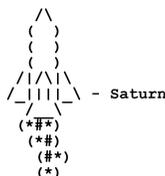


SATURN

Software Deobfuscation Framework Based on LLVM

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ABSTRACT

The strength of obfuscated software has increased over the recent years. Compiler based obfuscation has become the de facto standard in the industry and recent papers also show that injection of obfuscation techniques is done at the compiler level. In this paper we discuss a generic approach for deobfuscation and recompilation of obfuscated code based on the compiler framework *LLVM*. We show how binary code can be lifted back into the compiler intermediate language *LLVM-IR* and explain how we recover the control flow graph of an obfuscated binary function with an iterative control flow graph construction algorithm [3] based on compiler optimizations and satisfiability modulo theories (*SMT*) solving. Our approach does not make any assumptions about the obfuscated code, but instead uses strong compiler optimizations available in *LLVM* and *Super Optimizer* to simplify away the obfuscation. Our experimental results show that this approach can be effective to weaken or even remove the applied obfuscation techniques like constant unfolding, certain arithmetic-based opaque expressions, dead code insertions, bogus control flow or integer encoding found in public and commercial obfuscators. The recovered *LLVM-IR* can be further processed by custom deobfuscation passes that are now applied at the same level as the injected obfuscation techniques or recompiled with one of the available *LLVM* backends. The presented work is implemented in a deobfuscation tool called *SATURN* (Figure 1).

KEYWORDS

reverse engineering, llvm, code lifting, obfuscation, deobfuscation, static software analysis, binary recompilation, binary rewriting

1 INTRODUCTION

In recent years we observed the increase in popularity and rise of intermediate language and source-based obfuscators, specifically due to the growth and diverse landscape of target architectures, especially on the mobile market [11]. While classical binary-based obfuscations were previously attacked by applying pattern-based rules or simple static analysis, higher-level obfuscations applied on intermediate language or source code cannot be effectively compromised. Modern protection tools are mostly based on *state-of-the-art* compiler frameworks like *LLVM* that allow much more complex

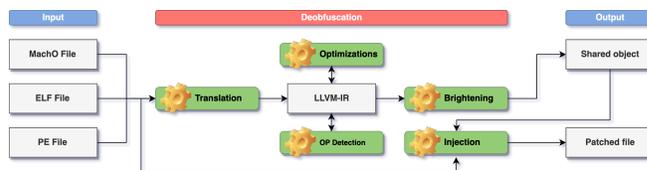


Figure 1: Workflow of the SATURN deobfuscation framework

obfuscation logic [11] [23].

In this paper we present an automatic deobfuscation approach based on *LLVM*'s strong code optimizations. The paper focuses on several aspects that need to be addressed during deobfuscation: *translation of binary code to LLVM-IR, control flow graph recovery, detection of opaque predicates, deobfuscation, brightening of the recovered function and recompilation.*

Translating binary code into *LLVM-IR* is not a straightforward task. A binary opcode does not only execute the operation itself, but might also address several other operations like the calculation of the condition codes/flags that influence later branch instructions. The information that could be used to translate the binary code into an intermediate language like the *LLVM-IR* is normally lost during compilation and, especially in obfuscated binary code, this task can be even harder. One approach to target the problem is to implement the exact semantic of each binary opcode and store the output into a structure that holds the current state of the registers. This is a generic approach that lifts the binary code into a virtualized context but does not make any assumptions about the binary code itself. The recovered *LLVM-IR* is fully functional but the readability of the IR might be very low. In this paper we make use of *Remill* [21] [14] to address the problem of binary code translation.

Control flow obfuscation is a technique to hide the original control flow of a function. To deobfuscate the function the attacker has to recover the control flow graph from the obfuscated binary code. Modern obfuscation tools that operate on intermediate languages

like *LLVM-IR* have the ability to heavily obfuscate the control flow graph. We introduce an algorithm that makes use of the **State** struct in *Remill* to recover the edges of each lifted basic block. The lifted basic blocks and edges represent the recovered control flow graph. The recovery of the control flow graph is done statically and automatically during the lifting of the obfuscated binary code. Compared to previous work ([13], [37], [12], [35], [26]) that was done on control flow graph recovery, our approach does not need any prior knowledge about the binary code and doesn't rely on traces of the function. Instead, the path exploration is done based on the partially deobfuscated basic blocks and their predecessors. Our algorithm is similar to the *Iterative Control Flow Graph Construction* in [3] but is superior in the way that it works independently of the order in which the branches are examined.

A technique to conceal the control flow graph of a function is the insertion of opaque predicates (**OP**) to thwart naïve control flow graph reconstruction algorithms. An opaque predicate is a conditional branch injected into the control flow graph whose condition exists to confuse or thwart reverse engineering, but whose evaluation is deterministic, and thus irrelevant to the greater logic of the program [7]. We present an effective approach to detect and remove opaque predicates. The shown approach is based on strong *LLVM* and *Souper Optimizer* optimizations. For opaque predicates that are resistant to the applied optimizations and/or to verify the optimization results, we use an approach based on *SMT* solving. The way to identify opaque predicates with *SMT* solving is not new [19], but we believe that the way we combine several tools and algorithms are a rich contribution to this paper.

Brightening [COMP.] *verb* – *Reshaping code to make it more readable and understandable for humans*

Constant unfolding, arithmetic-based opaque expressions, dead code, bogus control flow and integer encoding are not only found in hardened code, but can also appear in non-obfuscated code. Normally, during compilation of the source code, the compiler detects this kind of patterns and optimizes them away to obtain the best possible result. The presented approach relies on the reshaping of the *LLVM-IR*, as the way the code gets lifted by *Remill* might hinder the optimizer to reach the best result. The needed steps to reshape the *LLVM-IR* are generic and don't rely on any prior knowledge about the obfuscator.

Without brightening, the *LLVM-IR* would be fully functional but in this paper we aim to reach a *vanilla*¹ state representation of the lifted function. This includes reconstruction of the original function arguments and transformation of the *Remill* specific lifted function based on the **State** struct (Listing 1) into a clean *LLVM* function with its original signature.

Once the control flow graph is recovered and the function is deobfuscated, one of the goals of the presented approach is to recompile and execute the lifted function. Due to the choice of *LLVM-IR* as destination language for the lifted binary code, we can easily compile the recovered code back into binary code by using one of the

```
struct State {
    VectorReg vec[kNumVecRegisters];
    ArithFlags aflag;
    Flags rflag;
    Segments seg;
    AddressSpace addr;
    GPR gpr;
    X87Stack st;
    MMX mmx;
    FPUStatusFlags sw;
    XCR0 xcr0;
    FPU x87;
    SegmentCaches seg_caches;
}
```

Listing 1: Remill State struct definition for x86_64

available *LLVM* backends (X86, ARM, AArch64, RISC-V and others).

Our experiments show that we are able to apply our approach on current *state-of-the-art* obfuscations and also, to partially defeat the *anti-symbolic deobfuscation* tricks introduced in [22].

Our work is not only useful for deobfuscation. In fact this approach can also be used for further applications like fuzzing, as input for dynamic symbolic execution (**DSE**) engines like *KLEE* [4], as input for *LLVM* based obfuscators like *O-LLVM* [11], to achieve automatic payload creation for exploitation as shown in [34] or in general to recompile binary code with the best available *CPU* optimizations (`-march=native`) to improve the performance of applications or to introduce new compiler based security features. This applies especially to applications where the source code is not available.

