, static verification of dynamic properties extends data-flow analysis by providing an additional theoretical framework that allows the mathematical justification of data-flow analyzers, the design of new data-flow analyses and the handling of particular infinite sets of properties ([2], [3] and [4]).

To further describe how static verification of dynamic properties works, we now consider a simple flowchart language as an example. This consists in:

- 32 bits integer variables and integers;
- arithmetic operations;
- assignments;
- conditionals and loops.

In this language, states are pairs consisting of:

- An integer representing the current flowchart instruction to be executed
- A vector of integers in a n-dimensional state where n is the number of variables in program P

We define what strongest global invariants SGI(k) are: SGI(k) is the set of all possible states that are at program point k and reachable in program P. For the flowchart language defined previously, it is a set of points in an n dimensional space. A run-time error is then triggered when SGI(k) intersects a forbidden zone.

SGI(k) is the result of formal proof methods, or it can be expressed as least fixed-points of a monotonic operator on the lattice of a set of states. SGI(k) may thus be seen as the solution of a system of equations whose unknowns are sets of states.
We use the Floyd/Park/Clarke method [5], [6] and [7] as follows:

Step 1: Translate program P to a system:

$X_1 = F_1(X_1,\dots,X_m)$
$X_2 = F_2(X_1,\dots,X_m)$
…
$X_m = F_m(X_1,\dots,X_m)$

Step 2: Compute the least solution $(V_1,\dots,V_m)$
We do this by using a Kleene ascending sequence:

$X_{i,0} = \varnothing$
$X_{i,k+1}=F_i(X_{1,k},\dots,X_{m,k})$

We now define the result: $SGI(p)=V_p$

Let us consider an example of such a computation with the following program:

```
        K=ioread_i32();
1.      I=2;
2.      J=K+5;
3.      while (I<10)  {
```

```
        4. I=I+1;
        5. J=J+3;
6.    }
7.
8.    … / (I-J)
```

Here the non-obvious risk is a divide-by-zero. That is what we are going to check with the Floyd/Park/Clarke method.

Step 1: Translate program P to a system

We get the following set of equations:

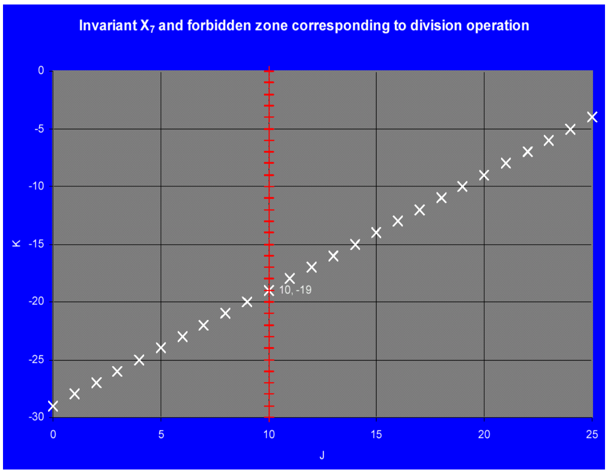
$$
\begin{aligned}
&X_0=\{(0,0,k) \mid k\in[-2^{31},2^{31}-1]\}\\
&X_1=\{(2,j,k) \mid (i,j,k) \in X_0\}\\
&X_2=\{(i,k+5,k) \mid (i,j,k) \in X_1\}\\
&X_3= X_2 \cup X_6\\
&X_4=\{(I+1,j,k) \mid (i,j,k) \in X_3, i<10\}\\
&X_5=\{(i,j+3,k) \mid (i,j,k) \in X_4\}\\
&X_6= X_5\\
&X_7=\{(i,j,k) \mid (i,j,k) \in X_3, i =10\}\\
&X_8=\{(i,j,k) \mid (i,j,k) \in X_7, i-j\neq 0\}\\
&X_{error}=\{(i,j,k) \mid (i,j,k) \in X_7, i-j =0\}
\end{aligned}
$$

Step 2: Compute the least solution

$X_0=\{(0,0,k) \mid k\in [-2^{31},2^{31}-1]\}$
$X_1=\{(2,0,k) \mid k\in [-2^{31},2^{31}-1]\}$
$X_2=\{(2,k+5,k) \mid k\in [-2^{31},2^{31}-1]\}$
$X_3=\{(i,j,k) \mid k\in [-2^{31},2^{31}-1], i\in [2,10], j=k+3i-1\}$
$X_4=\{(i,j,k) \mid k\in [-2^{31},2^{31}-1], i\in [3,10], j=k+3i-4\}$
$X_5=\{(i,j,k) \mid k\in [-2^{31},2^{31}-1], i\in [3,10], j=k+3i-1\}$
$X_6= X_5$
$X_7=\{(10,j,k) \mid k\in [-2^{31},2^{31}-1], j=k+29\}$
$X_8=\{(10,j,k) \mid k\in [-2^{31},2^{31}-1], j=k+29, j\neq 0\}$
$X_{error}=\{(10,10,-19)\}$

Dividing by zero will occur at point 8 when K = -19. Observe that this constant does not appear in the source.

