Targeting Infeasibility Questions on Obfuscated Codes

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Abstract—Software deobfuscation is a crucial activity in security analysis and especially, in malware analysis. While standard static and dynamic approaches suffer from well-known shortcomings, Dynamic Symbolic Execution (DSE) has recently been proposed as an interesting alternative, more robust than static analysis and more complete than dynamic analysis. Yet, DSE addresses certain kinds of questions encountered by a reverser namely feasibility questions. Many issues arising during reverse, e.g. detecting protection schemes such as opaque predicates fall into the category of infeasibility questions. In this article, we present the Backward-Bounded DSE, a generic, precise, efficient and robust method for solving infeasibility questions. We demonstrate the benefit of the method for opaque predicates and call stack tampering, and give some insight for its usage for some other protection schemes. Especially, the technique has successfully been used on state-of-the-art packers as well as on the government-grade X-Tunnel malware – allowing its entire deobfuscation. Backward-Bounded DSE does not supersede existing DSE approaches, but rather complements them by addressing infeasibility questions in a scalable and precise manner. Following this line, we propose sparse disassembly, a combination of Backward-Bounded DSE and static disassembly able to avoid dynamic disassembly in a guaranteed way, hence getting the best of dynamic and static disassembly. This work paves the way for robust, efficient and precise disassembly tools for heavily-obfuscated binaries.

I. INTRODUCTION

Context. Obfuscation [1] is a prevalent practice aiming at protecting some functionalities or properties of a program. Yet, while its legitimate goal is intellectual property protection, obfuscation is widely used for malicious purposes. Therefore, (binary-level) software deobfuscation is a crucial task in reverse-engineering, especially for malware analysis.

A first step of deobfuscation is to recover the most accurate control-flow graph of the program (disassembly), i.e. to recover all instructions and branches of the program under analysis. This is already challenging for non-obfuscated codes due to tricky (but common) low-level constructs [2] like indirect control flow (computed jumps, jmp eax) or the interleaving of code and data. But the situation gets largely worst in the case of obfuscated codes.

Standard disassembly approaches are essentially divided into static methods and dynamic methods. On one hand, static (syntactic) disassembly tools such as IDA or Objdump have the potential to cover the whole program. Nonetheless, they are easily fooled by obfuscations such as code overlapping [3], opaque predicates [4], opaque constants [5], call stack tampering [6] and self-modification [7]. On the other hand, dynamic analysis cover only a few executions of the program and might miss both significant parts of the code and crucial behaviors. Dynamic Symbolic Execution (DSE) [8], [9] (a.k.a concolic execution) is a recent and fruitful formal approach to automatic testing, has recently been proposed as an interesting approach for disassembly [10], [11], [12], [13], [14], more robust than static analysis and covering more instructions than dynamic analysis. Currently, only dynamic analysis and DSE are robust enough to address heavily obfuscated codes.

Problem. Yet, these dynamic methods only address reachability issues, namely feasibility questions, i.e. verifying that certain events or setting can occur, e.g. that an instruction in the code is indeed reachable. Contrariwise, many questions encountered during reversing tasks are infeasibility questions, i.e. checking that certain events or settings cannot occur. It can be used either for detecting obfuscation schemes, e.g. detecting that a branch is dead (i.e. it cannot be taken) or to prove their absence, e.g. proving that a computed jump cannot lead to an improper address.

These infeasibility issues are currently a blind spot of both standard and advanced disassembly methods. Dynamic analysis and DSE do not answer the question because they only consider a finite number of paths while infeasibility is about considering all paths. Also, (standard) syntactic static analysis is too easily fooled by unknown patterns. Finally, while recent semantic static analysis approaches [15], [13], [16], [17] can in principle address infeasibility questions, they are currently neither scalable nor robust enough.

At first sight infeasibility is a simple mirror of feasibility, however from an algorithmic point of view they are not the same problem. Indeed, since solving feasibility questions on general programs is undecidable, practical approaches have to be one-sided, favoring either feasibility (i.e. answering “feasible” or “I don’t know”) or infeasibility (i.e. answering “I don’t know” or “infeasible”). While there currently exist robust methods for answering feasibility questions on heavily obfuscated codes, no such method exist for infeasibility questions.

Goal and challenges. In this article, we are interested in

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solving automatically infeasibility questions occurring during the reversing of (heavily) obfuscated programs. The intended approach must be precise (low rates of false positives and false negatives) and able to scale on realistic codes both in terms of size (efficient) and protection – including self-modification (robustness), and generic enough for addressing a large panel of infeasibility issues. Achieving all these goals at the same time is particularly challenging.

Our proposal. We present Backward-Bounded Dynamic Symbolic Execution (BB-DSE), the first precise, efficient, robust and generic method for solving infeasibility questions. To obtain such a result, we have combined in an original and fruitful way, several state-of-the-art key features of formal software verification methods, such as deductive verification [18], bounded model checking [19] or DSE. Especially, the technique is goal-oriented for precision, bounded for efficiency and combines dynamic information and formal reasoning for robustness.

Contribution. The contribution of this paper are the following:

- First, we highlight the importance of infeasibility issues in reverse and the urgent need for automating the investigation of such problems. Indeed, while many deobfuscation-related problems can be encoded as infeasibility questions (cf. Section V), it remains a blind spot of state-of-the-art disassembly techniques.
- Second, we propose the new Backward-Bounded DSE algorithm for solving infeasibility queries arising during deobfuscation (Section V). The approach is both precise (low rates of false positives and false negatives), efficient and robust (cf. Table I), and it can address in a generic way a large range of deobfuscation-related questions – for instance opaque predicates, call stack tampering or self-modification (cf. Section V). The technique draws from several separated advances in software verification, and combines them in an original and fruitful way. We present the algorithm along with its implementation within the BINSEC open-source platform [20], [21].
- Third, we perform an extensive experimental evaluation of the approach, focusing on two standard obfuscation schemes, namely opaque predicates and call stack tampering. In a set of controlled experiments with ground truth based on open-source obfuscators (cf. Section VI), we demonstrate that our method is very precise and efficient. Then, in a large scale experiment with standard packers (including self-modification and other advanced protections), the technique is shown to scale on realistic obfuscated codes, both in terms of efficiency and robustness (cf. Section VI).
- Finally, we present two practical applications of Backward-Bounded DSE. First, we describe an in-depth case-study of the government-grade malware X-TUNNEL [22] (cf. Section VIII), where BB-DSE allows to identify and remove all obfuscations (opaque predicates). We have been able to automatically extract a de-obfuscated version of functions – discarding almost 50% of dead and “spurious” instructions, and providing an insights into its protection schemes, laying a very good basis for further in-depth investigations. Second, we propose sparse disassembly (cf. Section XI), a combination of Backward-Bounded DSE, dynamic analysis and standard (recursive, syntactic) static disassembly allowing to enlarge dynamic disassembly in a precise manner – getting the best of dynamic and static techniques, together with encouraging preliminary experiments.

Our implementation and experimental data will be made available if the paper is accepted for publication.

Discussion. Several remarks must be made about the work presented in this paper.

- First, while we essentially consider opaque predicates and call stack tampering, BB-DSE can also be useful in other obfuscation contexts, such as flattening or virtualization. Also self-modification is inherently handled by the dynamic aspect of BB-DSE.
- Second, while we present one possible combination for sparse disassembly, other combinations can be envisioned, for example by replacing the initial dynamic analysis by a (more complete) DSE [10] or by considering more advanced static disassembly techniques [2].
- Finally, some recent works target opaque predicate detection with standard forward DSE [12]. As already pointed out, DSE is not tailored to infeasibility queries, while BB-DSE is – cf. Sections VI and XI).

Impact. Backward-Bounded DSE does not supersede existing disassembly approaches, it complements them by addressing infeasibility questions. Altogether, this work paves the way for robust, precise and efficient disassembly tools for obfuscated binaries, through the careful combination of static/dynamic and forward/backward approaches.

**TABLE I: Disassembly methods for obfuscated codes**

| Method               | Feasibility query | Infeasibility query | Efficiency | Robustness |
|----------------------|------------------|---------------------|------------|------------|
| Dynamic analysis     | ✓ / × (†)        | ×                   | ✓          | ✓          |
| DSE                  | ✓                | ×                   | ✓          | ✓          |
| Static analysis      | ✓ / ✓ (††)       | ✓                   | ✓          | ×          |
| (syntactic)          |                  |                     |            |            |
| Static analysis      | ×                | ✓                   | ×          | ×          |
| (semantic)           |                  |                     |            |            |
| BB-DSE               | ×                | ✓ (††)              | ✓          | ✓          |

(†): follow only a few traces
(††): very limited reasoning abilities
(†): can have false positive and false negative, yet very low in practice

II. BACKGROUND

Obfuscation. These transformations [11] aim at hiding the real program behavior. While approaches such as virtualization or

1 http://binsec.gforge.inria.fr/
junk insertion make instructions more complex to understand, other approaches directly hide the legitimate instructions of the programs – making the reverser (or the disassembler) missing essential parts of the code while wasting its time in dead code. The latter category includes for example code overlapping, self-modification, opaque predicates and call stack tampering.