1.1 Goals and Challenges

We want to propose a deobfuscation framework based on *LLVM* and its strong optimizations for real world applications. Using *LLVM* for reverse engineering might look like an overcomplication in the beginning, but it's similar to what is done during the compilation of source code. The *LLVM* compiler framework has all the needed tools to easily create and modify the control flow graph, its basic blocks and instructions. The challenge is to lift the binary code into the *LLVM-IR* and get it into a shape that is equal to a non-obfuscated compiled source code. The techniques to reach this goal should be generic, non error-prone and lightweight. The framework should always generate working *LLVM-IR* that can be recompiled and executed. We aim at proposing a framework to lift the binary code back into a clean and understandable *LLVM-IR* that is built on mature tools around the *LLVM* ecosystem. Our vision is to get the attack surface back to the level it was implemented at – the compiler level.

1.2 Contribution

We summarize our contributions as follows.

- We propose an automatic deobfuscation tool that is generic enough to deal with several obfuscation techniques.

¹As close as possible to a non-obfuscated compiled source code

- We propose a framework that can recompile and inject the *LLVM-IR* code back into the given binary.
- We propose an effective and efficient method to identify opaque predicates at the *LLVM-IR* level, that are then solved and verified using compiler optimizations and *SMT* solvers.
- We propose a generic method to transform the binary code lifted by *Remill* into a cleaner *LLVM-IR* without the *Remill State* struct. This includes the recovery of the stack and the function arguments.
- We show that our work can be used to weaken or even remove anti-symbolic execution tricks like the ones introduced in the work of [22] and allows the usage of *state-of-the-art* source-level dynamic symbolic execution tools.
- We propose a framework that can generate a compact representation of the obfuscated constraints that are easier to solve or check for satisfiability.

1.3 Discussion

We explore several steps to recover the binary code from an obfuscated binary, based on the lifting of the code to the compiler intermediate language *LLVM-IR*. We propose several algorithms that were implemented in the tool *SATURN* that help to handle different aspects of binary code deobfuscation. To our knowledge the implementation of *SATURN* is *state-of-the-art* and lifts the attacking surface from the obfuscated binary code back to the compiler level. Our work has a high impact on the security of obfuscated binaries and allows the usage of efficient *state-of-the-art* source-/IR-level dynamic symbolic execution tools like *KLEE* to further analyze the recovered code. We provide an experimental setup that includes several corner cases that might hinder binary code lifting, but also apply our method to strong obfuscated real world binaries.

2 BACKGROUND

2.1 LLVM

"*LLVM* began as a research project at the University of Illinois, with the goal of providing a modern, SSA-based compilation strategy [33] capable of supporting both static and dynamic compilation of arbitrary programming languages. Since then, *LLVM* has grown to be an umbrella project consisting of a number of sub-projects, many of which are being used in production by a wide variety of commercial and open source projects as well as being widely used in academic research" [16]. To understand our approach it's not crucial to understand how *LLVM* and its internal language *LLVM-IR* are designed, but the reader should keep in mind that the *LLVM-IR* is based on the Static Single Assignment form (**SSA**) [8] which makes it easier to construct the final formula passed to the *SMT* solver [34].

2.2 Remill

"*Remill* is a static binary translator that translates machine code instructions into *LLVM* bytecode. It translates x86 and amd64 machine code (including *AVX* and *AVX512*) into the *LLVM-IR*" [21]. In our work we make extensive use of *Remill* to lift the binary code into the *LLVM-IR*. *Remill* does not make any assumptions about the stack or the arguments of a lifted function since it only lifts single

instructions.

2.3 Souper optimizer

Souper is particularly convenient because it's an *LLVM*-based project that, with the help of *KLEE* [4], is capable of converting a sequence of *LLVM-IR* instructions into an *SMT* formula and use several *SMT* solvers to discover additional peephole optimizations. As a desired side-effect we can benefit from its results to determine the opacity of a conditional branch. *Souper* has the possibility to cache the *SMT* queries and results into an external *Redis* database [24] to improve the performance. This leaves us with a database full of opaque predicates and obfuscation patterns that could be analyzed in further studies.

2.4 KLEE

"*KLEE* is a symbolic execution tool capable of automatically generating tests that achieve high coverage on a diverse set of complex and environmentally-intensive programs and operates on the *LLVM-IR*" [4]. *KLEE* is not only a useful tool for testing software but it's also very effective in attacking several code obfuscation techniques. Current work proposed in [22] tries to hinder symbolic execution tools like *KLEE* to do their work effectively.

3 MOTIVATION

3.1 Attacker model

Goal. We consider a man-at-the-end (**MATE**) scenario where the attacker has full access to a protected binary under attack and no access to the source code or unprotected binary. The attack model and the methodology follow closely the survey by Schrittwieser et al. [28] and are similar to the ones considered in [22]. To be more concrete, we will focus on the following goals: 1. *Recovery of the control flow graph*. Retrieving the control flow graph of an obfuscated function is a crucial step to understand what the original function performs. 2. *Detection of opaque predicates*. Recovery of the control flow graph can only be successful if the injected opaque predicates can be detected and removed. 3. *Deobfuscation of several obfuscation techniques*. To make the code readable and understandable the injected obfuscation patterns have to be detected and removed. 4. *Recovery of the stack and arguments*. If the attacker can rebuild the stack and arguments, the code of the function will become tidy. 5. *Execution of the recovered code*. If the attacker is able to execute a semantically equivalent deobfuscated code, further analysis can be done with tools like a debugger if needed.

3.2 Motivating example

Let us illustrate some anti-symbolic path-oriented protections on a toy program like those introduced in the work of [22]. Listing 2 displays an unoptimized obfuscation of a simple toy example that is protected against symbolic execution attacks with the **FOR** and **SPLIT** tricks as introduced in [22] and extended with an opaque predicate to protect the final calculation.

```

int func(char chr, char ch1, char ch2) {
    char garb = 0; char ch = 0;
    // FOR trick
    for (int i = 0; i < chr; i++)
        ch++;
    // SPLIT trick
    if (ch1 > 60)
        garb++;
    else
        garb--;
    if (ch2 > 20)
        garb++;
    else
        garb--;
    // MBA based opaque predicate
    if ((chr + ch2) == ((chr ^ ch2) + 2 * (chr & ch2)))
        ch ^= 97;
    else
        ch ^= 23;
    return (ch == 31);
}

```

Listing 2: Anti-symbolic path-oriented protections FOR and SPLIT applied on a toy program based on [22]

```

define dso_local @i32 @func(i8 signext) local_unnamed_addr #0 {
    %2 = icmp eq i8 %0, 126
    %3 = zext i1 %2 to i32
    ret i32 %3
}

```

Listing 3: Unprotected toy program compiled to LLVM-IR

The anti-symbolic tricks that we considered are not resistant to compiler optimizations and can easily be removed by compiling the code with `clang -O3` optimization. The introduced opaque predicate is resistant to compiler optimizations and can only be recovered by *SMT* solving. In our tests we will compile the toy example with `clang -O0` to hinder the optimizer from optimizing away the introduced tricks. The output binary therefore contains several stack slots, that are required to be recovered during the brightening step. If we fail to recover the stack slots and arguments, the *LLVM* optimizations will fail to work and the anti-symbolic tricks won't be removed. If we succeed, the retrieved *LLVM-IR* should look similar to the output of `clang -O3 -S -emit-llvm` in Listing 3 applied on the toy program without any obfuscation.

