

BINSEC/SE: A Dynamic Symbolic Execution Toolkit for Binary-level Analysis

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Abstract—When it comes to software analysis, several approaches exist from heuristic techniques to formal methods, which are helpful at solving different kinds of problems. Unfortunately very few initiative seek to aggregate this techniques in the same platform. The BINSEC platform intent to fulfill this lack for binary software by allowing to perform modular and parametric analysis. This work focusses on BINSEC/SE, the new dynamic symbolic execution engine (DSE) implemented in BINSEC. We will highlight the novelties of the engine, especially in terms of interactions between concrete and symbolic execution or optimization of formula generation. Finally, two reverse engineering applications are shown to emphasize the tool effectiveness.

I. INTRODUCTION

While security can be checked and enforced at different level, we focus here on binary-level security analysis, such as malware comprehension or vulnerability analysis. Reverse engineering of binary codes is a key component of these activities, yet it is notoriously difficult. Especially, low-level assembly constructs can lured disassemblers, while dynamic execution explores only a few possible behaviors. Our long-term goal is to adapt formal methods, which have been very successful in source-level safety analysis, to binary-level security analysis. We present in this paper a binary-level dynamic symbolic execution engine, named BINSEC/SE, geared toward security analysis, especially reverse-engineering.

The main contribution is a highly configurable generic DSE engine toolkit, with a strong interaction between the tracer and the symbolic execution core, as well as heavy optimizations of the path predicate. Two reverse engineering applications are shown to emphasize the tool effectiveness.

II. BACKGROUND

Dynamic Symbolic Execution [5, 10] is a formal technique allowing to explore in a systematic way the paths of a program. Basically, the technique amounts to compute for a single path its *path predicate*, i.e. the set of constraints on the program input that, if met, leads to follow that path at runtime. This predicate is then fed to an automatic constraint solver¹: a solution to the predicate is a new test input exploring

the targeted path. Systematic exploration is achieved through iterating on all (user-bounded) paths of the program.

BINSEC [9] is a recent platform for formal analysis of binary codes. The platform currently proposes a front-end from `x86` to a generic intermediate representation called DBA [9] (including decoding, disassembling, simplifications), a simulator and a static analysis engine (typically for dynamic jump resolution). The platform is written in OCaml (~ 30000 *loc*), and will be released under an open source license soon². Our DSE engine BINSEC/SE is built upon BINSEC. The current tool paper describes only BINSEC/SE, a consequent add-on to BINSEC reusing only the `x86` to DBA translation.

III. USER VIEW

From a user point of view, the advance of using a DSE engine is twofold. First, nowadays closed source binaries and malwares are so commonly widespread that having tool for working at binary level is mandatory. Second, recovering information from a binary can be tedious task, especially in heavily obfuscated binaries. Therefore applying automatic techniques for recovering information is crucial with regards to the usual amount of code to review.

During a reverse-engineer task or a information retrieval task, the analyst can be interested in knowing information about the binaries like, the register value at a given location, the possible values at a given memory address, whether a given branch can be covered or not or the possible targets of a dynamic jump. These problems can be addressed by DSE.

Various dynamic analysis are already implemented in BINSEC/SE and new ones can conveniently be written using a callback mechanism. An analysis takes a JSON configuration file as input and a trace file. Both the configuration and trace files format are open and specified.

IV. BINSEC/SE ARCHITECTURE

We describe hereafter the new module for DSE, named BINSEC/SE. Its implementation is made of three components, presented in Figure 1.

¹Typically, SMT solvers. See <http://smtlib.cs.uiowa.edu/> for an overview.

²<http://binsec.gforge.inria.fr/>

- a pintool named PINSEC, written in C++ (~ 2000 *loc*), based on the Pin DBI framework [11] for dynamic tracing;
- the core DSE engine written in OCaml (~ 7500 *loc*), whose task is to generate path predicates, send them to a solver and get back new input data;
- the path selector, written in OCaml (~ 1200 *loc*), in charge of choosing which path to explore next.