We are interested here in this latter category. For the sake of clarity, this paper mainly focuses on opaque predicates and call stack tampering.

An opaque predicate always evaluates to the same value, and this property is ideally difficult to deduce. The infeasible branch will typically lead the reverser (or disassembler) to a large and complex portion of useless junk code. Figure 1 shows the x86 encoding of the opaque predicate $7y^2 - 1 \neq x^2$, as generated by O-LLVM [23]. This condition is always false for any values of DS:X, DS:Y, so the conditional jump jz <addr_trap> is never going to be taken.

A (call) stack tampering, or call/ret violation, consists in breaking the assumption that a ret instruction returns to the instruction following the call (return site), as exemplified in Figure 2. The benefit is twofold: the reverser might be lured into exploring useless code starting from the return site, while the real target of the ret instruction will be hidden from static analysis.

Fig. 1: opaque predicate: $7y^2 - 1 \neq x^2$

Disassembly. We call legit, an instruction in a binary if it is executable in practice. Two qualities expected for a disassembly are (1) soundness: does the algorithm recover only legit instructions? and (2) completeness: does the algorithm recover all legit instructions? Standard disassembly approaches essentially include (static) recursive disassembly, (static) linear sweep and dynamic disassembly.

Recursive disassembly consists in exploring the executable file from a given (list of) entry point(s), recursively following the possible successors of each instructions. This technique may miss a lot of instructions, typically due to computed jumps (jmp eax) or self-modification. In addition, the approach is easily fooled into disassembling junk code obfuscated by opaque predicates or call stack tampering. As such, the approach is neither safe nor complete.

Linear sweep consists in decoding linearly all possible instructions in the code sections. The technique aims at being more complete than recursive traversal, yet it comes at the price of many additional misinterpreted code instructions. Meanwhile, the technique can still miss instructions hidden by code overlapping or self-modification. Hence the technique is unsafe, and incomplete on obfuscated codes.

Dynamic disassembly retrieves only legit instructions and branches observed at runtime on one or several executions. The technique is safe, but potentially highly incomplete – yet, it does recover part of the instructions masked by self-modification, code overlapping, etc.

For example, while Objdump is solely based on linear sweep, IDA performs a combination of linear sweep and recursive disassembly (geared with heuristics).

Dynamic Symbolic Execution. Dynamic Symbolic Execution (DSE) [9], [8] (a.k.a. concolic execution) is a formal technique for exploring program paths in a systematic way. For each path $\pi$, the technique computes a symbolic path predicate $\Phi_\pi$ as a set of constraints on the program input leading to follow that path at runtime. Intuitively, $\Phi_\pi$ is the conjunction of all the branching conditions encountered along $\pi$. This path predicate is then fed to an automatic solver (typically a SMT solver [24]). If a solution is found, it corresponds to an input data exercising the intended path at runtime. Path exploration is then achieved by iterating on all (user-bounded) program paths, and paths are discovered lazily thanks to an interleaving of dynamic execution and symbolic reasoning [25], [26]. Finally, concretization [25], [26], [27] allows to perform relevant under-approximations of the path predicate by using the concrete information available at runtime.

The main advantages of DSE are correctness (no false negative in theory, a bug reported is a bug found) and robustness (concretization does allow to handle unsupported features of the program under analysis without losing correctness). Moreover, the approach is easy to adapt to binary code, compared to other formal methods [28], [8], [29], [30]. The very main drawback of DSE is the so-called path explosion problem: DSE is doomed to explore only a portion of all possible execution paths. As a direct consequence, DSE is incomplete in the sense that it can only prove that a given path (or objective) is feasible (or coverable), but not that it is infeasible.

DSE is interesting for disassembly and deobfuscation since it enjoys the advantages of dynamic analysis (especially, safe disassembly and robustness to self-modification or code overlapping), while being able to explore a larger set of

| <main> | <fun> |
|--------|-------|
| call <fun> | push X |
| ...... // return site | ret //jump to X instead |
| ...... // junk code | of return site |

Fig. 2: Standard stack tampering
behaviors. Yet, while on small examples DSE can achieve complete disassembly, it often only slightly improves coverage (w.r.t. pure dynamic analysis) on large and complex programs.

III. MOTIVATION

Let us consider the obfuscated pseudo-code given in Figure 3. The function <main> contains an opaque predicate in (1) and a call stack tampering in (2).

| <main>:                      | <fun1>:                      |
|------------------------------|------------------------------|
| if (C) {                    | .....                        |
|   call <fun1>              | push <X>                    |
|     // junk @              | ret                          |
| }                           |                             |
| else {                     |                             |
|   call <fun2> @            |                             |
| }                           | <fun2>:                      |
| // junk @                   | .....                        |
| ret // fake end of fun     | ret                          |
| <X>:                       |                             |
| // payload                 |                             |

Fig. 3: Motivating example

Getting the information related to the opaque predicate and the call stack tampering would allow to:

- (1) to know that <fun1> is always called and reciprocally that <fun2> is never called. As consequence (2) and (3) are dead instructions;
- (2) to know that the ret of <fun1> is tampered and never return to the caller. As consequence (4) and (5) are dead instructions. Such trick would also allow to hide the real payload located at <X>.

Hence the main motivation is not to be fooled by such infeasibility-based tricks that slow-down the program reverse-engineering and its global understanding.

Applications. The main application is to improve a disassembly algorithm with such information, since static disassembly will be fooled by such tricks and dynamic disassembly will only cover a partial portion of the program. Our goal is to design an efficient method for solving infeasibility questions. This approach could then passes the original code annotated with infeasibility highlights to other disassembly tools, which could take advantage of this information – for example by avoiding disassembling dead instructions. Such a view is depicted in Figure 4 and a throughout study of such combination is discussed in Section IX.

Moreover, such infeasibility related information could also be used in other contexts, for instance to obtain more accurate code coverage rates in software testing or to guide vulnerability analysis toward weak parts of the code.

IV. BACKWARD-BOUNDED DSE

We present in this section the new Backward-Bounded DSE technique dedicated to solving infeasibility queries on binary codes.

Preliminaries. We consider a binary-level program $P$ with a given initial code address $a_0$. A state $s \triangleq (a, \sigma)$ of the program is defined by a code address $a$ and a memory state $\sigma$, which is a mapping from registers and memory to actual values (bitvectors, typically of size 8, 32 or 64). By convention, $s_0$ represents an initial state, i.e. $s_0$ is of the form $(a_0, \sigma)$. The transition from one state to another is performed by the post function that execute the current instruction. An execution $\pi$ is a sequence $\pi \triangleq (s_0 \cdot s_1 \cdot \ldots \cdot s_n)$, where $s_{j+1}$ is obtained by applying the post function to $s_j$ ($s_{j+1}$ is the successor of $s_j$).

Let us consider a predicate $\varphi$ over memory states. We call reachability condition a pair $c \triangleq (a, \varphi)$, with $a$ a code address. Such a condition $c$ is feasible if there exists a state $s \triangleq (a, \sigma)$ and an execution $\pi_s \triangleq (s_0 \cdot s_1 \cdot \ldots \cdot s_n)$ such that $\sigma$ satisfies $\varphi$. It is said infeasible otherwise. An feasibility (resp. infeasibility) question consists precisely in trying to solve the feasibility (resp. infeasibility) of such a reachability condition.

These definitions do not take self-modification into account. They can be extended to such a setting by considering code addresses plus waves or phases [3].

Principles. We build on and combine 3 key ingredients from popular software verification methods:

- backward reasoning from deductive verification, for precise goal-oriented reasoning;
- combination of dynamic analysis and formal methods (from DSE), for robustness;
- bounded reasoning from bounded model checking, for scalability and the ability to perform infeasibility proofs.

The initial idea of BB-DSE is to perform a backward reasoning, similar to the one of DSE but going from successors to predecessors (instead of the other way). Formally, DSE is based on the post operation while BB-DSE is based on its inverse $\pre$. Perfect backward reasoning $\pre^*$ (i.e. fixpoint iterations of relation $\pre$, collecting all predecessors of a given state or predicate) can be used to check feasibility and infeasibility questions. But this relation is not computable.
Hence, we rely on computable bounded reasoning, namely \( \text{pre}^k \), i.e. collecting all the “predecessors in \( k \) steps” (\( k \)-predecessors) of a given state (or predicate). Now symmetry does not hold anymore: while \( \text{pre}^k \) can answer positively to infeasibility queries (if a predicate has no \( k \)-predecessor, it has no \( k' \)-predecessor for any \( k' > k \) and cannot be reached), but cannot falsify them (because it could happen that a predicate is infeasible, for a reason beyond the bound \( k \)). Moreover, it is efficient as the computation does not depend on the program size or trace length, but on the user-chosen bound \( k \).

In practice, checking whether \( \text{pre}^k = \emptyset \) can be done in a symbolic way, like it is done in DSE: the set \( \text{pre}^k \) is computed implicitly as a logical formula (typically, a quantifier-free first-order formula over bitvectors and arrays), which is unsatisfiable iff the set is empty. This formula is then passed to an automatic solver, typically a SMT solver \([24]\) such as \( \text{Z3} \).