4 FUNCTION RECOVERY

Two of the core features of *SATURN* are the exploration and control flow graph reconstruction phases. The *LLVM* ecosystem relies on powerful and correct algorithms that we made use of during the development of *SATURN*'s passes. In this section we explain how *SATURN* achieves full function recovery starting from the binary code.

4.1 Code lifting to LLVM-IR

SATURN heavily relies on *Remill*. That's why it's important to understand how *Remill* is lifting a native instruction to *LLVM-IR*. *Remill* makes use of the target architecture's CPU instruction semantics to lift an instruction. In Listing 1 we can see the *State*

struct for the *x86_64* architecture.

To emulate an *x86_64* instruction like `add rax, rcx` *Remill* will create a call to a helper function that implements the emulation for the instruction. This function takes the *State* variable as an argument (Listing 4) and calculates the result according to the semantic of the instruction. This also includes the *Flags* registers. Once all instructions of a basic block are lifted, the generated calls get inlined into the caller. The output *LLVM-IR* is not very readable at this step, but it behaves functionally the same as the native counterpart.

```

Memory *__remill_basic_block(State &state, addr_t curr_pc, Memory *
    ↪ memory);

```

Listing 4: *Remill* basic block function signature C/C++

During the lifting, *SATURN* stores each recovered basic block into its own *LLVM-IR* function. The basic block functions then get connected in a separate *LLVM-IR* function, which is representing the recovered control flow graph (Figure 2).

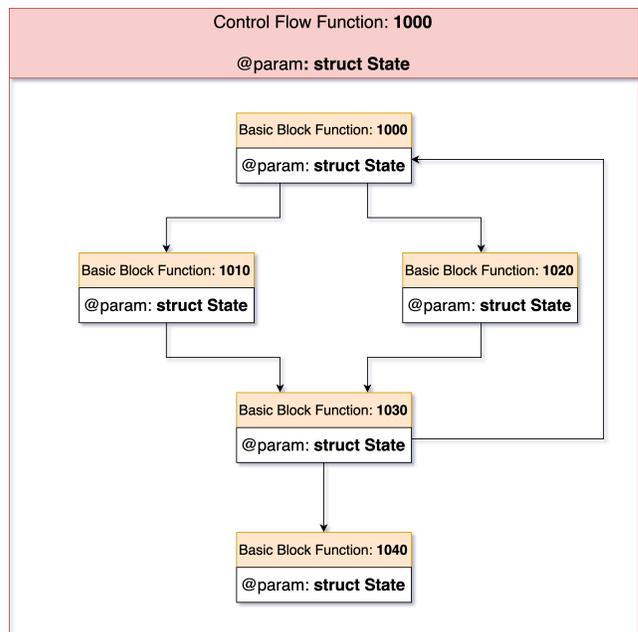


Figure 2: LLVM function that contains the control flow graph of the recovered function at address 1000. The basic blocks are lifted as LLVM functions themselves and get called according to their usage. The result of the call decides the destination of the branch.

With this design decision we can directly optimize the lifted basic block function and achieve a performance improvement in further deobfuscation steps. Applying optimizations at this step also removes some simple obfuscation patterns. The control flow

function is kept as simple as possible, which allows us to add/remove edges without the need to change the lifted code and avoids dealing with *LLVM*'s *PHI*-nodes [33].

SATURN decides how to proceed with the path exploration during the lifting of basic blocks. For that *SATURN* is using the *Remill* instruction categories that are generated for each lifted instruction. Based on the instruction category *SATURN* will try to detect if the basic block is ending with an opaque predicate (Table 1) or not. If the basic block is a candidate for an opaque predicate, *SATURN* will first try to prove the outgoing edges by applying *LLVM*'s optimization passes. If after optimization the count of the outgoing edges is greater than one, *SATURN* will try to solve the outgoing edges by making use of *Souper* and the *Z3* SMT solver [9]. *SATURN* is always trying to use *LLVM*'s optimizations first, since they are much cheaper, performance-wise, compared to the use of an SMT solver. Our tests with various obfuscation engines show that most of the generated opaque predicates are not resistant to *LLVM*'s optimizations. The handling of opaque predicates is well described in Section 5.

Table 1: Path Exploration

kCategory	Exploration	Opacity Proof
NoOp	Continue	No
Normal	Continue	No
FunctionReturn	Stop	Yes
IndirectJump	Stop	Yes
DirectJump	Stop	No
ConditionalBranch	Stop	Yes
IndirectFunctionCall	Stop	Yes
DirectFunctionCall	Continue	No

SATURN continues with the lifting process as long as new edges are discovered. When *SATURN* is discovering a new incoming edge for a basic block, it has to prove that the new edge does not change the opacity of an already (temporarily) proven basic block (Table 1). The following steps are applied:

- (1) create a new function, called **FSlice**, based on the definition in Listing 4
- (2) find all the basic blocks that dominate the lifted basic block, that we identify as **BBLift**
- (3) if more than one predecessor is found, stop and continue at step 5
- (4) repeat step 2 - 3 with the predecessor as input and store the result in a sorted list, called **PSort**, based on the dominance
- (5) for each predecessor in **PSort** create a call in **FSlice** in reverse order
- (6) connect the called predecessors with a branch instruction
- (7) call **BBLift** at the end of **FSlice** and connect it to the called dominating predecessor with a branch
- (8) inline all calls in **FSlice** and apply the *LLVM* optimizations.

Now *SATURN* is using one of the solutions explained in Section 5.3 to determine the opacity of the basic block.

The basic block opacity might change to non-opacity and help us to detect false positives. This step is important, as it guides further code exploration. We also need this step because we can't know about all the incoming edges in the beginning and we gain the needed knowledge about the control flow graph only during the exploration phase. The opacity of the basic block will change according to Table 2.

Table 2: Basic Block Opacity

Current Opacity	New Edge	New Opacity
No OP	No OP	No OP
No OP	OP	No OP
OP	No OP	No OP
OP	OP	OP

5 DEOBFUSCATION BY OPTIMIZATION

The capability to easily build custom optimization passes is part of the core design of *LLVM*. In this section we are going to cover the custom optimization passes that we implemented to facilitate the propagation of constants and the identification of opaque predicates.

5.1 Constants

Storing constants in data sections is a common obfuscation technique to trick disassemblers like *IDA Pro* [10] into generating wrong results or simply stop the disassembling of the function. During deobfuscation, *SATURN* tries to detect accesses to such constants and replace the *read* instruction with a constant value in the *LLVM-IR*. Demoting the global variables helps the *LLVM* optimization passes to apply constant folding and defeat such kind of obfuscation tricks. The user has to supply the ranges where to look for such constant data with the *SATURN* option *constantPool*. Our tests with several obfuscators show that it's not enough to use the constant binary data sections. In the obfuscators we looked at, we could find sections with read/write attributes that contained such constants.

5.2 Stack pointer aliasing

Remill does not know about the concept of a stack. Instead of trying to emulate the stack, it handles the stack operations by using read and write intrinsics (Listing 5) relying on the stack register as address. The stack register is part of the **State** struct and is defined as an *unsigned integer* value like `uint64_t State.gpr.rsp.qword` for the *x86_64* architecture. In *SATURN* the access to the stack will be represented as a load/store of an **IntToPtr** value. This makes it impossible for *LLVM* to apply pointer aliasing, because *LLVM* does not support pointer aliasing on integer values [17].

