WCET measurement using modified path testing

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Abstract

Prediction of Worst Case Execution Time (WCET) is made increasingly difficult by the recent developments in microprocessor architectures. Instead of predicting the WCET using techniques such as static analysis, the effective execution time can be measured when the program is run on the target architecture or a cycle-accurate simulator. However, exhaustive measurements on all possible input values are usually prohibited by the number of possible input values. As a first step towards a solution, we propose path testing using the PathCrawler tool to automatically generate test inputs for all feasible execution paths in C source code. For programs containing too many execution paths for this approach to be feasible, we propose to modify PathCrawler's strategy in order to cut down on the number of generated tests while still ensuring measurement of the path with the longest execution time.

1 Introduction

Prediction of Worst Case Execution Time (WCET) is made increasingly difficult by the recent developments in processor architectures [3]. This is because the execution time of an instruction in the source code has become strongly dependent on the state of the machine at the time the instruction is executed because events such as data cache misses and bad branch prediction use up many more cycles than individual instructions. These events are difficult to predict by static analysis of the program code, especially when the precise architecture of the processor is not divulged by the manufacturer. Moreover, static analyses must continually keep up with the latest architectural innovations.

2 First step to a solution : path testing

The structural testing field provides a first step towards an alternative to pure static analysis. The 100%-feasible-path structural test criterion guarantees that at least one test case is executed for each feasible execution path in the source code of the program under test. Suppose that the longest effective execution time is found for a test set which satisfies this criterion. This will be the WCET if we can suppose that execution of the same path in the source code, starting from the same initial state of the machine, will always give the same execution time. In fact, we need to make the following assumptions, each of which requires careful analysis to be sure that a safe WCET is obtained:

1. *Each feasible execution path in the source code gives rise to at most one feasible execution path in the binary code* (even if it is not the same path): this is true for most compilers and options.
2. *The execution time of a feasible execution path in the binary code is the same for all input values which cause the execution of this path*: in fact the execution time of some instructions such as division or square root may vary for different values of input data but it should be possible to measure this variation and either choose input values accordingly or else add a penalty to the measured execution time for each such instruction in the path. Cache behaviour may also cause this condition to be violated, e.g. if an execution path contains successive references to elements of a data structure with variable indices and the data structure is large enough to provoke a cache miss for some values of the indices but not for others. Input values should therefore be chosen so as to maximise the difference between index values of the same data structure used in neighbouring references.
3. *For each test case it is possible to set the machine to some worst possible initial state concerning cache behaviour, branch prediction, etc before running the test*: in fact, it is impossible to prove which initial state is the worst possible for a given test case without detailed knowledge of the microprocessor. However, by using our knowledge of the test case (branches, addressed variables,…) and broad characterisations of cache and dynamic branch prediction behaviour we

can construct a program to be run just before the program under test and put it into what should be the worst possible state. Cache and branch prediction algorithms are based on past behaviour so such a program might aim to fill the caches with useless data and instructions and repeatedly run the program under test on paths with branches which are the opposite of those in the test case. Note that in the case of embedded, reactive, cyclical systems, the initial state of the machine is often the state in which it was left by the last execution of the same program. In this case, all possible sequences of previous test cases which create the initial conditions for a given case can be either run (if not too numerous) or analysed to find which seems to be the worst.

4. *Variations in external system behaviour such as bus activity, DRAM refresh, do not influence execution time*: in fact, the measured time may have to be weighted to account for such aspects [1][7].

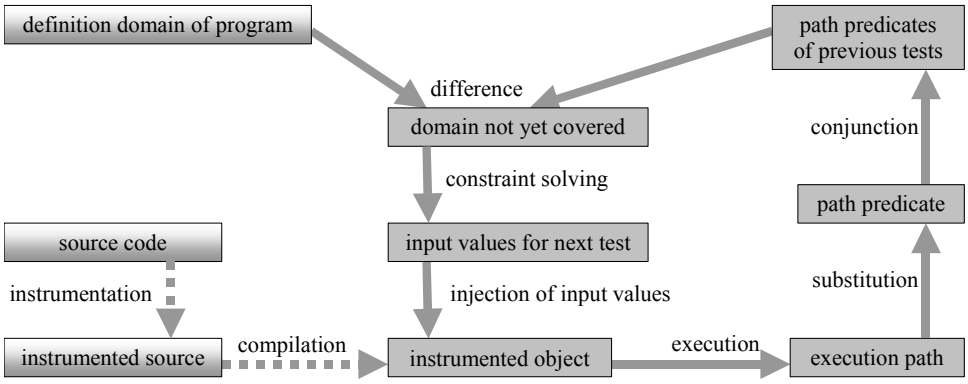
3 The PathCrawler tool for automatic generation of path tests