Yet, backward reasoning is still very fragile at binary-level, since computing \( \text{pre} \) in a perfect way may be highly complex because of dynamic jumps or self-modification. The last trick is to combine this \( \text{pre}^k \) reasoning with dynamic traces, so that the whole approach benefits from the robustness of dynamic analysis. Actually, the \( \text{pre}^k \) is now computed w.r.t. the control-flow graph induced by a given trace \( \pi \) – in a dynamic disassembly manner. We denote this sliced \( \text{pre}^k \) by \( \text{pre}^k_{\pi} \).

Hence we get robustness, yet since some real parts of \( \text{pre}^k \) may be missing from \( \text{pre}^k_{\pi} \), we now lose correctness: we may have false positive FP (because \( \text{pre}^k_{\pi} \) will be incomplete w.r.t \( \text{pre}^k \)), additionally to the false negative FN due to “boundedness” (because of too small \( k \)). A picture of the approach is given in Figure \([5]\).

**Algorithm.** Considering a reachability condition \((a, \varphi)\), \( \text{BB-DSE} \) starts with a dynamic execution \( \pi \):

- if \( \pi \) reaches code address \( a \), then compute \( \text{pre}^k_{\pi}((a, \varphi)) \) as a formula and solve it
  - if it is UNSAT, then the result is INFEASIBLE;
  - if it is SAT, then the result is UNKNOWN;
  - if it is TO (timeout), then the result is TO;
- otherwise the result is UNKNOWN.

As a summary, this algorithm enjoys the following good properties: it is efficient (depends on \( k \), not on the trace or program length) and as robust as dynamic analysis. On the other hand, the technique may report both false negative (bound \( k \) too short) and false positive (dynamic CFG recovery not complete enough). Yet, in practice, our experiments demonstrate that the approach performs very well, with very low rates of FP and FN. Experiments are presented in Sections \([VI]\)–\([VII]\) and \([VIII]\).

By convenience, we will not distinguished anymore between the predicate \( \varphi \) and the reachability condition \((a, \varphi)\) if \( a \) is clear from context.

**Implementation.** This algorithm is implemented on top of \( \text{BINSEC/SE} \) \([21]\), a forward DSE engine inside the open-source platform \( \text{BINSEC} \) \([20]\) geared to formal analysis of binary codes. The platform currently proposes a front-end from x86 (32bits) to a generic intermediate representation called DBA \([31]\) (including decoding, disassembling, simplifications). It also provides several semantic analyses, including the \( \text{BINSEC/SE} \) DSE engine \([21]\). \( \text{BINSEC/SE} \) features a strongly optimized path predicate generation as well as highly configurable search heuristics \([21]\), \([13]\) and C/S policies \([27]\). The whole platform amount for more than 40k of Ocaml line of codes.

\( \text{BINSEC} \) also makes use of two other components. First, the dynamic instrumentation called \( \text{PINSEC} \), based on Pin in charge to run the program and to record all runtime values along with self-modification layers. Written in C++ it amounts for more than 3k lines of code. Second, \( \text{IDASEC} \) is an IDA plugin written in Python (\(~13\)k loc) aiming at triggering analyzes and post-processing results generated by \( \text{BINSEC} \).

The \( \text{BB-DSE} \) algorithm is tightly integrated in the \( \text{BINSEC/SE} \) component. Indeed, when solving a predicate feasibility, \( \text{BINSEC/SE} \) DSE performs a backward pruning pass aiming at removing any useless variable or constraint. \( \text{BB-DSE} \) works analogously, but also takes into account the distance from the predicate to solve: any definition beyond the \( k \) bound is removed. In a second phase, the algorithm creates a new input variable for any variable used but never defined in the sliced formula. The \( k \) bound value is defined by the user and can be modulated as needed.

V. SOLVING INFEASIBILITY QUESTIONS WITH BB-DSE

We show in this section how several natural problems encountered during deobfuscation and disassembly can be thought of as infeasibility questions, and solved with \( \text{BB-DSE} \).

**A. Opaque Predicates**

As already stated in Section \([1]\), an opaque predicate (OP) is a predicate always evaluating to the same value. They have successfully been used in various domains \([32]\), \([1]\). Recent works \([12]\) identify three kinds of opaque predicates:

\[\text{http://binsec.gforge.inria.fr/tools}\]
- **invariant**: always true/false due to the structure of the predicate itself, regardless of inputs values,
- **contextual**: opaque due to the predicate and its constraints on input values,
- **dynamic**: similar to contextual, but opaqueness comes from dynamic properties on the execution (e.g. memory).

**Approach with BB-DSE.** Intuitively, to detect an opaque predicate the idea is to backtrack all its data dependencies and gather enough constraints to conclude to the infeasibility of the predicate. If the predicate is local (invariant), the distance from the predicate to its input instantiation will be short and the predicate will be relatively easy to break. Otherwise (contextual, dynamic) the distance is linear with the trace length, which does not necessarily scale.

This is a direct application of BB-DSE, where \( p = (a, \varphi) \) is the pair address-predicate for which we want to check for opacity. We call \( \pi \) the execution trace under attention (extension to a set of traces is straightforward). Basically, the detection algorithm is the following:

- if \( p \) is dynamically covered by \( \pi \), then returns FEASIBLE;
- otherwise, returns BB-DSE \((p)\), where INFEASIBLE is interpreted as “opaque”.

The result is guaranteed solely for FEASIBLE, since BB-DSE has both false positives and false negatives. Yet, experiments (Sections [VI] [VII] [VIII]) show that these error ratios are very low in practice.

Concerning the choice of bound \( k \), experiments in Section [VI] demonstrates that a value between 10 and 20 is a good choice with invariant opaque predicates. Interestingly, the X-TUNNEL case study (Section [VIII]) highlights that such rather small bound values may be sufficient to detect opaque predicates with long dependency chains (up to 230 in the study, including contextual opaque predicates), since we do not always need to recover all the information in order to conclude on the infeasibility.

**B. Call Stack Tampering**

Call stack tampering consists in altering the standard compilation scheme switching from function to function by associating a call and a ret and making the ret to return to the call next instruction. The ret is tampered (a.k.a violated) if it does not return to the expected return site pushed on the stack at the call.

**New taxonomy.** In this work we refine the definition of a stack tampering in order to characterize it better.

- **integrity**: does ret return to the same address as pushed by the call? It characterizes if the tampering takes place or not. A ret is then either [genuine] (always returns to the caller) or [violated].
- **alignment**: is the stack pointer (esp) identical at call and ret? If so, the stack pointer is denoted [aligned], otherwise [disaligned].
- **multiplicity**: in case of violation, is there only one possible ret target? This case is noted [single], otherwise [multiple].

**Approach with BB-DSE.** The goal is to check several properties of the tampering using BB-DSE. We consider the following predicates on a ret instruction:

- \( @[\text{esp}_{\text{call}}] = @[\text{esp}_{\text{ret}}] \): Compare the content of the value pushed at call \( @[\text{esp}_{\text{call}}] \) with the one used to return \( @[\text{esp}_{\text{ret}}] \). If it evaluates to \( \text{VALID} \), the ret cannot be tampered [genuine]. If it evaluates to \( \text{UNSAT} \), a violation necessarily occurs [violated]. Otherwise, cannot characterize integrity.
- \( \text{esp}_{\text{call}} = \text{esp}_{\text{ret}} \): Compare the logical ESP value at the call and at ret. If it evaluates to \( \text{VALID} \), the ret necessarily returns at the same stack offset [aligned], if it evaluates to \( \text{UNSAT} \) the ret is [disaligned]. Otherwise cannot characterize alignment.
- \( T \neq @[\text{esp}_{\text{ret}}] \): Check if the logical ret jump target \( @[\text{esp}_{\text{ret}}] \) can be different from the concrete value from the trace \( T \). If it evaluates to \( \text{UNSAT} \) the ret cannot jump elsewhere and is flagged [single]. Otherwise cannot characterize multiplicity.

The above cases can be checked by BB-DSE (for checking \( \text{VALID} \) with some predicate \( \psi \), we just need to query BB-DSE with predicate \( \neg \psi \)). Then, our detection algorithm works as follow, taking advantage of BB-DSE and dynamic analysis:

- the dynamic analysis can tag a ret as: [violated], [disaligned], [multiple];
- BB-DSE can tag a ret as: [genuine], [aligned], [single] ([violated] and [disaligned] are already handled by dynamic analysis).

As for opaque predicates, dynamic results can be trusted, while BB-DSE results may be incorrect. Table [II] summarizes all the possible situations.

**TABLE II: Call stack tampering detection**

| Runtime Status | integrity | alignment | multiplicity |
|----------------|-----------|-----------|--------------|
| RT Genuine     | VALID: [genuine] | RT: KO{disaligned} | - VALID: [aligned] |
| RT Tampered    | [violated] | RT: KO{disaligned} | - RT: (2){multiple} |

This call stack tampering analysis uses BB-DSE, but with a slightly non-standard setting. Indeed, in this case the bound \( k \) will be different for every call/ret pair. The trace is analysed in a forward manner, keeping a formal stack of call instructions. Each call encountered is pushed to the formal stack. Upon ret, the first call on the formal stack is popped and BB-DSE is performed, where \( k \) is the distance between the call and the ret.