In *SATURN* this problem is handled by concretizing the stack register in the function representing the control flow graph. We then inline the basic block functions and optimize the code. During

```
uint<T>_t __remill_read_memory<T>(Memory *, addr_t);

Memory *_remill_write_memory<T>(Memory *, addr_t, uint<T>_t);
```

Listing 5: Remill’s memory read and write intrinsics definition

optimization the concrete stack register value will be propagated through the *LLVM-IR* and will replace the **IntToPtr** operand with a concrete memory location. This concrete value helps us to identify the stack slot. We then create a global variable and a *LLVM-IR* **Alloca** instruction for the stack slot at the beginning of the control flow graph function. After that we load the value from the global variable and store it into the **Alloca** value right after the **Alloca** instruction. We keep a map of known stack slots, their global variables and of the generated **Alloca** instructions. We optimize the code again and now, based on the *allocas*, *LLVM* is able to apply a proper pointer aliasing pass. These steps may reveal new concrete stack slots and we repeat this algorithm until no new stack slots are detected. Once it’s finished we remove the unused global variables.

After the algorithm is done, some global variables are not optimized away. These global variables represent the return value, the function arguments passed on the stack and the values popped from the stack and stored in the execution context by the function. This is a side effect that we can use in the further two deobfuscation steps *code brightening* and recovering of the function arguments.

Pointer aliasing on the stack is an important feature for deobfuscation. It’s crucial that this step gives accurate results, since it’s needed for the following optimization steps.

```
0x146253057: lea rsp, [rsp-8]
0x14625305F: push rcx
0x146253060: xchg rcx, [rsp+8]
0x146253065: mov rcx, r14
0x146253068: mov [rsp+8], rcx
0x14625306D: mov rcx, [rsp]
0x146253071: mov [rsp], r14
0x146253075: push rcx
0x146253076: lea rcx, [rsp+8]
0x14625307B: not r14
0x14625307E: xor r14, [rcx]
0x146253081: pop rcx
0x146253082: push rbx
0x146253083: mov ebx, 0xD4469D6E
0x146253088: push rsi
0x146253089: mov esi, 0xB7E07B2A
0x14625308E: add esi, ebx
0x146253090: mov ebx, esi
0x146253092: xor ebx, 0x533C089A
0x146253098: mov esi, 0xAB832EC0
0x14625309D: ror ebx, 0x14
0x1462530A0: and esi, 0x5B171CFB
0x1462530A6: rcl ebx, 0x1E
0x1462530A9: or ebx, 0xE4E97533
0x1462530AF: shld esi, ebx, 6
0x1462530B3: rcl ebx, 0xD
0x1462530B6: jb 0x1465C8B69
```

Listing 6: Obfuscated x86_64 opaque predicate

5.3 Breaking Opaque Predicates with LLVM-IR Optimizations

SATURN is approaching the opaque predicates problem in two steps. First it creates a slice of the instruction pointer and then applies *LLVM* optimizations on it. If the optimization is successful, the slice will fold into a single concrete value.

The available open source slicers ([38][5][29]) seem to be too outdated or unreliable to produce a valid slice for a given function. Conversely, our algorithm is based on modelling the slicing process in *C* and then relying on the *LLVM* optimizations to produce the slice.

5.3.1 *SATURN’s slicing.* The *Remill’s* basic block definition in Listing 4 contains the information to control and inspect the value of a general purpose register before and after the execution of a *Remill* function. Based on the *Remill* basic block, the slicing is achieved with the following steps:

- (1) initialize a *Remill State* struct with a symbolic state
- (2) concretize the initial instruction pointer (**RIP**)
- (3) call the opaque basic block, that has been previously optimized with the constant promotion and stack aliasing passes. This call is inlined during further optimization
- (4) pass the initialized **State** struct to the basic block to be proven to be opaque
- (5) get the resulting **State** struct after the basic block execution, specifically inspecting the final instruction pointer.

```
extern "C" uint64_t __saturn_slice_rip(State state, addr_t curr_pc,
    ↪ Memory *memory, uint64_t *Stack) {
    // 1 Allocate a local Remill State structure and initialize it
    State S;
    S.gpr.rax.qword = state.gpr.rax.qword;
    ...
    S.gpr.rsp.qword = (uint64_t) Stack;
    S.gpr.r15.qword = state.gpr.r15.qword;
    S.aflag.af = state.aflag.af;
    ...
    S.aflag.zf = state.aflag.zf;
    // 2 Concretize RIP
    S.gpr.rip.qword = curr_pc;
    // 3/4 Call opaque basic block with initialized State struct
    // This function call will be replaced with the lifted one
    __remill_basic_block(S, curr_pc, memory);
    // 5 Inspect the value of RIP
    return S.gpr.rip.qword;
}
```

Listing 7: SATURN’s slicing helper function

The initialization and further inspection steps are in Listing 7. The final step is taking the generated *__saturn_slice_rip* function and applying *LLVM* optimizations on it. If the function implements an opaque predicate and *LLVM* is able to optimize it away, the function will end with a concrete return value. This is the deterministic instruction pointer address where the basic block will continue. Listing 6 is showing an example of the obfuscated opaque predicate. In Listing 8 we can appreciate the result of the previously described

6.1 Post Translation Optimization

Once the obfuscated function is recovered, *SATURN* starts the post translation optimization phase, where the input is the control flow graph function shown in Figure 2. The steps are as follows:

- (1) the stack register (**RSP**) and the instruction pointer register (**RIP**) contained in the **State** variable are concretized
- (2) *allocas* are created for the flag calculation and stored into the **State** struct. This helps to optimize and remove unneeded flag calculations
- (3) the basic block functions are inlined like seen in Figure 2
- (4) the *LLVM* optimizations are applied to the function
- (5) the constant promotion algorithm (Section 5.1) and the stack alias analysis (Section 5.2) are applied to the function
- (6) the steps 2–4 are repeated until no further changes are detected.

After the post translation is done, the output *LLVM-IR* is in a deobfuscated state but it's still difficult to understand the code because of the operations applied on the *Remill State* struct like shown in Listing 11. At this point the concretization of the registers can be removed and the *LLVM-IR* can be compiled to binary code by making use of one of *LLVM*'s backends. In the tests we use *Clang* to compile the output *LLVM-IR* into a shared object. *SATURN* has two options to recompile the *LLVM-IR*:

- the first option keeps the lifted function with the *Remill* signature as defined in Listing 4. The created C++ helper functions do the context switch from the *x86_64* to the virtual context and take care of the **State** struct handling;
- the second option recovers the original function arguments and removes the **State** struct. This method has the benefit that the function can be called directly without a context switch. This approach is detailed in Section 6.2.

6.2 Code Brightening

The function lifted by *Remill* is operating on a virtual context (Listing 11), the **State** struct. This hinders the optimizer from detecting some optimization opportunities, as it has to store the results for each register back to the **State** struct. This happens for all the registers shown in Listing 11. At this point the output code is still too difficult to understand in further analysis steps like reverse engineering. In this section we address this problem and show how the original signature of the function can be reconstructed. This includes recovering the function arguments and removing the **State** struct, which leads to *vanilla*-like results.