We have developed the PathCrawler prototype tool to automatically generate test inputs to cover 100% of feasible execution paths in a C program. It takes as inputs the C source code and a specification of the legitimate input values. This consists of a list of the input variables and the range of values and dimensions they may have, as well as any preconditions to avoid run-time errors. Indeed, the effective input parameters of a C function cannot always be deduced from its code: not all of the formal parameters may be effectively referenced, some may have their value changed but their value on input may never be read and, conversely, values of some global variables may be read by the code. Moreover, in the case of structured variables and pointers, it may only be the values of certain elements or fields that are read on input, or the values accessed by pointer de-references. This why PathCrawler currently calculates the set of all possible input parameters (fields, elements, de-references, etc of formal parameters and global variables of the program under test), which may contain many elements which are not in fact input parameters, and then asks for the user's help in reducing the set.

PathCrawler also starts with the default input range of each input parameter given by its type declaration. For example, it is supposed that each integer input could take any value from -2^{31} to $2^{31}-1$. However, the user has the opportunity to reduce these ranges if the effective values of the inputs will always be much more restricted. In this way the user can also define different modes or scenarios for which the WCET is to be measured. Finally, the program may contain operations which will cause a runtime error if applied to certain values (e.g. division by zero). The user can specify a pre-condition (using a limited form of quantification in the case of array elements) to restrict input values to those which avoid such runtime errors or exclude other illegitimate program inputs. Note that no annotations of source or object code are necessary. The output of the PathCrawler tool is a set of test inputs with the execution path covered by each.

PathCrawler is based on a novel approach to test case generation which is illustrated in Figure 1. It starts with an instrumentation of the source code so as to recover the symbolic execution path each time that the program under test is executed. The instrumented code is executed for the first time using a "test-case" which can be any set of inputs from the domain of legitimate values. PathCrawler recovers the corresponding symbolic path and transforms it into a path predicate which defines the "domain" of the path covered by the first test-case, i.e. the set of input values which would cause the same path to be followed (see Figure 2). The next test-case is found by solving the constraints defining the legitimate input values outside the domain of the path which

Figure 1 : the PathCrawler test generation process



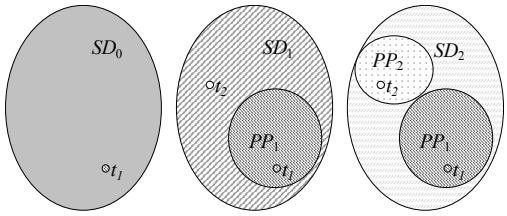


Figure 2:Incremental coverage of the input domain

is already covered. The instrumented code is then executed on this test-case and so on, until all the feasible paths have been covered. In Figure 2 SD_0 is the set of legitimate inputs, t_1 is the first test case generated, PP_1 is defined by the predicate of the path covered by t_1, SD_1 is the difference between SD_0 and PP_1, t_2 the second test case generated, PP_2 defined by the predicate of the path covered by t_2 and SD_2 is the difference between SD_1 and PP_2.

PathCrawler could be implemented to treat source code in any imperative programming language. The current prototype [8] treats a wide range of ASCII C programs, which may include arrays and pointers but it cannot yet treat type unions, pointers to functions and recursive functions.

The inputs for each successive test case are found using constraint solving techniques. For integer, Boolean and character variables constraint solving is NP-complete in the worst case, but PathCrawler uses heuristics which give much lower complexity in practice. Note that this is the complexity of the search for inputs for a given path if it is feasible, or of the determination of its infeasibility if not. Constraint solving can determine which paths are infeasible and so can automatically discover the maximum number of iterations of a loop (by determining the infeasibility of paths with too many iterations). This is why the user does not need to provide the maximum number of iterations.

Current constraint-solving techniques for floating-point variables model them using real numbers, which poses the problem of potential loss of precision during constraint resolution. Also, constraint solving based on real numbers has a complexity which is undecidable in non-linear cases. However, current research on constraint solving for floating point numbers proposes using a finite representation in order to avoid these problems [5].