From an implementation point of view, we must take care of possible corruptions of the formal stack, which may happen for example in the following situations:

- Call to a non-traced function: because the function is not traced, its ret is not visible. In our implementation these calls are not pushed in the formal stack;
- Tail call [2] to non-traced function: tail calls consists in calling functions through a jump instruction instead of call to avoid stack tear-down. This is similar to the
previous case, except that care must be taken in order to detect the tail call.

C. Other deobfuscation-related infeasibility issues

**Opaque constant.** Similar to opaque predicates, opaque constants are expressions always evaluating to a single value. Let us consider the expression \( e \) and a value \( v \) observed at runtime for \( e \). Then, the opaqueness of \( e \) reduces to the infeasibility of \( e \neq v \).

**Dynamic jump closure.** When dealing with dynamic jumps, switch, etc., we might be interested in knowing if all the targets have been found. Let us consider a dynamic jump \( \text{jump \ eax} \) for which 3 values \( v_1, v_2, v_3 \) have been observed so far. Checking the jump closure can be done through checking the infeasibility of \( \text{eax} \neq v_1 \land \text{eax} \neq v_2 \land \text{eax} \neq v_3 \).

**Virtual Machine & CFG flattening.** Both VM obfuscation and CFG flattening usually use a custom instruction pointer aiming at preserving the flow of the program after obfuscation. In the case of CFG flattening, after execution of a basic block the virtual instruction pointer will be updated so that the dispatcher will know where to jump next. As such, we can check that all observed values for the virtual instruction pointer have been found for each flattened basic block. Thus, if for each basic block we know the possible value for the virtual instruction pointer and have proved it cannot take other values, we can ultimately get rid of the dispatcher.

**A glimpse of conditional self-modification.** Self-modification is a killer technique for blurring static analysis, since the real code is only revealed at execution time. The method is commonly found in malware and packers, either in simple forms (unpack the whole payload at once) or more advanced ones (unpack on-demand, shifting-decode schemes \([33]\)). The example in Figure 7(page 10) taken from AS Pack combines an opaque predicate together with a self-modification trick turning the predicate to true in order to fool the reverter. Other examples from existing malwares have been detailed in previous studies (NetSky.aa \([10]\)).

Dynamic analysis allows to overcome the self-modification as the new modified code will be executed as such. Yet, BB-DSE can be used as well, to prove interesting facts about self-modification schemes. For example, given an instruction known to perform a self-modification, we can take advantage of BB-DSE to know whether another kind of modification by the same instruction is possible or not (conditional self-modification). Let us consider an instruction \( \text{mov \ [addr]} \), \( \text{eax} \) identified by dynamic analysis to generate some new code with value \( \text{eax} = v \). Checking whether the self-modification is conditional reduces to the infeasibility of predicate \( \text{eax} \neq v \).

As a matter of example, this technique has been used on the example of Figure 7 to show that no other value than 1 can be written. This self-modification is thus unconditional.

VI. EVALUATION: CONTROLLED EXPERIMENTS

We present a set of controlled experiments with **ground truth values** aiming at evaluating the precision of BB-DSE as well as giving hints on its efficiency and comparing it with DSE.

A. Preliminary: Comparison with Standard DSE

We compare BB-DSE with standard forward DSE, as well as with (unbounded) backward DSE. We are interested in comparing their efficiencies and their adequacy to infeasibility questions – through the distribution of their results, between SAT, UNSAT and timeout. The experiment is performed on a trace of 115000 instructions and we check at each conditional jump if the branch not taken is infeasible (UNSAT) or not (SAT), which is equal to checking if the branch is dead. For BB-DSE, we take the algorithm for opaque predicate detection described in Section \([\Box]\) with bound values \( k = 100 \) and \( k = 20 \).

We argue in latter experiments (Section \([\Box]\)) that \( k = 20 \) is a reasonable bound. We use the forward DSE of Binsec/SE, and backward DSE is obtained from BB-DSE with a bound set to \( \infty \).

Results are presented in Table \( \blacksquare \). While forward and backward DSE provide similar results, BB-DSE clearly surpasses them in terms of efficiency, spending less than a second for every predicate without any timeout (\( \geq 2000 \) with DSE). From a result point of view, BB-DSE with \( k=16 \) returns very few UNSAT answers compared to the other methods (54 vs \( \geq 7000 \)). Actually, this was expected since DSE takes the whole path into account, and while dead branches are rare in normal code, dead paths are very common.

**TABLE III: Benchmark DSE versus BB-DSE**

| bound \( k \) | \#SAT | \#UNSAT | #Timeout | Total time |
|--------------|-------|---------|----------|------------|
| forward DSE  | /      | 575     | 7749     | 2460       | 17h43m     |
| backward DSE | \( \infty \) | 575     | 7748     | 2461       | 17h48m     |
| BB-DSE 100   | 575    | 7748    | 0        | 18m78s     |
| BB-DSE 20    | 10730  | 54      | 0        | 4m14s      |

**Conclusion.** This preliminary experiment gives a clear demonstration on the advantages of BB-DSE over DSE on infeasibility questions. Indeed, besides the dramatic gap in efficiency (which was of course expected since DSE depends on the whole size trace), DSE reports far more infeasible branches – which would lead in practice to too many false positives. These results were expected, as they are direct consequences of the design choices behind DSE and BB-DSE. On the opposite, BB-DSE is not suitable for feasibility questions.

B. Opaque Predicates evaluation

We consider here the BB-DSE-based algorithm for opaque predicate detection. We want to evaluate its precision, as well as to get insights on the choice of the bound \( k \).

**Protocol and benchmark.** We consider two sets of programs: (1) all 100 coreutils without any obfuscation, as a genuine reference data set, and (2) 5 simple programs taken from the
State-of-the-Art in DSE deobfuscation [10] and obfuscated with O-LLVM [23]. Each of the 5 simple programs was obfuscated 20 times (with different random seeds) in order to balance the numbers of obfuscated samples and genuine coreutils. We have added some new opaque predicates in O-LLVM (which is open-source) in order to maximize diversity (Table IV).

**TABLE IV: OP implemented in O-LLVM**

| Formulas                          | Comment                                      |
|----------------------------------|----------------------------------------------|
| \forall x, y \in \mathbb{Z} \quad y < 10 \mid 2(x \times (x - 1)) | (initially present in O-LLVM)               |
| \forall x, y \in \mathbb{Z} \quad 7y^2 - 1 \neq x^2         |                                              |
| \forall x \in \mathbb{Z} \quad 2 \mid x + x^2         |                                              |
| \forall x \in \mathbb{Z} \quad 2 \mid \frac{x^2}{2}   | (2^{nd} bit of square always 0)             |
| \forall x \in \mathbb{Z} \quad 4(x^2 + (x + 1)^2)   |                                              |
| \forall x \in \mathbb{Z} \quad 2 \mid x \times (x + 1) |                                              |

In total, 200 binary programs were used. For each of them a dynamic execution trace was generated with a maximum length of 20,000 instructions. By tracking where opaque predicates were added in the obfuscated files, we are able a priori to know if a given predicate is opaque or not, ensuring a ground truth evaluation. Note that we consider all predicates in coreutils to be genuine. The 200 samples sums up a total of 1,091,986 instructions trace length and 11,725 conditional jumps with 6,170 genuine and 5,556 opaque predicates. Finally, experiments were carried using different values for the bound \(k\), and with a 5 second timeout per query.

**Results.** Among the 11,725 predicates, 987 were fully covered by the trace and were excluded from these results, keeping 10,739 predicates (and 5,183 genuine predicates). Figure 6 and Table [V] show the relation between the number of predicates detected as opaque (OP) or genuine (OK) as well as false positive (FP) and false negatives (FN) depending of the bound value \(k\). The experiment shows a tremendous peak of opaque detection with \(k = 10\). Alongside, the number of false negative steadily decreases as the number of false positive grows. An optimum is reached for \(k = 16\), with no false negative, no timeout and a small number of false positive (293), representing 6.28% of all predicates marked opaque and only 3.17% of all predicates. In that case, the detection method achieves 1.46 false positive per sample (very low). Results are still very precise up to \(k = 30\), and very acceptable for \(k = 50\).