It can be represented graphically as follows:



However, for general purpose languages, SGI(k) is non-computable. Indeed, the halting problem (deciding if a program stops) is reducible to checking that SGI(k)=∅ but the halting problem has been proved undecidable [8]. Thus computing SGI(k)=∅ is undecidable, as shown in [9].

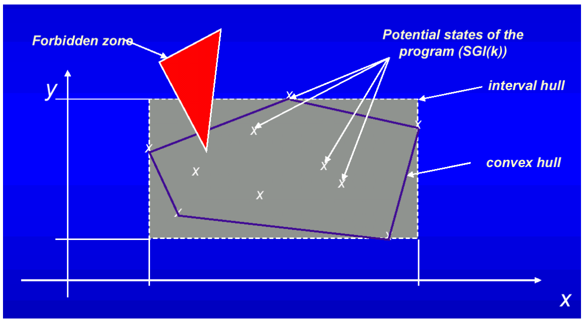
Static verification of dynamic properties aims at computing *approximate solutions* to SGI(k) ([3] and [4]). The seminal idea is to:

1. Replace the system of exact equations by its image with a closure operator ρ that is :
   - monotonic: $x\subseteq y \Rightarrow \rho(x)\subseteq\rho(y)$
   - extensive : $x\subseteq\rho(x)$
   - idempotent : $\rho(\rho(x)) = \rho(x)$

2. Solve this approximate system in the abstract lattice $\rho(L)$, possibly aided with widening operators.

Thus, the solution of the approximate system is necessarily a superset of the solution of the exact system. This approach is thus semantically safe.

We now represent graphically how it works:



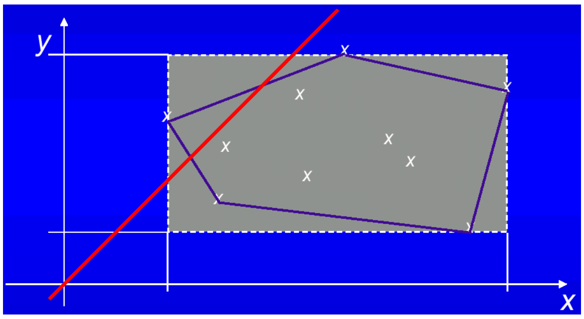
Let's take an example. We want to check the following C language statement:

```
A = x / (x-y);
```

The correctness condition to check to make sure that no zero division runtime error can occur is (x-y)≠0

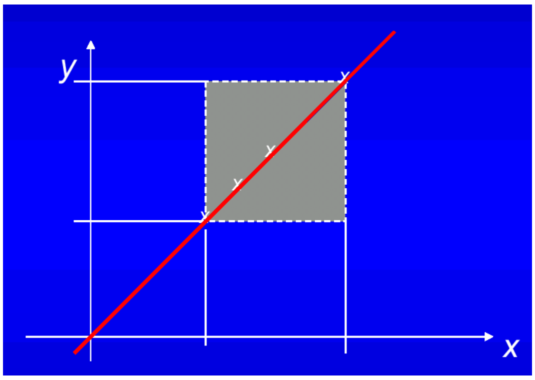
We may encounter three different situations.

1. The intersection between the failure state and the state space of the program is not empty :



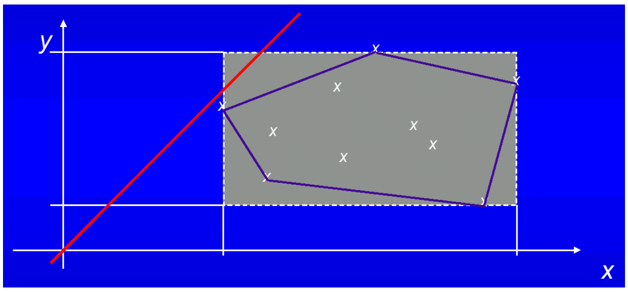
In this case, there is a potential error.