6.2.1 Function Arguments. Based on the algorithm in Section 5.2, the arguments of a lifted function that are passed through the stack, are detected by inspecting the remaining global variables. During the execution of the algorithm in Section 5.2, *SATURN* keeps track of the global variables and their stack offsets. This information will be used to detect the number of arguments, with the knowledge about the application binary interface (**ABI**) and the calling convention [18] used by the function. If no stack arguments are passed to the function, we detect the number of arguments through the register accesses on the **State** struct. We only focus on the reconstruction of the general purpose registers in the following steps:

```
define dlllexport i64 @F_140001000(%struct.State.32* %S, i64 %curr_pc,
    ↪ %struct.Memory.0* %memory) {
entry:
  %0 = getelementptr inbounds %struct.State.32, %struct.State.32* %S,
    ↪ i64 0, i32 6, i32 33, i32 0, i32 0
  %1 = getelementptr inbounds %struct.State.32, %struct.State.32* %S,
    ↪ i64 0, i32 13
  store i8 0, i8* %1, align 1
  %2 = getelementptr inbounds %struct.State.32, %struct.State.32* %S,
    ↪ i64 0, i32 6, i32 5, i32 0
  %3 = bitcast %union.anon.2* %2 to i8*
  %4 = getelementptr inbounds %struct.State.32, %struct.State.32* %S,
    ↪ i64 0, i32 6, i32 17, i32 0
  %5 = bitcast %union.anon.2* %4 to i8*
  %6 = load i8, i8* %5, align 1
  %7 = load i8, i8* %3, align 1
  store i64 5368713251, i64* %0, align 8
  %8 = sext i8 %7 to i64
  %phitmp = icmp eq i8 %7, 126
  %9 = getelementptr inbounds %struct.State.32, %struct.State.32* %S,
    ↪ i64 0, i32 6, i32 1, i32 0, i32 0
  %10 = getelementptr inbounds %struct.State.32, %struct.State.32* %
    ↪ S, i64 0, i32 6, i32 5, i32 0, i32 0
  %11 = sext i8 %6 to i64
  %12 = and i64 %11, 4294967295
  store i64 5368713372, i64* %0, align 8
  %13 = getelementptr inbounds %struct.State.32, %struct.State.32* %
    ↪ S, i64 0, i32 6, i32 7, i32 0, i32 0
  %14 = xor i8 %7, %6
  %15 = sext i8 %14 to i64
  %16 = getelementptr inbounds %struct.State.32, %struct.State.32* %
    ↪ S, i64 0, i32 6, i32 17, i32 0, i32 0
  store i64 %12, i64* %16, align 8
  %17 = and i64 %12, %8
  %18 = shl nuw nsw i64 %17, 1
  %19 = and i64 %18, 4294967294
  store i64 %19, i64* %13, align 8
  %20 = add nsw i64 %18, %15
  %21 = and i64 %20, 4294967295
  store i64 %21, i64* %10, align 8
  store i8 0, i8* %1, align 1
  %22 = zext i1 %phitmp to i8
  store i8 %22, i8* %3, align 1
  %23 = zext i1 %phitmp to i64
  store i64 %23, i64* %9, align 8
  ret i64 %23
}
```

Listing 11: Recovered toy program LLVM-IR in the *Remill State* struct form

- (1) based on the function's *calling convention*, start with the last register argument in the function's [18] argument list and search for the first *getElementPtr* (**GEP**) instruction that's accessing the register and is also dominating all the other **GEP** instructions that access that register
- (2) if no **GEP** instruction is found, continue with the next register and decrease the number of arguments by one
- (3) if a **GEP** instruction was found, forward slice the **GEP** value to get a tree of users that have a reference to the **GEP** instruction
- (4) sort the users based on their position in the dominance tree **DT** of the function
- (5) look for **load** and **store** instructions to detect how the **GEP** is used

- (6) if a dominating **load** or **store** can be found, assume that this register is an argument
- (7) else decrease the number of arguments by one and continue at step 3.

6.2.2 *Function reconstruction.* Based on the recovered number of arguments we start to rebuild the lifted function to be detached from the **State** struct. We use helper functions in C/C++ that assist us to easily map the function arguments to their slots in the **State** struct as shown in Listing 12.

```
extern "C" Memory * F_Lifted(State &state, addr_t curr_pc, Memory *
    ↪ memory);
extern "C" uint64_t x64_MS_2_ARG(uint64_t *RCX, uint64_t *RDX) {
    struct State S;
    // Set 1. arg
    S.gpr.rcx.qword = (uint64_t) RCX;
    // Set 2. arg
    S.gpr.rdx.qword = (uint64_t) RDX;
    // Call lifted function which will be replaced and inlined
    F_Lifted(S, 0, nullptr);
    // Return result
    return S.gpr.rax.qword;
}
```

Listing 12: SATURN’s helper C/C++ function to handle a Windows 64-bit ABI function with 2 arguments

We only need to prepare helpers for the register based arguments. On functions that pass arguments on the stack we can simply add new arguments to the helper function in the *LLVM-IR* and replace all the references of the global value representing the stack argument to the newly created function argument. The further steps are independent from the number of arguments:

- (1) find the call to the **F_Lifted** dummy function
- (2) replace the reference of **F_Lifted** to the lifted function
- (3) inline the call into the helper function
- (4) run *LLVM*’s strongest optimizations.

Based on *LLVM*’s optimizations we get a clean *LLVM-IR* function that looks *vanilla*-like as shown in Listing 13. If we compare the input *LLVM-IR* in Listing 11 and the result in Listing 13, we can see how strong and effective the *LLVM* optimizations are.

```
define dlllexport i64 @F_140001000_args(i64* %RCX, i64* %RDX, i64* %
    ↪ R8) {
entry:
    %0 = ptrtoint i64* %RCX to i64
    %1 = trunc i64 %0 to i8
    %2 = icmp eq i8 %1, 126
    %3 = zext i1 %2 to i64
    ret i64 %3
}
```

Listing 13: Optimized MBA LLVM-IR function with recovered arguments

7 EXECUTION

SATURN is not only able to lift, deobfuscate and brighten the code. It’s also able to inject the deobfuscated function back into the input binary. Based on the recovery result (with or without **State** struct) there are two different ways to call the recovered function.

In both described ways the shared library gets injected into the input binary. In portable executable (**PE**) files the *import table* gets replaced with an updated *import table* that contains an *import* to a function in our shared library from Section 6.

7.1 Direct Function Redirection

When *SATURN* is able to fully recover the function and its arguments, we can choose to patch the original function and insert a branch instruction to the imported symbol.

7.2 Context Switch

If the recovery of the function arguments fails, *SATURN* is able to keep the **State** struct in the recovered function. This approach needs a more advanced way to execute the function. The needed *runtime* is implemented in C++ and **x86_64 assembly**. The *runtime* will be compiled into the shared library that is generated in Section 6. The needed steps to call the function are:

- (1) patch an instruction at the beginning of the obfuscated function to push one integer value on the stack (used as function identifier)
- (2) patch a second instruction to jump into our imported symbol in the import table.

When the function is reached during execution, it will jump into our *runtime* that does the following:

- (1) create a virtual stack and use it in place of the original one
- (2) store all the register values into a local **State** struct
- (3) call the lifted function with the generated **State** struct
- (4) on calls/jumps outside of the lifted function restore the registers from the **State** struct and handle the return of the function
- (5) if the function returns, restore the registers and jump back to the caller.