**TABLE V: Opaque predicate detection results**

| \(k\) | OP (5556) | Genuine (5183) | TO | FP/Tot (%) | FP/OP (%) |
|-------|-----------|---------------|----|------------|-----------|
| 2     | 0         | 5556          | 5182| 1          | 0.01      | 0.02      |
| 4     | 903       | 4653          | 5153| 30         | 0.26      | 3.22      |
| 8     | 4561      | 995           | 4987| 196        | 1.67      | 4.12      |
| 12    | 5545      | 11            | 4890| 293        | 2.50      | 5.02      |
| 16    | 5556      | 0             | 4811| 372        | 3.17      | 6.28      |
| 20    | 5556      | 0             | 4715| 604        | 5.15      | 9.81      |
| 24    | 5556      | 0             | 4658| 525        | 7.77      | 11.56     |
| 32    | 5552      | 4             | 4579| 604        | 5.15      | 9.81      |
| 40    | 5548      | 8             | 4523| 660        | 5.63      | 10.63     |
| 50    | 5544      | 12            | 4458| 725        | 6.18      | 11.56     |

*Timeout: 5 sec*
*a TO counts as a UNKNOWN result (hence, classify the predicate as genuine)*

In total, 10,739 predicates, 5,556 opaque predicates, 5,183 genuine predicates

**A glimpse at efficiency.** Taking the same detection algorithm and queries, we want to evaluate predicate solving time. Each predicate formula is solved using Z3\(^3\) with a 5 seconds timeout. **Table VI** gives for each value of \(k\) the total time taken for solving and the average time per query. For \(k = 16\) the average time per query is 0.018s which tends to prove that this technique scales. Previous works aiming at solving invariant opaque predicates [12] (based on forward DSE) reports an average of 0.49s per queries (min:0.09, max:0.79). Hence, BB-DSE seems to provides a very significant speed up.

**TABLE VI: Solving time (10,739 queries)**

| \(k\) | Total time(s) | Avg/query(s) |
|-------|---------------|--------------|
| 2     | 89            | 0.008        |
| 4     | 96            | 0.009        |
| 8     | 120           | 0.011        |
| 12    | 152           | 0.014        |
| 16    | 197           | 0.018        |
| 20    | 272           | 0.025        |
| 24    | 384           | 0.036        |
| 32    | 699           | 0.065        |
| 40    | 1145          | 0.107        |
| 50    | 2025          | 0.189        |

*http://github.com/Z3Prover/z3*

**Conclusion.** BB-DSE is very precise at detecting opaque predicates, and while a bound is of importance, the technique still performs very well if the bound is not too far from the optimal one \((k\) between 10 and 30\). Query solving time is also very low.

**C. Call Stack Tampering evaluation**

We want to assess the precision of the BB-DSE algorithm for stack tampering detection (Section VI-C). We consider two sets of programs: (1) the 5 samples used Section VI-B obfuscated with the source-to-source obfuscator Tigress [32]; (2) 5 randomly selected coreutils without any obfuscation.
Files have been obfuscated with the AntiBranchAnalysis transformation that replace all conditional branches with calls and rets. The two schemes used by the obfuscator are:

- push; call; ret; ret (the last ret jumps on pushed value)
- push; ret (idem)

**Results.** Results are given in Table VII. The 5 obfuscated samples sums up 218 different ret. Among them 77 are genuine and 141 violated (including 132 single-target). Our detection method achieves here a perfect score, with no false positive nor false negative. On The 5 coreutils, our method does not yield any false positive and most of the ret are proved genuine (149/156). The few remaining unproved ret come from unhandled libc side-effects, making formulas wrongly UNSAT.

| Sample      | runtime genuine | runtime violation |
|-------------|-----------------|-------------------|
|             | #ret | proved genuine | align/ disal | #ret | alg/ disal | proved single |
| simple-if   | 6    | 6    | 6/0    | 9     | 0/0   | 8        |
| bin-search  | 15   | 15   | 15/0   | 25    | 0/0   | 24       |
| bubble-sort | 6    | 6    | 6/0    | 15    | 0/1   | 13       |
| mat-mult    | 31   | 31   | 31/0   | 69    | 0/0   | 68       |
| huffman     | 19   | 19   | 19/0   | 23    | 0/3   | 19       |

*each ret is counted only once*

**Conclusion.** BB-DSE performs very well here, with no false positive and a perfect score on obfuscated samples. The technique recovers both genuine ret and single-source tampered ret. Interestingly, no tampered ret were found on the few (randomly selected) coreutils, supporting the idea that such tampering is not meant to occur in legitimate programs.

**D. Conclusion**

These different controlled experiments demonstrate clearly that BB-DSE is a very precise approach for solving different kinds of infeasibility questions. They also demonstrate that finding a suitable bound $k$ is not a problem in practice. Finally, the approach seems to be scalable. This last point will be definitely proved in Sections VII and VIII.

**VII. LARGE-SCALE EVALUATION ON PACKERS**

To validate the scalability of BB-DSE on representative codes, in terms of both size and protection, we perform a large scale experiment on packers with the two detection algorithms already used in Section VI.

**Context.** Packers are programs embedding other programs and decompressing/deciphering them at runtime. Since packers are used for software protection, most of them contain several obfuscation schemes (including self-modification). As a matter of fact, packers are also widely used by malware, and actually in many cases they are the only line of defense. Hence, packers are very representative for our study, both in terms of malware protections and size, as packed programs tend to have huge execution traces.

**Protocol.** We want to check if BB-DSE is able to detect opaque predicates or call stack tampering on packed programs. For that, a large and representative set of packers was chosen, ranging from free to commercial tools. Then a stub binary (hostname) was packed by each packer. Analyses are then triggered on these packed programs in a black-box manner, that is to say, without any prior knowledge of the internal working of the packers – we do not know which obfuscation are used. For homogeneity, trace length are limited to 10M instructions and packers reaching this limit were not analysed.

**A. Results**

Table VIII shows the partial results on 10 packers. The complete results are given in Table [XVII] in appendix. First, BB-DSE is efficient and robust enough to pass on most of the packed programs, involving traces of several millions of instructions and advanced protections such as self-modification. Second, over the 32 packers, 420 opaque predicates and 149 call/stack tampering have been found, and many functions have also been proved genuine. All the results that have been manually checked appeared to be true positive (we did not checked them all because of time constraints).

**B. Other Discoveries**

**Opaque predicates.** Results revealed interesting patterns, for instance ACProtect tends to add opaque predicates by chaining conditional jumps that are mutually exclusive like: j1 0x100404c ; jge 0x100404c. In this example the second jump is necessarily opaque since the first jump strengthens the path predicate, enforcing the value to be lower. This example shows that our approach can detect both invariant and contextual opaque predicates, and should also detect dynamic opaque predicates since they are similar to contextual opaque predicates. Many other variants of this pattern were found: jp/jnp, jo/jno, etc. Similarly, the well-known opaque predicate pattern xor ecx, ecx; jnz was detected in ARMADILLO. As a value xor(ed) by itself always return 0, the jnz is never taken.

The dynamic aspect of BB-DSE allowed to bypass some tricks that would misled a reverser into flagging a predicate as opaque. A good example is a predicate found in ASPack seemingly opaque but that turned not to be opaque due to a self-modification (Figure 7). Statically, the predicate is opaque since BL is necessarily 0 but it turns out that the second opcode bytes of the MOV BL, 0X0 is being patched to 1 in one branch in order to take the other branch when looping back later on.

**Call/stack tampering.** From the call/stack tampering perspective and according to the taxonomy defined in Section IV many different kinds of violations were detected. The first two patterns found in ACProtect shown in Figures [8] and [9] are respectively detected as [violated], [single], [aligned]
### TABLE VIII: Packer experiment OP & Stack tampering

| Packers       | size | tr. len | Opaque Pred. | Stack tampering |
|----------------|------|---------|--------------|-----------------|
| Unk            |      | OP      | TO           | OK (a/d/g)      |
| ASProtect v2.0 | 10K  | 1.8M    | 74           | 0/0/0           |
| ASPack v2.12   | 10K  | 377K    | 159          | 0/0/0           |
| Crypter v1.12  | 45K  | 1.1M    | 11(7/0/7)    | 125(94/0/4)     |
| Expressor      | 13K  | 635K    |              | 0/0/0           |
| nPack v1.1.300 | 11K  | 2.3M    | 42           | 14(10/0/10)     |
| PE Lock        | 21K  | 3.3M    | 83           | 0/0/0           |
| RL Pack        | 6K   | 941K    | 42           | 14(8/0/8)       |
| TELock v0.51   | 12K  | 406K    | 11           | 3(0/3/0)        |
| Upack v0.39    | 4K   | 711K    | 11           | 3(0/3/0)        |
| UPX v2.90      | 5K   | 1.6M    | 42           | 0/0/0           |

opaque predicates: $k = 16$ - Unk: query return Unknown - OP: proved as opaque
stack tampering: OK: #ret runtime behavior is genuine - KO: #ret violated at runtime
  . a: proved aligned - d: proved disaligned - g: proved genuine - s: proved to have a single target

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![Fig. 7: ASPack opaque predicate decoy](image)

and [violated], [single], [disaligned]. Figures [1][10] and [2] show three different kinds of violation found in ASPack. In the first example (cf. Figure [1]) the tampering is detected with labels [violated], [disaligned] since the stack pointer read the ret address at the wrong offset. In the second example (cf. Figure [10]), the return value is modified in place. The tampering is detected with the [violated], [aligned], [single] tags. The last example (cf. Figure [2]), takes place between the transition of two self-modification layers and the ret is used for tail-transitioning to the packer payload (i.e., the original unpacked program). This violation is detected with [violated], [disaligned], [single] since the analysis matches a call far upper in the trace which is disaligned. Note that instruction push 0x10011d7 at address 10043ba is originally a push 0, but it is patched by instruction at address 10043a9, triggering the entrance in a new auto-modification layer when executing it. This pattern reflects a broader phenomenon found in many packers like nPack, TELock or Upack having a single ret tampered: these packers perform their tail transition to the entrypoint of the original (packed) program with push; ret. Thus, such analysis allows to find precisely that moment in the execution trace, where the payload is highly likely decompressed in memory.
C. Conclusion

By detecting opaque predicates and call/stack tampering on packers with multi-million trace length, this experiment clearly demonstrates both the ability of BB-DSE to scale to realistic obfuscated examples (without any prior-knowledge of the protection schemes) and its usefulness. This study yields also a few unexpected and valuable insights on the inner working on the considered packers, such as some kinds of protections or the location of the jump to the entrypoint of the original unpacked program.