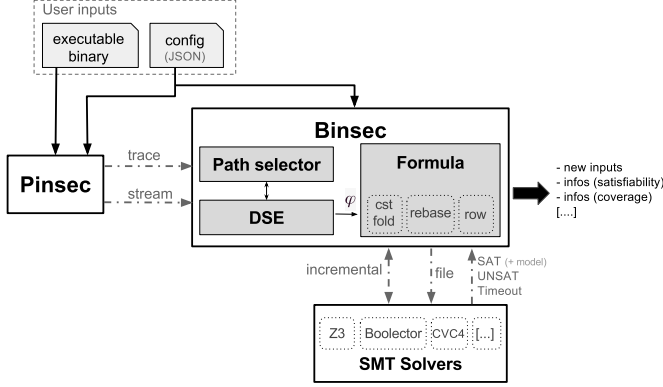


Fig. 1. BINSEC/SE architecture

A. The PINSEC tracer

The tracer, called PINSEC, is a pintool [11] specialized in analyzing x86/x86-64 architectures. It is designed to offer a generic and modular tracing for both Linux and Windows binaries, and to export results into a generic trace format, here `protobuf`³ which is readable using major programming languages. The tracing is parameterized via a JSON file also defined in `protobuf`. The main parameters are:

- `start` and `stop`: addresses indicating where to begin and end the tracing,
- `call_skips`: address of calls for which the callee should not be traced,
- `fun_skips`: function addresses that should not be traced.

Other command line parameters allow to limit the trace size, the tracing time or the instrumentation scope.

Advanced usage. What differentiate PINSEC from other pintools are the following functionalities:

- the automatic retrieval of function parameters and return values for (some) libraries functions;
- the possible retrieval of the concrete value of any register or memory location, even if not part of the operands / results of the currently instrumented instruction;
- the injection of symbolic or concrete values in any register or memory location, at any step of the execution;
- a remote command and control system allowing the DSE core and PINSEC to exchange messages in an interactive, debugger-like manner, in order to dynamically tune the instrumentation.

A full-fledged example using some of these parameters is presented in Section VI.

³<https://developers.google.com/protocol-buffers/>

B. DSE engine

Our DSE engine (Figure 1) follows a classical workflow. From an input trace, x86 instructions are translated to DBA instructions [9] (such a translation can be seen in Figure 2) on which the path predicate is computed [13], and then used to generate a formula (theory of arrays and bitvectors) which is then exported to the SMTLIB2 format [3], the standard input of modern SMT solvers. A SMT solver is finally used to check the satisfiability of the formula and if so, to get back a solution (new input). We currently rely on Z3, CVC4 and Boolector. The connexion between BINSEC/SE and PINSEC easily allows to re-inject the new input and get a new trace.

Implementation insight. Internally an analysis is represented as a OCaml class for which each analysis should inherit. This class provides appropriate callbacks and data structures for implementing any kind of analysis. Main callbacks are:

- `pre_execution`, `post_execution` triggered respectively once at the beginning and the end of the analysis;
- `visit_instr_before`, `visit_instr_after` triggered respectively before and after every asm instruction of the trace;
- `visit_dbainstr_before`, `visit_dbainstr_after` triggered respectively before and after every DBA instructions of an x86 instruction;
- `input_message_received` triggered when a message is received from PINSEC.

A summary of all the callbacks location call is given in Figure 2. These callbacks allow to apply specific actions at a specific step and/or location along the execution in a highly configurable manner. They help developing new analyses without a deep understanding of the whole inner-working of the DSE.

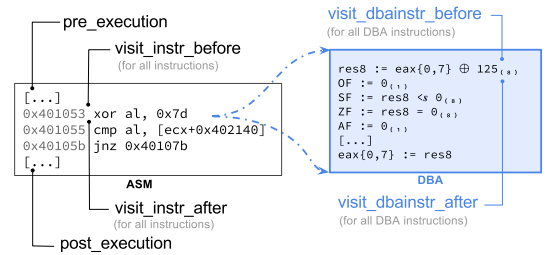


Fig. 2. BINSEC/SE callbacks

C. Path selection

Beside a fine-grained control of single trace execution, automatic multiple path exploration is also a desired feature of a DSE tool. Ideally, the path exploration engine should allow either to fulfill some standard coverage requirements, or to focus on specific parts of the code through dedicated (user-defined) search heuristics. The design of the exploration module of BINSEC/SE is inspired from the one of OSMOSE [1]. It relies on a simple API allowing to easily implement various exploration strategies. In particular this API offers a function `select(S)` returning the “best” trace from a set of trace S , w.r.t. a user-defined `score` function. Scores are built from

several (predefined or dynamically computed) trace criteria, such as length, call-depth of the last instruction, distance to a given target, etc. This approach allows to precisely define a wide-range of exploration strategies. Several such strategies are already implemented, (DFS, BFS, random path, MinCall-DFS and MinCall-BFS [2]).