PathCrawler adopts an approach to test-case generation which combines static and dynamic analysis so as to avoid the problems encountered by other, purely static or dynamic, approaches, as explained in [8]. The result is a very efficient generation of test inputs: for one example program described in [8] 20993 tests were generated and 15357 infeasible path prefixes detected in approximately 116 seconds of CPU execution time on a 2GHz PC running under Linux.

4 The next step: measuring fewer execution paths

Path testing avoids exhaustive testing of all inputs but some programs have too many feasible execution paths to be able to measure all of them. This is why some hybrid approaches to WCET prediction propose a combination of decomposition of the program and measurement of the effective execution time of each component [4][6].

We are exploring a different approach which is not based on path decomposition but instead takes advantage of the fact that PathCrawler's test generation strategy can be modified so as to decide not to generate inputs for certain paths, meaning that the excluded paths will not be tested. The decision can be based on information obtained beforehand (e.g. by static analysis of the control flow graph) or dynamically (e.g. by additional instrumentation) when the program is run on the other test cases.

We would like to use this possibility to define a new strategy which cuts down the number of paths for which test cases are generated, but guarantees coverage of the path with the longest execution time, so that the WCET is still safe. The idea is to first modify the strategy in order to favour early generation of test cases covering the paths with the most instructions in the hope that these will include some of the paths with longer execution times. Before generating a test for each new path prefix, PathCrawler would then determine which paths in the control flow graph could have this prefix. If any of those paths were sure to have a shorter execution time than an already measured path, then they could be excluded from test generation.

The problem is to identify the paths which certainly have a shorter execution time than a given path. Of course this is not always possible but the combinatorial explosion in the number of paths in a program can be partly due to very minor differences between paths. Even in the presence of features such as memory caches and branch prediction, we can suppose that the execution time of a path depends on the instructions in the path, including the variables referenced by each instruction, and their order. The order of instructions may be modified during compilation or execution but in some cases we should be able to suppose that it will be modified in the same way for the different paths. In these cases, a path which contains a subset of the instructions and variable references, in the same order, of another already measured path, cannot have more memory cache misses or bad branch predictions than the measured path. It therefore cannot have a longer execution time.

The most obvious example of this is two paths which are identical except in the number of iterations they perform of a loop with a variable number of iterations and with no branches in the body of the loop. Note that the parts of the path before, after and inside the loop must be identical. It seems safe to assume in this case that the path with fewer iterations has a shorter execution time than the other one. If the execution time of the path with more iterations has already been measured then there is no need to generate a test for the other path.

Other examples of common code constructions which result in paths which are very similar are :

a) the maximum: if (a > b) then max = a else max = b;

b) a limit: if (a > limit) then a = limit;

(but note that in these cases we may need to take into account the possibility of a bad branch prediction in one of the paths and not the other). We should also be able to identify paths which differ only by instructions which have the same execution time in the same context, e.g. x = a + b; and x = a – b;

Further study is needed to define a full set of conditions under which one path has a shorter execution time than another. Static analysis of the control flow graph can then be used to determine for each path in the graph those paths which have a shorter execution time, i.e. to impose a partial order on the paths in the control flow graph. The instrumentation and the test generation strategy of PathCrawler can then be modified to use this partial order to exclude paths from test generation.

For example, to eliminate paths differing only in the number of iterations of a certain loop, we annotate loop head instructions during instrumentation. PathCrawler's strategy is first modified to use these annotations to ensure that if the path covered by the previous test case contains a loop with a variable number of iterations then the next test generated covers a path with a prefix which increases the number of iterations of this loop. This favours early generation of paths with more loop iterations. Secondly, the strategy excludes from future test generation all the paths identical to the already generated ones except for a lower number of loop iterations.

5 Conclusions

Using PathCrawler to generate a test set to measure WCET promises the following advantages :

- no need for code annotations;
- most ANSI C programs can be treated;
- to measure the execution time of the whole program only two observation points are necessary ;
- no need to predict micro-architectural events such as cache miss, pipeline stall, out-of-order execution, as long as they are deterministic for a given execution path in the source code.

The feasibility of the approach we suggest relies on the extent to which the number of tests can be reduced using simple hypotheses about e.g. cache behaviour and branch prediction. The safety of the WCET obtained also depends on the validity of using such hypotheses to exclude paths and define the initial state(s) for each test case. Further analysis, as well as experiments on different program examples, are needed in order to evaluate the categories of program or micro-architecture for which a sufficient number of paths can be eliminated (in less time than it would take to generate tests for them) to effectively cut the combinatorial explosion in the number of paths and obtain a safe WCET.

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