VIII. REAL-WORLD MALWARE: X-TUNNEL

A. Context & Goal

Context. As an application of the previous techniques we focus in this section on the heavily obfuscated X-TUNNEL malware. X-TUNNEL is a ciphering proxy component allowing the X-AGENT malware to reach the command and control (CC) if it cannot reach it directly \[22\]. It is usually the case for machines not connected to internet but reachable from an internal network. These two malwares are being used as part of target attack campaigns (APT) from the APT28 group also known as Sednit, Fancy Bear, Sofacy or Pawn Storm. This group, active since 2006, targets geopolitical entities and is supposedly highly tight to Russian foreign intelligence. Among alleged attacks, noteworthy targets are NATO \[35\], EU institutions \[36\], the White House \[37\], the German parliaments \[38\] and more recently the American Democrat National Committee DNC \[39\] that affected the running of elections. This group also makes use of many 0-days \[40\] in Windows, Flash, Office, Java and also operate other malwares like rootkits, bootkits, droppers, Mac OSX malwares \[41\] as part of its ecosystem.

Goal. This use-case is based on 3 X-TUNNEL samples\[4\] covering a 5 month period (if timestamps are correct). While Sample #0 is not obfuscated and can be straightforwardly analyzed, Samples #1 and #2 are, and they are also much larger than Sample #0 (cf. Table IX). The main issue raised here is:

G1: Is there new functionalities in the obfuscated samples?

Answering this question requires first to be able to analyse the obfuscated binaries. Hence we focus here on a second goal:

\[4\]We warmly thank Joan Calvet for providing the samples.

G2: Recover a de-obfuscated version of the obfuscated samples.

| Table IX: Samples infos |
|-------------------------|
| Sample #0 | Sample #1 | Sample #2 |
| obfuscated | No | Yes | Yes |
| size | 1.1 Mo | 2.1 Mo | 1.8 Mo |
| creation date | 25/06/2015 | 02/07/2015 | 02/11/2015 |
| #functions | 3039 | 3775 | 3488 |
| #instructions | 231907 | 505008 | 434143 |

We show in the latter how BB-DSE can solve goal G2, and we give hints on what is to be done to solve G1.

Analysis context. Obfuscated samples appeared to contain a tremendous amount of opaque predicates. As a consequence, our goal is to detect and remove all opaque predicates in order to remove the dead-code and meaningless instructions to hopefully obtain a de-obfuscated CFG. This deobfuscation step is a prerequisite for later new functionality finding.

The analysis here has to be performed statically:

- as the malware is a network component, it requires to connect to the CC server, which is not desirable;
- following the same line, many branching conditions are network-event based, thus unreliable and more hardly reproducible (and would also require infected clients for connection to X-TUNNEL);
- X-TUNNEL does not look to use any self-modification obfuscation or neatly tricks to hamper the disassembly. Thus the whole disassembled code is available.

The only difference with previous experiments is the need to test the two branches for each conditional jumps.

B. Analysis

OP detection. The analysis performs a BB-DSE on every conditional jumps of the program, testing systematically both branches. Taking advantage of previous experiments, we set the the bound \(k\) to 16. The solver used is Z3 with a 6s timeout. If both branches are UNSAT, the predicate is considered dead, as the unsatisfiability is necessarily due to path constraints indicating that the predicate is not reachable.

Code simplification. We perform three additional computations in complement to the opaque predicate detection:

- predicate synthesis recovers the high-level predicate of an opaque predicate by backtracking on its logical operations. The goal of this analysis is twofold: (1) indexing the different kind of predicates used and (2) identifying instruction involved in the computation of an OP denoted spurious instructions (in order to remove them);
- liveness propagation based on obfuscation-related data aims at marking instruction by theirs status, namely alive, dead, spurious;
- **reduced CFG extraction** extracts the de-obfuscated CFG based on the liveness analysis.

### C. Results

#### Execution time. **Table X** reports the execution time of the BB-DSE and predicate synthesis. The predicate synthesis takes a non-negligible amount of time, yet it is still very affordable, and moreover our implementation is far from optimal.

|       | #preds | DSE   | Synthesis | Total |
|-------|--------|-------|-----------|-------|
| Sample #1 | 34505  | 57m36 | 48m33     | 1h46m |
| Sample #2 | 30147  | 50m59 | 40m54     | 1h31m |

#### OP diversity. Each sample presents a very low diversity of opaque predicates. Indeed, solely $7y^2 - 1 \neq x^2$ and $\frac{2}{x+1} \neq y^2 + 3$ were found. **Table XI** sums up the distribution of the different predicates. The amount of predicates and their distribution supports the idea that they were inserted automatically and picked randomly.

|       | $7y^2 - 1 \neq x^2$ | $\frac{2}{x+1} \neq y^2 + 3$ |
|-------|---------------------|---------------------|
| Sample #1 | 6016 (49.02%) | 6257 (50.98%) |
| Sample #2 | 4618 (54.62%) | 5560 (54.62%) |

#### Detection results. As the diversity of opaque predicates is very low, we are able to determine, with quite a good precision, the amount of false negatives and false positives based on the predicate synthesized. If a predicates matches one of the two OP and was detected OK, then we considered it false negative (respectively false positive). Results are given in **Table XII** and **Figure 13**. The detection rate is satisfactory as false negatives only represent 3% of all predicates. Conversely, 8.4 to 8.6% of false positive are wrongly tagged opaque.

**Table XII: Opaque predicates evaluation**

|       | #pred | OK     | OP   | Likely |
|-------|-------|--------|------|--------|
|       |       | FN     | FP   |        |
| Sample #1 | 34505  | 17197  | 1046 | 11973  |
|        |       | (49.8%)| (3.0%)| (34.7%)|
| Sample #2 | 30147  | 16148  | 914  | 9790   |
|        |       | (53.7%)| (3.0%)| (32.5%)|

#### Dependency evaluation. As seen previously, a large $k$ bound can lead to false positive due to nested opaque predicates while in the meantime a low bound misses some predicates. Finding the right balance is still an important issue, but results with 12138 OP detected against 1046 false negative tend to confirm that such a low bound is a good trade-off. Across the two samples, the maximum distance between a predicate and its variable definition where 230 (Sample #1) and 148 (Sample #2). Still, the average computed on all the OPs yield an average of 8.7.

#### Difference with O-LLVM. Interesting differences with OP found in O-LLVM are to be emphasized. Firstly, there is more interleaving between the payload and the OPs computation. Some meaningful instructions are often encountered within the predicate computation. Secondly, while O-LLVM OPs are really local to the basic block, there are here some code sharing between predicates. As a consequence, predicates are not fully independent from one another. Also, the obfuscator uses local function variables to store temporary results at the beginning of the function for later usage in opaque predicates. This leads to increase the depth of the dependency chain and to complicate the detection.

#### Code simplification, Reduced CFG extraction. **Table XIII** shows the number of instructions re-classified based on their status. The dead code represents 1/4 of all program instructions. Computing the difference with the original non-obfuscated program shows a very low difference. Therefore, the simplification pass allowed to retrieve a program which is roughly the size of the original one. The difference is highly likely to be due to the false negatives or missed spurious instructions. Finally, **Figure 14** shows a function originally using tags (red:dead, orange:spurious, green:alive). Although the CFG extracted still containing noise, it allows a far better understanding of the function behavior. A demo video showing the deobfuscation of a X-TUNNEL function with BINEC and IDASEC is available as material for this paper.

**Table XIII: Code simplification results**

|       | #instr | #alive | #dead | #spurious | diff sample #0$^5$ |
|-------|--------|--------|-------|-----------|-------------------|
| Sample #1 | 507,206 | 279,483 | 121,794 | 103,731 | 47,576 |
| Sample #2 | 436,598 | 241,177 | 113,764 | 79,202 | 9,270 |

$^5$[https://youtu.be/Z14ab_rzjFA](https://youtu.be/Z14ab_rzjFA)
D. Conclusion

About the case-study. We have been able to automatically detect opaque predicates in the two obfuscated samples of the X-TUNNEL malware, leading a significant (and automatic) simplification of these codes – removing all spurious and dead instructions. Moreover, we have gained insights (both strengths and weaknesses) into the inner working of X-TUNNEL protections. Hence, we consider that goal G2 has been largely achieved. In order to answer to the initial question (G1), some similarity algorithms should now be computed between the non-obfuscated and simplified samples, in order to detect if some new functions have been added to the code. Moreover, our analysis also pinpoints the protected functions (a small minority), and this information can surely be taken into account. For now, this second analysis step is left as a future work.