V. FORMULA GENERATION AND SOLVING

The bottom-line of DSE is path predicate generation. While we follow the standard approach [13], i.e. maintaining a symbolic memory state along the computation together with the encountered path constraints (i.e. branching conditions), our method is original in several respects:

- we can take into account constraints on the initial memory state (cf. Section V-B);
- we provide callback mechanisms for fine-tuning of concretization and symbolization (cf. Section V-C);
- the path predicate is highly optimized, and we take advantage of incremental solving (cf. Section V-A).

A. Optimizations

The core engine implements several optimizations of the path predicate, ranging from standard simplifications such as constant folding, local rewriting (e.g. $a \oplus a$ becomes 0) or pruning useless parts of the formula, to less common optimizations, such as Read-over-Write (RoW) simplifications over array load and store [6]. Finally, great care is taken in order to make these optimizations compatible with the incremental solving mode of modern SMT solvers, which is particularly well-suited to DSE, since path predicates are naturally built incrementally.

Table I shows the results of optimization on a set of malware samples (cf. Section VI-B), while Table II shows a more detailed view on a single trace taken from the Artelad malware. Time out is set to 20 seconds, the solver is Z3 and we use an Intel core i7 2.7 GHz with 16GB.

Malware	#inst	#br (#queries)	#Solved	no-Incr			Incr		
				no-opt	pruning	full-opt	no-opt	pruning	full-opt
Artelad	10K	1295	1295	42m36	31m27	18m18	12m34	11m57	9m6
Benny	10K	3150	3510	14m35	10m34	7m54	3.64	2.58	2.94
Bogus	10K	191	191	41m51	7.71	7.34	1.45	2.98	3.41
Cornad	404	32	21	4m10	4m10	4m5	4m43	4m40	4m37
Eva	1069	115	115	3.44	2.07	1.98	0.16	0.15	0.16
Htrip	2525	1410	1410	15m6	12m23	11m34	18.36	18.52	11.17
Total	303998	6193	6181	118m25	58m48	42m03	17m46	17m3	14m3
Avg/query				1.15	0.57	0.40	0.16	0.16	0.14

time in seconds, or minutes/seconds Avg/query: average time per query
 full-opt: all optimization turned on – no-opt: all optimizations turned off
 Incr: incremental solving – no-Incr: non-incremental solving

TABLE I
OPTIMIZATION BENCHMARKS

	no-opt	pruning	full-opt
#VarsDef	27375	8952	3026
#Constraints	1585	1581	379
#Memory operations	1589	1585	1136
#Operators	85805	6330	2278

TABLE II
EFFECTS OF OPTIMIZATIONS

B. Initial memory state

Logical arrays are unconstrained by default. Hence, modelling the initial memory state as a logical array implies that the solver is free to give any value to any memory location of the initial state, possibly leading to meaningless results, since the initial mapping of addresses in a real program is more complex. BINSEC/SE allows to specify constraints on the initial memory state (initial logical array).

C. Concretization/Symbolization

For scalability issues, the path predicate is often approximated, either by forcing some logical values to their runtime values (observed by the tracer) – concretization, or by injecting fresh logical input – symbolization. Both operations reduce the complexity of the formula, at the price of completeness and/or correctness. So choosing appropriately when to concretize or to symbolize is a major practical issue. While most tools offer only a hardcoded policy, BINSEC provides a complete set of callbacks to specify such choices.

VI. EXPERIMENTATIONS

A. Reverse engineering

In reverse-engineering, so-called *crackme* challenges simulate real world situations where binary programs are designed to make the analysis difficult. The goal is usually to find a string key (the flag) allowing to validate the challenge.

Flare-On is a reverse engineering challenge organized since 2014 by FireEye Security⁴. We consider the first problem of the 2015 challenge since it is straightforward enough to be discussed in detail. This is a 32 bits Windows crackme which asks for a password and prints “You are success” or “You are failure” depending on the keyboard input. Each byte of the input (`input_buffer`) is xored with `0x7d`, the result is then checked against a key stored in the data section (`data_str`), cf. Figure 3.