8 EXPERIMENTAL EVALUATION

The experiments below seek to answer the following Research Questions:

- RQ1** What is the effectiveness on the recovery of the control flow graph?
- RQ2** What is the detection rate of the opaque predicates?
- RQ3** What is the effectiveness of the deobfuscation?
- RQ4** Were all arguments and stack slots recovered?
- RQ5** Is the deobfuscated code semantically equivalent to the protected one during execution?

8.1 Experimental setup

The attacker has access to *SATURN* to reverse engineer the given binaries and has the goal to recover the obfuscated functions. For the defense we created some binaries that trigger corner cases and

Table 3: Results for datasets

Dataset #1											
Program	Time to lift	Time to optimize	Detected Opaque Predicates	Test passed	Arguments recovered (Lift./Orig.)	Stack Slots recovered	Processed Instructions	Recovered Basic Blocks	Obfuscation removed	Solving time with KLEE (Lift./Orig.)	Size reduction in Basic Blocks
args	0.541s	0.980s	0/0 ^a	Yes ^a	0/6 ^a	0 ^a	110	13/13	Yes	-	4
cmp_test	0.408s	0.342s	1/1	Yes	2/2	7	39	8/8	Yes	-	5
edges	0.129s	0.233s	2/2	Yes	1/1	5	16	4/4	Yes	-	3
edges2	0.428s	0.622s	0/0	Yes	2/3 ^d	11	120	10/10	Yes	-	9
fib	0.309s	0.287s	0/0	Yes	1/1	6	31	4/4	Yes	-	0
gotos	0.599s	0.564s	3/3	Yes	3/3	10	85	13/13	Yes	-	10
inf_loop	0.215s	0.285s	1/1	Yes	1/1	0	18	2/2	Yes	-	0
loop	0.152s	0.247s	0/0	Yes	1/1	5	21	4/4	Yes	-	3
multiedges	0.405s	0.251s	0/0	Yes	1/1	4	21	9/9	Yes	-	8
op1	0.188s	0.010s	1/1	Yes	2/2	5	24	3/3	Partially ^e	-	2
tig_virt	2.337s	1.018s	0/0	Yes	1/1	17	288	41/41	No	-	23
sse2	0.147s	0.429s	0/0	Yes	2/2	16	47	1/1	Yes ^f	-	0
Dataset #2											
binsec0	4.785s	1.144s	0/0	Yes	1/1	19	226	25/25	Yes	0.43s/2m6.30s	9
binsec0_virt	6.062s	0.595s	0/0	Yes ^a	0/2	0 ^a	464	86/86	No	-	36
binsec1	4.778s	0.141s	0/0	Yes ^a	0/2	0 ^a	273	27/27	Yes	-	3
forsplit	3.033s	0.738s	0/0	Yes	3/3	8	112	12/12	Yes	0.08s/16.13s	4
Dataset #3											
obf0_virt	27.998s	8.592s	0/0	No ^b	4/?	27	2059	10/? ^c	Yes	-	4
obf1_func0	0.754s	0.680s	11/11	No ^b	0/0	10	182	12/12	Yes	-	10
obf1_func1	1.060s	0.827s	0/0	No ^b	0/0	9	241	14/14	Yes	-	13

^aRemill **State** struct was used ^bBinary execution failed because of other protections like anti-tampering

^cUnknown amount of original basic blocks ^dDead argument was detected ^eMBA formula was not optimized away ^fRecovered integer arithmetic

use several obfuscation techniques that might hinder binary lifting. Some binaries are protected by Tigress [30], an open source *state-of-the-art* obfuscator. Some other binaries are protected by real world obfuscators where no source code is available. The machine for the experiments uses Windows 10 Pro x64 on a Intel Core i7-6700k CPU with 32 GB RAM.

8.2 Datasets

We select some small programs that trigger corner cases in several steps of the approach described in this paper. We also choose programs that contain selected obfuscation patterns and real world obfuscated binaries where no source code is available. The datasets and results are available in our online repository ².

Dataset #1. During the development of *SATURN* we created several test samples that can trigger corner cases. The tests include scenarios like overlapping stack slots, register and stack based arguments, loops, infinite loops, opaque predicates, MBA based opaque predicates and dead code. The programs take an input value from the command line, perform some calculations and print the output to the user. The sample *tigress_virtualize* is protected with the *tigress* virtualization obfuscation pass (*-Transform=Virtualize*).

Dataset #2. This dataset includes some programs that were taken from the repository provided by [22] and use the *SPLIT* and

FOR anti-*DSE* tricks.

Dataset #3. The last dataset contains two real world binaries that were protected with *Obfuscator0* and *Obfuscator1* ³. The binary from *Obfuscator1* was chosen because we have an unprotected binary and can easily compare the results. The *Obfuscator0* doesn't have an associated unprotected binary, but we choose it because it's a strong obfuscated real world example of a protected virtual machine entry point⁴. Both binaries are heavily obfuscated and were chosen to stress test *SATURN*.

8.3 Results & Observations

Table 3 shows the results for each tested program in the dataset. In programs for which the argument and stack recovery fails ^a, we are still able to recover the function by staying in the Remill **State** struct (**RQ1**). For all other programs the recovery of the arguments and the stack was successful (**RQ4**). In the programs *obf0_func0* and *obf1_func0* we don't know the exact amount of opaque predicates but based on the obfuscator we know that a missed opaque predicate would lead to a broken *LLVM-IR*. For the programs in dataset #1 and #2 all opaque predicates are detected (**RQ2**).

For each program we verified the deobfuscated function for correctness by comparing the output values to the one of the obfuscated program. Programs protected with the *Tigress* virtualization

²https://github.com/pgarba/Saturn_Results

³*Obfuscator0* and *Obfuscator1* are made up names

⁴Context switch from the original *x86_64* to the virtual context

stay in the virtualized form but the recovered code is clean and readable. The program *op1* is only partially deobfuscated. The *MBA* based opaque predicate is removed but the recovered calculation is still based on the *MBA* formula ^e. The result of *obf0_virt* can't be verified but the recovered code is clean, readable and meaningful (RQ3). For the programs in dataset #2 we are not able to remove the *FOR* and *SPLIT* tricks in the Tigress protected samples. In the other programs the tricks are detected and removed.

For dataset #1 and #2 we are able to execute the output binary and all the deobfuscated programs behave in a semantically equivalent way to the obfuscated ones (RQ5). For dataset #3 the recompiled binaries are not working because of some additional anti-tampering checks in those binaries ^b.

For all the programs we verified the output binary obtained by *SATURN* with the *IDA Pro* [10] decompiler. The decompiler is returning meaningful and readable pseudo C code (RQ3). This was failing before as *IDA Pro* struggles with obfuscated code.

9 DISCUSSION

We compared our work to existing *LLVM* based binary lifting frameworks. All of them were failing in lifting obfuscated code ([36], [15], [20], [14]) as they were not built for this task. A good overview of the existing *LLVM*-based lifters is given in the comparison table that can be found in [20]. One exception is *S2E* [6], the symbolic execution tool based on *QEMU* [2]. *S2E* is able to export the generated traces in pure *LLVM-IR* form but, considering it is a dynamic approach, we can't compare it to our work.