About X-TUNNEL protections. The obfuscation found here are quite sophisticated compared with existing opaque predicates found in the state-of-the-art. It successfully manages to spread the data dependency across a function so that some predicates cannot be solved locally at the basic block level. Hopefully, this is not a general practice across predicates so that the BB-DSE works very well in the general case. The main issue of the obfuscation is the low diversity of opaque predicates in the way that some pattern matching can come in relay of symbolic approaches to classify a posteriori false positives and false negatives.

IX. APPLICATION: SPARSE DISASSEMBLY

A. Principles

As already explained, static and dynamic disassembly methods tend to have complementary strengths and weaknesses, and BB-DSE is the only robust approach targeting infeasibility questions. Hence, we propose sparse disassembly, an algorithm based on recursive disassembly reinforced with a dynamic trace and complementary information about obfuscation (computed by BB-DSE) in order to provide a more precise disassembly of obfuscated codes. The basic idea is to enlarge and initial dynamic disassembly by a cheap syntactic disassembly in a guaranteed way, following information from BB-DSE, hence getting the best of dynamic and static approaches.

The approach takes advantage of the two analyses presented in Sections VI-B and VI-C in the following way (cf. Figure 15):

- use dynamic values found in the trace to keep disassembling after indirect jump instructions;
- use opaque predicates found by BB-DSE to avoid disassembling dead branches (thus limiting the number of recovered non legit instructions);
- use stack tampering information found by BB-DSE to disassemble ret targets in case of violation, as well as not to disassemble the return site of the call in this case.

Implementation. A preliminary version of this algorithm has
been integrated in BINSEC, taking advantage of the existing recursive disassembly algorithm. The BB-DSE procedure sends OP and ret information to the modified recursive disassembler, which takes the information into account.

### B. Preliminary Evaluation

We report two sets of experiments, designed to assess the precision of the approach and its ability to enlarge an initial dynamic trace. We compare our method mainly to the well-known disassembly tools IDA and Objdump. IDA relies on a combination of recursive disassembly, linear sweep and dedicated heuristics. Objdump performs only linear sweep.

**Precision.** In the first evaluation, we compare these different tools on simple programs obfuscated either by O-LLVM (opaque predicates) or Tigress (stack tampering). In each experiment, we compare the set of disassembled instructions with the set of legitimate instructions of the obfuscated program (i.e. those instructions which can be part of a real execution). It turns out on these small examples that all methods are able to find all the legitimate instructions, yet they may nor may not be lured into dead instructions introduced by obfuscation.

Tables XIV and XV present our results. We report for each program and each disassembly method the number of recovered instructions. It turns out that this information is representative of the quality of the disassembly (the less instruction, the better), given the considered obfuscations and the fact that here all methods recover all legitimate instructions (actually, all results have been checked manually).

**TABLE XIV: Sparse disassembly opaque predicates**

| sample  | no obf. | Obfuscated | gain vs IDA (sparse) |
|---------|---------|------------|----------------------|
|         |         | perfect    | IDA                  | Objdump               | BINSEC sparse |
| simple-if | 37      | 185        | 240                  | 244                   | 185           | 23.23% |
| huffman | 558     | 3226       | 3594                 | 3602                  | 3226         | 10.26% |
| mat_mult | 249     | 854        | 1075                 | 1080                  | 854          | 20.67% |
| bin_search | 105    | 833        | 1110                 | 1115                  | 833          | 24.95% |
| bubble_sort | 121    | 1026       | 1531                 | 1537                  | 1026         | 32.98% |

**TABLE XV: Sparse disassembly stack tampering**

| sample  | no obf. | Obfuscated | gain vs IDA (sparse) |
|---------|---------|------------|----------------------|
|         |         | perfect    | IDA                  | Objdump               | BINSEC sparse |
| simple-if | 37      | 83         | 95                   | 98                   | 83           | 14.45% |
| huffman | 558     | 659        | 678                  | 683                  | 659          | 2.80%  |
| mat_mult | 249     | 461        | 524                  | 533                  | 461          | 12.05% |
| bin_search | 105    | 207        | 231                  | 238                  | 207          | 10.39% |
| bubble_sort | 121    | 170        | 182                  | 185                  | 170          | 6.6%   |

In both cases, sparse disassembly achieves a perfect score – recovering all but only legitimate instructions, performing better than IDA and Objdump. Especially, when opaque predicates are considered, sparse disassembly recovers up to 32% less instructions than IDA.

**Improvement over dynamic analysis.** We now seek to assess whether sparse disassembly can indeed enlarge a dynamic analysis in a significant yet guaranteed way, i.e. without adding dead instructions. We consider 5 larger coreutils programs obfuscated with O-LLVM. We compare sparse disassembly to dynamic analysis (starting from the same trace).

Here again, the number of recovered instructions is a good metric of precision (the bigger, the better), since both methods report only legitimate instructions on these examples (we checked that BB-DSE was able to find all inserted opaque predicates). Results are reported in Table XVI. We also report the output of IDA and Objdump in order to give an upper-bound of the number of instructions, yet the two tools recover many dead instructions.

**TABLE XVI: Sparse disassembly coreutils**

| sample  | Tr.len | Objdump | IDA | Dynamic disas. | BINSEC sparse |
|---------|--------|---------|-----|----------------|---------------|
| basename | 1.783  | 20.776  | 20.507 | 1.159          | 7.894         |
| env     | 3.692  | 19.714  | 19.460 | 477            | 6.743         |
| head    | 17.682 | 32.840  | 32.406 | 1.299          | 19.807        |
| mkdir   | 1.436  | 57.238  | 56.767 | 1.407          | 10.428        |
| mv      | 14.346 | 115.278 | 114.067 | 5.261          | 81.596        |

Actually, these experiments demonstrate that sparse disassembly is an effective way to enlarge a dynamic disassembly, in a both significant and guaranteed manner. Indeed, sparse disassembly recovers between 6x and 16x more instructions than dynamic disassembly, yet it still recovers much less than linear sweep – due to the focused approach of dynamic disassembly and the guidance of BB-DSE. Hence, sparse disassembly stays close to the original trace.

**Conclusion.** The carried experiments showed very good and accurate results on controlled samples, achieving perfect disassembly. From this stand-point, sparse disassembly performs better than combination of both recursive and linear like in IDA, with up to 30% less recovered instructions than IDA. The coreutils experiments showed that sparse disassembly is also an effective way to enlarge a dynamic disassembly in a both significant and guaranteed manner. In the end, this is a clear demonstration of infeasibility-based information used in the context of disassembly.

Yet, our sparse disassembly algorithm is still very preliminary. It is currently limited by the inherent weaknesses of recursive disassembly (rather than sparse disassembly shortcomings), for example the handling of computed jumps would require advanced pattern techniques.

**X. DISCUSSION: SECURITY ANALYSIS**

From the attacker point of view, two main counter-measures can be employed to hinder our approach. We present them as well as some possible mitigation.

The first counter-measure is to artificially spread the computation of the obfuscation scheme over a long sequence of code, hoping either to evade the “k” bound of the analysis (false negatives) or to force a too high value for k (false positives or timeouts). Nevertheless, it is often not necessary to backtrack
all the dependencies to prove infeasibility. An example is given in X-TUNNEL were many predicates have a dependency chain longer than the chosen bound (k=16, chain up to 230) but this value was most of the time sufficient to gather enough constraints to prove predicate opacity. Moreover, a very good mitigation for these “predicates with far dependencies” is to rely on a more generic notion of the k bound, based for example on def-use chain length or some formula complexity criteria rather than a strict number of instructions.

The second counter-measure is to introduce hard-to-solve predicates (based for example on Mixed-Boolean Arithmetic or cryptographic hashing functions) in order to lead to inconclusive solver responses (timeout). As we cannot directly influence the solving mechanism of SMT solvers, there is no clear mitigation from the defender perspective. Nonetheless, solving such hard formula is an active topic research and some progress can be expected in a middle-term. Moreover, triggering a timeout is already a valuable information, since BB-DSE with reasonable k bound usually does not timeout. The defender can take advantage of it by manually inspecting the timeout root cause and deduce a hard-to-solve (in-)feasible pattern, which can now be detected through mere syntactic matching. Finally, such counter-measures would greatly complicate the malware design (and its cost!) and a careless insertion of such complex patterns could lead to atypical code structures prone to relevant malware signatures.

XI. RELATED WORK

DSE and deobfuscation. Dynamic Symbolic Execution has been used in multiple situations to address obfuscation, generally for discovering new paths in the code to analyze. Recently, Debray at al. [10], [11] used DSE against conditional and indirect jumps, VM and return-oriented programming on various packers and malware in order to prune the obfuscation from the CFG. Mizuhto et al. also addressed exception-based obfuscation using such techniques [43]. Recent work from Ming et al. [12] used (forward) DSE to detect different classes of opaque predicates. Yet, their technique has difficulties to scale due to the trace length (this is consistent with experiments in Section VI-A). Indeed, by doing it in a forward manner they needlessly have to deal with the whole path predicate for each predicate to check. As consequence they make use of taint to counterbalance which far from being perfect brings additional problems (under-tainting/over-tainting).