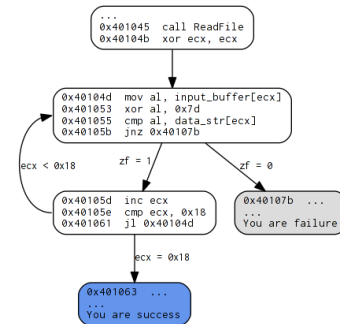


Fig. 3. Flare-on #1 key loop computation

Solving the crackme by symbolic execution aims at checking that the predicate $ZF=1$ is true at the location `0x40105b`; and this, for every character of the key. If the generated formula is satisfiable, then the right character can simply be retrieved in the formula solution at `input_buffer[ecx]`. Yet,

⁴<http://www.flare-on.com/>

the last remaining problem arising is the initial state. If none is specified, the solver is allowed to give any valuation to the content of `data_str`, which are not user-controllable. Hence, an initial state constraining the value of the `data_str` bytes is required in order to get meaningful results for `input_buffer` (cf. Section V-B). Finally, iterating over `input_buffer` can be done in two ways:

- 1) From a trace taking the fail branch, solve $ZF=1$ at `0x40105b` to get the right char and inject it as input via the configuration file for generating a new trace that will do a second loop iteration. Repeat until the whole key is found;
- 2) Configure a breakpoint at `0x40105b` (the address of `jnz`), compute the right character value, send a command to patch the `ZF` flag and resume to force the tracer to take the right branch and looping again. This method allows to solve all the character value in $\mathcal{O}(n)$ with regard to the trace matching the right key.

We obtain the right key solving the challenge, `bunny_sl0pe@flare-on.com`⁵. Note that we have solved several other Flare-on challenges with the same principle.

B. Malware exploration

We are interested here in demonstrating the ability of BINSEC/SE to automatically discover new code areas of a program, which is especially crucial in malware analysis. We consider 11 malware programs taken from the VX Heaven database⁶ and used in recent work on deobfuscation [12]. Table III shows our results. We report the number of new explored paths (i.e. each time DSE manages to negate a branch of the original trace), and of new behaviours (i.e. each time DSE covers a branch not yet cover by the initial trace or a generated one). On our sample, we are able to discover 43 new code areas of the malware under consideration.

File	#inst	#br	#uniq	#path	#behavior	Avg	Total
Virus.Win32.Artefad.2173	10K	1295	3	652	2	0.59	759.72
Virus.Win32.Belial.a	10K	1551	3	602	2	0.10	152.94
Virus.Win32.Benny.3219.a	10K	3153	121	4	4	0.0	3.10
Virus.Win32.Bogus.4096	10K	191	1	0	0	0.02	4.45
Virus.Win32.Cabanas.a	10K	2269	479	1	1	0.00	8.72
Virus.Win32.Cornad	404	32	17	12	12	0.63	20.05
Virus.Win32.Eva.a	1069	115	49	4	4	0.01	0.87
Virus.Win32.Htrip.a	2525	1105	9	598	6	0.10	137.23
Virus.Win32.Pulkfer.a	10K	1526	9	766	6	2.25	3434
Virus.Win32.Seppuku.1606	1696	147	61	4	4	0.01	1.85
Virus.Win32.Wita	10K	3334	2	3334	2	3.00	9985.96
Total	75694	14718	754	5977	43	6.71	14508.89

br: number of branches – uniq: unique conditional jumps – path: number of new paths – behavior: new path covering a new code area – Avg: Average solving time per paths

TABLE III
MALWARE EXPLORATION

VII. RELATED WORK

A few other initiatives aim at applying DSE on binary programs for security purposes, most notably BAP [4], S2E [8] and FuzzBall [7]. These three approaches rely on intermediate representations similar to DBA. Concerning dynamic tracing,

these tools are built either on Qemu or on Pin. BINSEC/SE provides a generic DSE engine, with highly configurable path exploration strategies and concretization/symbolization choices, a strong interaction between the tracer and the DSE core, and highly optimized path predicate computation.

VIII. CONCLUSION

The dynamic symbolic execution implemented in the platform shows the interesting property of being modular w.r.t the analysis configuration and to provide a strong interaction between the DSE (BINSEC) and the tracer (PINSEC). Some functionalities like the formula optimizations makes it original from the existing state-of-the art tools. This generic platform comes really handy for reverse-engineering and information recovery tasks like it is the case for source-less programs and malwares. Such a generic and parameterizable platform paves the way for more complex guidance/exploration algorithms and more complex concretization and symbolization algorithms.

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⁵A complete demo is available at <https://youtu.be/0xUc2jbpjQo>

⁶<http://vxheaven.org/>