We also compared our work to the symbolic execution tool *Triton* [31]. We were interested to see how *SATURN* compares to *Triton* while processing the opaque predicates with an *SMT* solver. We noticed that *SATURN* is able to create much smaller and optimized *SMT* queries due to prior optimizations. In this regard our approach is much more efficient compared to the one in *Triton* and therefore reduces the solving times⁵. This complies with the assumption in [3].

The work presented in [19], although based on binary execution traces, is a valid starting point to improve the detection of the dynamic opaque predicates in *SATURN*. While the work presented in [3] describes a strong simplification methodology based on the *Drill&Join* synthesis technique [1] which is orthogonal to the ones in *SATURN* and could further improve the *MBA* expressions handling. As discussed in Section 12, a plugin system would enable us to integrate these approaches during the exploration phase.

10 RELATED WORK

Machine Learning. One of the side products of *SATURN* is a database with normalized opaque predicates and obfuscation patterns thanks to the *Redis* [24] cache used in the *Souper Optimizer* [27]. We think that it would be interesting to see what a machine learning based method like the one introduced in the work of Tofighi-Shirazi et al. [32] could make of this information to improve the opaque

predicate recovery rate in *SATURN*.

Exploit generation. Rolles et al. described how *SMT* solving can help to automatically chain together sequences of *ROP* gadgets, so that the sequence is semantically equivalent to a model payload [34]. We think that *SATURN* can be used to create such *ROP* gadgets and, in combination with a *DSE* tool like *KLEE* [4] model the needed sequence and payload for an exploit.

Effectiveness of Synthesis in Concolic Deobfuscation. Biondi et al. summarize in [3] that *SMT* solvers alone are not efficient enough against *MBA* based obfuscation. As future work they proposed to study a tool that could drive the concolic execution of obfuscated programs by retrieving a compact representation of obfuscated constraints. They expect that the simplified constraints are easier to solve or check for satisfiability. We believe that *SATURN* is exactly the tool that they are looking for. It would be interesting to study the work done in *SATURN* in combination with the work in [3].

11 CONCLUSION

In this paper we have proposed a *state-of-the-art* framework for software deobfuscation based around the *LLVM* ecosystem. The work implemented in the tool *SATURN* lifts the attack surface away from the binary level up to the *LLVM-IR* and solves the problems that appear during binary deobfuscation directly on this level. The results that we reach are not based on any assumptions, instead we use general optimization techniques and *SMT* solving to extract the control flow graph and deobfuscate the code. The achieved optimized representation can help to apply advanced practical attacks. We believe that the presented work highlights a new perspective on program deobfuscation and complements existing work by lifting the attack surface to a new level.

12 FUTURE WORK

We would like to add a plugin system to let the user hook in several phases of the code recovery in *SATURN* and write their own transformation passes. This could be used to devirtualize a protection like the *Tigress* virtualization or handle *MBA* expressions with customized approaches. Right now we are concretizing the stack pointer to be able to retrieve the stack slots, but we think that we could change this step to be based on a completely symbolic approach. We would also like to try out some new ideas in which we change the type of the registers used in *Remill* into pointers, as this may help to avoid *IntToPtr* casts in *LLVM* and generate cleaner code to begin with. Right now we are only able to lift *x86_64* binary code but *Remill* also supports lifting of *AArch64* and *x86* binary code. We are aware that a constant range analysis was recently added to the constant synthesis in *Souper* [25]. We believe this could be used to tackle the difficulties related with the identification of switch-case destination addresses.

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⁵The comparison is available in the results' repository