2. The state space of the program is completely included in the failure state:



In this case, there is a certain error.

3. The failure state is outside the state space of the program :



In this case, there is provably no zero-divide error for this program statement that can occur in any future execution of the program.

However, to efficiently analyze real-world programs, this framework is not enough. Indeed, real-world programming languages set other challenges, such as the use of functions/subprograms, pointers, data structures (arrays, records…), dynamic allocation or multi-tasking. Thus, other abstract lattices must be defined. For example, it may be necessary to define a lattice of unitary-prefix monomial relations ([10] and [11]) to represent complex pointer aliasing patterns such as:

{((*(X+I) +4), *(Y+j)) I i = 2j+1}*

In this case, the principle of the solution is to reduce the problem of representing relations over regular language L∈ Σ* to that of finitely representing sets of points in Z^n. To do so, we use Eilenberg's unitary-prefix (UP) decomposition that maps each L to a finite number of UP monomials. Each UP monomial is then mapped to a set of points through Parikh's mapping or through free modular group decompositions.

To summarize, the key properties of this approach are the following:

- A real error will never be signaled as *no error* due to the fact that we take into account a superset of all possible states
- An instruction which is always correct will never be signaled as *certain error*
- Exhaustive analysis of run-time errors is done by examining only operations signaled as *potential* or *certain* errors. The others can be seen as proven to be error-free.
- There is no need to provide test cases as inputs: the analysis is totally automatic
- Diagnostics are valid for any future execution: only one analysis is needed

3. APPLYING STATIC VERIFICATION OF DYNAMIC PROPERTIES: POLYSPACE VERIFIER

Because the concepts of static verification of dynamic properties were developed in the seventies, one may wonder why it has not been industrialized earlier. The answer to this question is a lack of available computing power – it is now possible to use static verification of dynamic properties on a high-end PC – and the fact that precise and scalable analyses were simply not available. Indeed, many published methods were either too imprecise or too costly (not scaling to more than a few hundred lines of code) to be actually usable in an industrial context.

Before exploring how static verification of dynamic properties has been industrialized, let us define what it cannot do. Indeed, it is essential to understand that it addresses the dynamic behavior of the program *by essence*. Static verification of dynamic properties doesn't check any syntactic properties (such as readability, testability, maintainability or portability), but instead focuses on semantics. Syntax is the domain of rule-checking tools, and static verification of dynamic properties is not applied in such tools. Semantics is the realm of static verification of dynamic properties.

Static verification of dynamic properties has been successfully applied to detect run-time errors. Run-time errors are a well-defined set of errors that may lead to non-determinism, incorrect results or processor stop. A study conducted by Sullivan and Chillarege at IBM Watson and Berkeley found that 26% of all observed software faults and more than 57% of the highest severity faults (causing system outage or major disruption) were due to run-time errors.

Detecting run-time errors statically and at compilation time, thanks to static verification of dynamic properties, allows shortening and/or replacing the following activities :

- Debugging, by finding run-time errors automatically
- Robustness testing, by pinpointing exhaustively sources of run-time errors
- Functional testing, by allowing these tests to not be interrupted by the late detection of robustness issues (requiring further work to localize the bug, fix it and then run non-regression tests)
- Code reviews and documentation, by extracting control and data flow information
- Code acceptance review, by providing an objective, third-party, way of measuring the quality of a given code

The first industrial tool for detecting runtime errors using static verification of dynamic properties is PolySpace Verifier. This tool has been commercially available since 1999 for the analysis of Ada programs and since 2000 for the analysis of ANSI C programs. This tool addresses two essential needs of embedded software development:

- Static verification : it statically predicts specific classes of run-time errors and sources of non-determinism
- Semantic browsing: it statically computes data and control flow to improve program understanding, ease verification and demonstrate the compliance of the program with industry standards (SIL, DO178-B, MISRA, …)

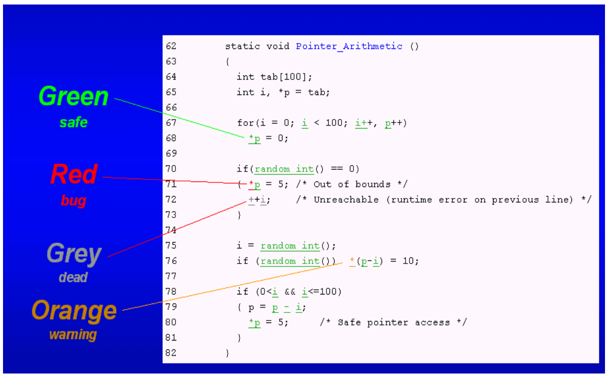
Run-time errors detected by PolySpace Verifier include:

- Dereferencing through null
- Out-of-bounds pointers
- Out-of-bounds array accesses
- Read access to non-initialized data
- Access conflicts on shared data (multithreaded applications and/or interrupt routines)
- Invalid arithmetic operations: division by zero, square root of a negative number …
- Overflow and underflow on integers and floating-point numbers
- Unreachable (dead) code

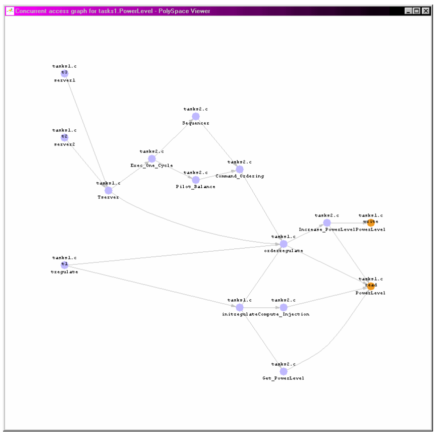
The use of the tool is very simple. It takes as an input the code source of an application and produces as a result a color-coded source where each operation is classified according to the risk of run-time errors if it were executed. There are four categories:

- Green: the operation will never trigger a run-time error for all possible executions of the program
- Red: the operation will always (i.e. at each execution of the program) generate a run-time error.
- Grey: the operation cannot be executed – it is a piece of dead code
- Orange: this is a warning – there may be an error, depending on the specific calling context of the function that contains the operation

The following is an example of a color-coded source code provided by PolySpace Verifier:



As to control and data flow documentation and understanding, PolySpace Verifier builds the global data dictionary and a concurrent access graph for each shared variable of the program. The following figure is an example of concurrent access graph provided by PolySpace:



4. INDUSTRIAL USE OF STATIC VERIFICATION OF DYNAMIC PROPERTIES

Among static verification of dynamic properties first industrial uses is the static analysis of the embedded ADA flight software and inertial central of the Ariane 5 launcher and the ARD (Atmospheric Reentry Demonstrator). The analyzer designed by the author was used on the Ariane 502 flight program [12]. Since then, it has been successfully used by CNES and Aerospatiale on Ariane flight programs. As described in [12], these software programs consist of about 70,000 lines of code with five interacting parallel tasks.

After this first successful industrial use, static verification of dynamic properties has been industrialized by our team and turned into commercially available tools. New users from several industry sectors have experienced the efficiency of these tools:

- An end-user in the avionics industry analyzed a Flight Management System (FMS) of about 500,000 lines. The conclusion of this end-user was that "*the cost savings allowed by the tool in the final phase of the project was between $150,000 and $250,000*" as a consequence of several serious errors uncovered by the tool – including data races.
- CSEE, a railway signaling systems company, also reported successful use of static verification of dynamic properties in its development teams for the analysis of several embedded software programs in Ada and ANSI C with sizes between 20,000 and 80,000 lines of code.
- Triconex, a chemical industry company analyzed a fault-tolerant controller software for safety-critical units in petrochemical and chemical plants. Two applications of 70,000 lines of C code and 140,000 lines of Ada code were analyzed, yielding a savings of 10,000 man-hours of testing and a time-to-market shortened by 6 to 12 months according to the user.
- A major international automotive supplier used static verification of dynamic properties to conduct a module-by-module analysis of 200,000 lines of diesel engine control software code. Several serious errors were found on a sample of 32 modules of a validated application despite 100% unit-test coverage with automated test tools.

These examples are only a very partial list of industry sectors that benefit from static verification of dynamic properties. Indeed, more than 50 development teams all over the world have already adopted our tools and every embedded software developer which aims at reducing the cost of its testing effort and increasing the quality of its applications is a potential user of this kind of tool.

5. CONCLUSION

Static analysis to demonstrate the absence of run-time errors, once the domain of theoretical researchers, has come of age. Researchers gave it solid foundations. Yet using static verification of dynamic properties does not require any theoretical background. It is a radical breakthrough in software engineering that makes it possible to shorten the verification and validation cycle thanks to an earlier detection of run-time errors. It is a repeatable technique that may be used at any time, without any prior knowledge of the code to be analyzed. It also provides a strong improvement in reliability, as it is exhaustive by design.

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