DSE is designed to prove the reachability of certain parts of code (such as path, branches or instructions). It is complementary to BB-DSE in that it addresses feasibility queries rather than infeasibility queries. Moreover, BB-DSE scales very well, since it does not depend on the trace length but on the user-defined parameter $k$. Thus, while backward-bound DSE seems to be the most appropriate way to solve infeasibility problems no researches have used this technique.

Backward reasoning. Backward reasoning is well-known in infinite-state model checking, for example for Petri Nets [44]. It is less developed in formal software verification, where forward approaches are prevalent, at the notable exception of deductive verification based on weakest precondition calculi [18]. Interestingly, Charreteur et al. have proposed (unbounded) backward symbolic execution for goal-oriented testing [45]. Forward and backward approaches are well-known to be complementary, and can often be combined with benefit [46].

Yet, purely backward approaches seem nearly impossible to implement at binary level, because of the lack of a priori information on computed jumps. We solve this problem in BB-DSE by performing backward reasoning along some dynamic execution paths observed at runtime, yet at the price of (a low-rate of) false positives.

Disassembly. Standard disassembly techniques have already been discussed in Section VI-A. Advanced static techniques include recursive-like approaches extended with patterns dedicated to difficult constructs [2]. Advanced dynamic techniques take advantage of DSE in order to discover more parts of the code [14], [28]. Binary-level semantic program analysis methods [15], [16], [17], [13], [47] do allow in principle a guaranteed exhaustive disassembly. Even if some interesting case-studies have been conducted, these methods still face big issues in terms of scaling and robustness. Especially, self-modification is very hard to deal with. The domain is recent, and only very few work exist in that direction [48], [49]. Several works attempt to combine static analysis and dynamic analysis in order to get better disassembly. Especially, CODISASM [3] take advantage of the dynamic trace to perform syntactic static disassembly of self-modifying programs.

Again, our method is complementary to all these approaches which are mainly based on forward reasoning [50].

Obfuscations. Opaque predicates were introduced by Collberg [4] giving a detailed theoretical description and possible usages [51], [52] like watermarking. In order to detect them various methods have been proposed [53], notably by abstract interpretation [49] and in recent work with DSE [12]. Issues raised by stack tampering and most notably non-returning functions are discussed by Miller [2]. Lakhotia [6] proposes a method based on abstract interpretation [6]. None of the above solutions address the problem in such a scalable and robust way as BB-DSE does.

XII. Conclusion

Many problems arising during the reverse of obfuscated codes come down to solve infeasibility questions. Yet, this class of problem is mostly a blind spot of both standard and advanced disassembly tools. We propose Backward-Bounded DSE, a precise, efficient, robust and generic method for solving infeasibility questions related to deobfuscation. We have demonstrated the benefit of the method for several realistic classes of obfuscations such as opaque predicate and call stack tampering, and given insights for other protection schemes. Backward-Bounded DSE does not supersede existing disassembly approaches, but rather complements them by addressing infeasibility questions. Following this line, we showed how these techniques can be used to address state-sponsored
malware (X-TUNNEL) and how to merge the technique with standard static disassembly and dynamic analysis, in order to enlarge a dynamic analysis in a precise and guaranteed way. This work paves the way for precise, efficient and disassembly tools for obfuscated binaries.

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APPENDIX
## TABLE XVII: Packer experiment: Opaque Predicates & Call stack tampering

| Packers                  | Static size | #tr.len | (tr.ok/host) | #proc | #th | self-mod. #layers | Obfuscation detection | Stack tampering |
|--------------------------|-------------|---------|--------------|-------|-----|-------------------|------------------------|-------------------|
|                          | prog        |         |              |       |     |                   |                         |                   |
| ACProtect v2.0           | 101K        | 1,813,598 | (✓, ✓)       | 1     | 1   | 4                 | 74                     | OK (0/0)          |
| Armadillo v3.78          | 460K        | 150,014  | (✓, ✓)       | 2     | 11  | 1                 | 1                      | 2 (2/0)           |
| Aspack v2.12             | 10K         | 377,349  | (✓, ✓)       | 1     | 1   | 2                 | 32                     | 136 (7/0)         |
| BoxedApp v3.2            | 903K        | /       | (✓, ✓)*      | 1     | 15  | -                 | -                      | -                |
| Crypter v1.12            | 45K         | 1,170,108 | (✓, ✓)       | -     | -   | 0                 | 263                    | 136 (94/0)       |
| Enigma v3.1              | 1,1M        | 10,000,000 | (✓, ✓) j      | -     | -   | 1                 | -                      | -                |
| EP Protector v0.3        | 8,6K        | 250     | (✓, ✓)       | 1     | 1   | 1                 | 10                     | 2 (4/0)           |
| Expressor                | 13K         | 635,356  | (✓, ✓)       | 1     | 1   | 1                 | 42                     | 39 (10/0)        |
| FSF v2.0                 | 3.9K        | 68,987   | (✓, ✓)       | 1     | 1   | 1                 | 11                     | 14 (4/0)         |
| JD Pack v2.0             | 53K         | 42      | (✓, ✓)       | 1     | 1   | 0                 | 2                      | 0 (0/0)           |
| Mew                      | 2.8K        | 59,320  | (✓, ✓) j      | -     | -   | 1                 | 11                     | 18 (4/0)         |
| MoleBox                  | 70K         | 5,288,567 | (✓, ✓) j      | 1     | 1   | 2                 | 307                    | 128 (X)           |
| Mystic                   | 50K         | 4,569,154 | (✓, ✓) j      | 1     | 1   | 1                 | X                      | X                |
| Neolite v2.0             | 14K         | 42,335   | (✓, ✓) j      | 1     | 1   | 1                 | 95                     | 42 (3/0)          |
| nPack v1.1.300           | 11K         | 138,231  | (✓, ✓) j      | 1     | 1   | 1                 | 41                     | 34 (21/4/0)      |
| Obsidium v1364           | 116K        | 21      | (✓, ✓) j      | -     | -   | 0                 | 10                     | 0 (0/0)           |
| Packman v1.5             | 5.9K        | 130,174  | (✓, ✓) j      | 1     | 1   | 1                 | 12                     | 21 (7/4/0)       |
| PE Compact v2.20         | 7.0K        | 202     | (✓, ✓) j      | 1     | 1   | 1                 | 11                     | 1 (4/2/0)        |
| PE Lock                  | 21K         | 2,389,260 | (✓, ✓) j      | 1     | 1   | 6                 | 53                     | 42 (3/0)          |
| PE Spin v1.1             | 26K         | /       | (✓, ✓)* j     | 1     | 1   | -                 | -                      | -                |
| Petite v2.2              | 12K         | 260,025  | (✓, ✓) j      | 1     | 1   | 0                 | 60                     | 45 (1/0)          |
| RLPACK                   | 6.4K        | 941,291  | (✓, ✓) j      | 1     | 1   | 1                 | 21                     | 25 (14/8/0)      |
| Setisoft v2.7.1          | 378K        | 4,040,403 | (✓, ✓) j      | 1     | 5   | 4                 | X                      | X                |
| svk 1.43                 | 137K        | 10,000,000 | (✓, ✓) j      | -     | -   | 0                 | -                      | -                |
| TELock v0.51             | 12K         | 406,580  | (✓, ✓) j      | 1     | 1   | 5                 | 0                      | 5 (3/0)           |
| Temidha v1.8             | 1.2M        | 10,000,000 | (✓, ✓) j      | 1     | 28  | 0                 | -                      | -                |
| Upack v0.39              | 4.1K        | 711,447  | (✓, ✓) j      | 1     | 1   | 2                 | 11                     | 30 (7/5/0)       |
| UPX v2.90                | 5.5K        | 62,091   | (✓, ✓) j      | 1     | 1   | 1                 | 11                     | 26 (4/2/0)       |
| VM Protect v1.50         | 13K         | /       | (✓, ✓)* j     | 1     | 1   | 0                 | -                      | -                |
| WinUPack                 | 4.0K        | 657,473  | (✓, ✓)        | 1     | 1   | 2                 | 12                     | 33 (7/5/0)       |
| Yoda's Crypter v1.3      | 12K         | 240,900  | (✓, ✓) j      | 1     | 1   | 3                 | 38                     | 16 (4/3/0)       |
| Yoda's Protector v1.02   | 18K         | 17      | (✓, ✓) j      | 1     | 1   | 0                 | 10                     | 0 (0/0)           |

- **size prog**: size of the program
- **#tr.len**: execution trace length
- **tr.ok**: whether the executed trace was successfully gathered without exception/detection
- **host**: whether the payload was successfully executed (printing the hostname of the machine)
- **#proc**: number of process spawned
- **#th**: number of threads spawned
- **#layers**: number of self-modification layers recorded
- **OK, OP, To, Covered**: predicate ok, opaque predicate, timeout, predicate fully covered (both branches)
- **(a/d/s)**: (aligned/disaligned/single)
- † failed to record the trace
- ‡ maximum trace length reached (thus packer not analyzed)
- ‡ analysis failed (due to lack of memory)