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REFERENCES

- [1] Remis Balaniuk. 2015. Drill and Join: A Method for Exact Inductive Program Synthesis. In *Logic-Based Program Synthesis and Transformation*, Maurizio Proietti and Hirohisa Seki (Eds.). Springer International Publishing, Cham, 219–237.
- [2] Fabrice Bellard. 2005. QEMU, a Fast and Portable Dynamic Translator. In *Proceedings of the Annual Conference on USENIX Annual Technical Conference (ATEC '05)*. USENIX Association, Berkeley, CA, USA, 41–41. <http://dl.acm.org/citation.cfm?id=1247360.1247401>
- [3] Fabrizio Biondi, Sébastien Josse, Axel Legay, and Thomas Sirvent. 2017. Effectiveness of Synthesis in Concolic Deobfuscation. *Computers and Security* 70 (Sept. 2017), 500–515. <https://doi.org/10.1016/j.cose.2017.07.006>
- [4] Cristian Cadar, Daniel Dunbar, and Dawson Engler. 2008. KLEE: Unassisted and Automatic Generation of High-coverage Tests for Complex Systems Programs. In *Proceedings of the 8th USENIX Conference on Operating Systems Design and Implementation (OSDI'08)*. USENIX Association, Berkeley, CA, USA, 209–224. <http://dl.acm.org/citation.cfm?id=1855741.1855756>
- [5] Marek Chalupa. 2016 [cit. 2019-07-12]. *Slicing of LLVM Bitcode [online]*. Master's thesis. Masaryk University, Faculty of Informatics, Brno. <https://theses.cz/id/ok0jh1/>
- [6] Vitaly Chipounov, Volodymyr Kuznetsov, and George Candea. 2012. The S2E Platform: Design, Implementation, and Applications. *ACM Trans. Comput. Syst.* 30, 1, Article 2 (Feb. 2012), 49 pages. <https://doi.org/10.1145/2110356.2110358>
- [7] Christian Collberg, Clark Thomborson, and Douglas Low. 1997. *A Taxonomy of Obfuscating Transformations*. Technical Report 148. Department of Computer Sciences, The University of Auckland. <http://www.cs.auckland.ac.nz/~collberg/Research/Publications/CollbergThomborsonLow97a/index.html>
- [8] Ron Cytron, Jeanne Ferrante, Barry K. Rosen, Mark N. Wegman, and F. Kenneth Zadeck. 1991. Efficiently Computing Static Single Assignment Form and the Control Dependence Graph. *ACM Trans. Program. Lang. Syst.* 13, 4 (Oct. 1991), 451–490. <https://doi.org/10.1145/115372.115320>
- [9] Leonardo De Moura and Nikolaj Bjørner. 2008. Z3: An Efficient SMT Solver. In *Proceedings of the Theory and Practice of Software, 14th International Conference on Tools and Algorithms for the Construction and Analysis of Systems (TACAS'08/ETAPS'08)*. Springer-Verlag, Berlin, Heidelberg, 337–340. <http://dl.acm.org/citation.cfm?id=1792734.1792766>
- [10] Chris Eagle. 2008. *The IDA Pro Book: The Unofficial Guide to the World's Most Popular Disassembler*. No Starch Press, San Francisco, CA, USA.
- [11] Pascal Junod, Julien Rinaldini, Johan Wehrli, and Julie Michielin. 2015. Obfuscator-LLVM – Software Protection for the Masses. In *Proceedings of the IEEE/ACM 1st International Workshop on Software Protection, SPRO'15, Firenze, Italy, May 19th, 2015*, Brecht Wyseur (Ed.). IEEE, 3–9. <https://doi.org/10.1109/SPRO.2015.10>
- [12] Johannes Kinder and Dmitry Kravchenko. 2012. Alternating Control Flow Reconstruction. In *Proc. 13th Int. Conf. Verification, Model Checking, and Abstract Interpretation (VMCAI) (LNCS)*, Vol. 7148. Springer, 267–282.
- [13] Johannes Kinder and Helmut Veith. 2008. Jakstab: A Static Analysis Platform for Binaries. In *Proc. 20th Int. Conf. Computer Aided Verification (CAV) (LNCS)*, Vol. 5123. Springer, 423–427.
- [14] Lukas Korencik. 2019. *Decompiling Binaries into LLVM IR Using McSema and Dyninst*. Master's thesis. Masaryk University, Faculty of Informatics, Brno. <https://is.muni.cz/th/pxe1j/>
- [15] J. Kroustek, P. Matula, and P. Zemek. 2017. RetDec: An Open-Source Machine-Code Decompiler. [talk]. Presented at Botconf 2017, Montpellier, FR.
- [16] Chris Lattner and Vikram Adve. 2004. LLVM: A Compilation Framework for Lifelong Program Analysis & Transformation. In *Proceedings of the International Symposium on Code Generation and Optimization: Feedback-directed and Runtime Optimization (CGO '04)*. IEEE Computer Society, Washington, DC, USA, 75–. <http://dl.acm.org/citation.cfm?id=977395.977673>
- [17] LLVM Mailing List. 2019. Optimization Problem. Retrieved July 12, 2019 from <http://llvm.1065342.n5.nabble.com/llvm-dev-Optimization-Problem-t127994.html#a127998>
- [18] Microsoft. 2018. x64 calling convention. Retrieved July 13, 2019 from <https://docs.microsoft.com/en-us/cpp/build/x64-calling-convention?view=vs-2019>
- [19] Jiang Ming, Dongpeng Xu, Li Wang, and Dinghao Wu. 2015. LOOP: Logic-Oriented Opaque Predicate Detection in Obfuscated Binary Code. In *Proceedings of the 22nd ACM SIGSAC Conference on Computer and Communications Security (CCS '15)*. ACM, New York, NY, USA, 757–768. <https://doi.org/10.1145/2810103.2813617>
- [20] Trail of Bits. 2019. McSema - Framework for lifting X86, AMD64, and AARCH64 program binaries to LLVM bitcode. Retrieved August 24, 2019 from <https://github.com/trailofbits/mcsema>
- [21] Trail of Bits. 2019. Remill - Library for lifting of x86, amd64, and aarch64 machine code to LLVM bitcode. Retrieved July 10, 2019 from <https://github.com/trailofbits/remill>
- [22] Mathilde Ollivier, Sébastien Bardin, Richard Bonichon, and Jean-Yves Marion. 2019. How to Kill Symbolic Deobfuscation for Free; or Unleashing the Potential of Path-Oriented Protections. *CoRR* (2019). <http://arxiv.org/abs/1908.01549>
- [23] Quarkslab. 2019. Epona - Epona is a new compiler that integrates innovative software protection for code integrity, obfuscation, and tamper-proofing. Retrieved August 27, 2019 from <https://epona.quarkslab.com/en/>
- [24] Redislabs. 2019. Redis: open source, in-memory data structure store, used as a database, cache and message broker. Retrieved August 22, 2019 from <https://redis.io>
- [25] John Regehr. 2019. Souper github - Use ConstantRange analysis to help Constant Synthesis. Retrieved August 24, 2019 from <https://github.com/google/souper/commit/20b20ef8c8883513a9cc388b5c01743b70033fb5>
- [26] Thomas Reinbacher and Jörg Brauer. 2011. Precise Control Flow Reconstruction Using Boolean Logic. In *Proceedings of the Ninth ACM International Conference on Embedded Software (EMSOFT '11)*. ACM, New York, NY, USA, 117–126. <https://doi.org/10.1145/2038642.2038662>
- [27] Raimondas Sasnauskas, Yang Chen, Peter Collingbourne, Jeroen Ketema, Jubi Taneja, and John Regehr. 2017. Souper: A Synthesizing Superoptimizer. *CoRR* (2017). <http://arxiv.org/abs/1711.04422>
- [28] Sebastian Schrittwieser, Stefan Katzenbeisser, Johannes Kinder, Georg Merzdownik, and Edgar Weippl. 2016. Protecting Software Through Obfuscation: Can It Keep Pace with Progress in Code Analysis? *ACM Comput. Surv.* 49, 1, Article 4 (April 2016), 37 pages. <https://doi.org/10.1145/2886012>
- [29] Jiri Slaby. 2016. LLVM Slicer - Static slicer based on the Mark Weiser's algorithm. Retrieved July 12, 2019 from <https://github.com/sdasgup3/llvm-slicer>
- [30] Clark Taylor and Christian Colberg. 2016. A Tool for Teaching Reverse Engineering. In *2016 USENIX Workshop on Advances in Security Education (ASE 16)*. USENIX Association, Austin, TX. <https://www.usenix.org/conference/ase16/workshop-program/presentation/taylor>
- [31] Philippe Tillet, H. T. Kung, and David Cox. 2019. Triton: An Intermediate Language and Compiler for Tiled Neural Network Computations. In *Proceedings of the 3rd ACM SIGPLAN International Workshop on Machine Learning and Programming Languages (MAPL 2019)*. ACM, New York, NY, USA, 10–19. <https://doi.org/10.1145/3315508.3329973>
- [32] Rantine Tofighi-Shirazi, Irina Măriuca Asăvoae, Philippe Elbaz-Vincent, and Thanh-Hà Lê. 2019. Defeating Opaque Predicates Statically through Machine Learning and Binary Analysis. In *3rd International Workshop on Software Protection*. London, United Kingdom. <https://hal.archives-ouvertes.fr/hal-02269192>
- [33] Linda Torczon and Keith Cooper. 2011. *Engineering A Compiler* (2nd ed.). Morgan Kaufmann Publishers Inc., San Francisco, CA, USA.
- [34] Julien Vanegue, Sean Heelan, and Rolf Rolles. 2012. SMT Solvers for Software Security. In *Proceedings of the 6th USENIX Conference on Offensive Technologies (WOOT'12)*. USENIX Association, Berkeley, CA, USA, 9–9. <http://dl.acm.org/citation.cfm?id=2372399.2372412>
- [35] Shuai Wang, Pei Wang, and Dinghao Wu. 2015. Reassembleable Disassembling. In *Proceedings of the 24th USENIX Conference on Security Symposium (SEC'15)*. USENIX Association, Berkeley, CA, USA, 627–642. <http://dl.acm.org/citation.cfm?id=2831143.2831183>
- [36] S. Bharadwaj Yadavalli and Aaron Smith. 2019. Raising Binaries to LLVM IR with MCTOLL (WIP Paper). In *Proceedings of the 20th ACM SIGPLAN/SIGBED International Conference on Languages, Compilers, and Tools for Embedded Systems (LCTES 2019)*. ACM, New York, NY, USA, 213–218. <https://doi.org/10.1145/3316482.3326354>
- [37] B. Yadegari, B. Johannesmeyer, B. Whitely, and S. Debray. 2015. A Generic Approach to Automatic Deobfuscation of Executable Code. In *2015 IEEE Symposium on Security and Privacy*. 674–691. <https://doi.org/10.1109/SP.2015.47>
- [38] Yingzhou Zhang. 2019. SymPas: Symbolic Program Slicing. *CoRR* (2019). <http://arxiv.org/abs/1903.05333>