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 Souper 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 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 naive 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 is 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 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=specific) 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.

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\(^1\)As close as possible to a non-obfuscated compiled source code

```
struct State {
    VectorReg vec[kNumVecRegisters];
    ArithFlags aflag;
    Flags rflag;
    Segments seg;
    AddressSpace addr;
    GPR gpr;
    X87Stack st;
    MMX mmx;
    FPUsStatusFlags sw;
    X89 rcr0;
    FPU x87;
    SegmentCaches seg_caches;
}
```

Listing 1: Remill State struct definition for x86_64
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 bitcode. 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 opaque-ness 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 methodology follow closely the survey by Schrittweiser 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.

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 proof 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.

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

The basic block opaqueness might change to non-opaque 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 opaqueness of the basic block will change according to Table 2.

| Current Opaqueness | New Edge | New Opaqueness |
|--------------------|----------|----------------|
| 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

| Table 1: Path Exploration |
|---------------------------|
| **kCategory** | **Exploration** | **Opaqueness 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 opaqueness 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.

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
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.

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 implementations are outdated or unreliable to produce a valid slice for a given function. Conversely, our algorithm is based on modeling the slicing process in C and then relying on the LLVM optimizations to produce the slice.

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 models 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.

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 implementation is 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

Listing 6: Obfuscated x86_64 opaque predicate

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 implementation is 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
The previous approach might fail because LLVM's optimizations are not successful in reducing the sliced instruction pointer to a constant. This means the conditional branch is either based on a Z3 solver has been found.

SATURN has two options to control the amount of basic blocks to be used while slicing the value of the instruction pointer. This is needed as some obfuscators reuse values from previous basic blocks in subsequent opaque predicates. The SATURN options `solverBBCountJcc` and `solverBBCountReturn` let the user specify the amount of basic blocks with a single predecessor to connect to the current opaque block before optimizing it.

In the next section we approach the problem of hard to optimize opaque predicates, most commonly based on Mixed-Boolean-Arithmetic (MBA) expressions, as seen in our motivating example in Listing 2.

5.4 Solving Opaque Predicates with Souper and Z3

The previous approach might fail because LLVM's optimizations are not successful in reducing the sliced instruction pointer to a constant. This means the conditional branch is either based on a stronger opaque predicate or might be a real conditional branch. To further analyze the branch we use the Souper Optimizer [27] and a SMT solver. The steps taken to prove the opaqueness with the Z3 theorem prover integrated within Souper are the following:

1. extract the sliced instruction pointer value from the opaque basic block (Value %17 in Listing 9)
2. collect a set of candidate expressions to be solved by Souper
3. select the Souper expression corresponding to the sliced instruction pointer value from the set
4. build an SMT query that aims at finding one valid solution for the sliced instruction pointer expression
5. if the query is not satisfiable, something went wrong in the proving process and the pass fails
6. if the query is satisfiable, a valid solution for the expression has been discovered and a second SMT query is built to determine if the unique solution has been found, as shown in Listing 10
7. if the last query is satisfiable, the conditional branch has been proven to be opaque and the real destination has been determined
8. if the last query is not satisfiable, a real conditional branch or an opaque predicate which is not provable by the SMT solver has been found.

In the next section we approach the problem of hard to optimize opaque predicates, most commonly based on Mixed-Boolean-Arithmetic (MBA) expressions, as seen in our motivating example in Listing 2.
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. allocs 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:

```c
define dllexport i64 @1_44000180(%struct.State.32 x %S, i64 %curr_pc, i64 %curr_mem, %struct.Rip %Rip) {
entry:
  %b = getelementptr inbounds %struct.State.32, %struct.State.32* %S, i64 0, i32 6, i32 31, i32 0, i32 0
  %l = getelementptr inbounds %struct.State.32, %struct.State.32* %S, i64 0, i32 13
  store i8 0, i8* %l, align 1
  %c = getelementptr inbounds %struct.State.32, %struct.State.32* %S, i64 0, i32 0, i32 6, i32 32, i32 5
  %g = getelementptr inbounds %struct.State.32, %struct.State.32* %S, i64 0, i32 17, i32 0
  %w = load i8, i8* %c, align 1
  %s = load i16, i16* %w, align 1
  %d = load i64, i64* %s, align 8
  %e = sext i8 %d to i64
  %f = load i8, i8* %c, align 1
  %g = load i16, i16* %w, align 8
  %h = sext i8 %g to i64
  %i = load i8, i8* %c, align 1
  %j = load i8, i8* %w, align 8
  %k = load i16, i16* %s, align 8
  %l = sext i8 %k to i64
  %m = load i8, i8* %c, align 1
  %n = load i16, i16* %w, align 8
  %o = load i8, i8* %c, align 1
  %p = load i8, i8* %w, align 8
  %q = load i16, i16* %s, align 8
  %r = load i8, i8* %c, align 1
  %s = load i8, i8* %c, align 1
  %t = load i16, i16* %w, align 8
  %u = load i8, i8* %c, align 1
  %v = load i8, i8* %w, align 8
  %w = load i16, i16* %s, align 8
  %x = load i8, i8* %c, align 1
  %y = load i8, i8* %w, align 8
  %z = load i16, i16* %s, align 8

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
6.2.2 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.

```c
extern "C" Memory * F_Lifted(State &state, addr_t curr_pc, Memory * mem);
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.

```c
define dlexport i64 @F_140001000_args(
    i64 * %RCX, i64 * %RDX
) {
    entry:
    %0 = ptrtoint i64 * %RCX to i64
    %1 = trunc i64 %0 to i8
    %2 = icmp eq i8 %1, 162
    %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 of the recovery on 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
We select some small programs that trigger corner cases in several
world obfuscators where no source code is available. The machine
taken from the repository provided by [22] and use the
gress virtualization obfuscation pass (the command line, perform some calculations and print the output
predicates and dead code. The programs take an input value from
ments, loops, infinite loops, opaque predicates, MBA based opaque
scenarios like overlapping stack slots, register and stack based argu-
several test samples that can trigger corner cases. The tests include
and results are available in our online repository
2.

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 pro-
grams 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 argu-
ments, 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 ti-
gress 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

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.

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steps of the approach described in this paper. We also choose pro-
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command line, perform some calculations and print the output to
the user. The sample tigress_virtualize is protected with the ti-
gress 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 point 4. 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 4, 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 predi-
cates but based on the obfuscator we know that a missed opaque
predicate would lead to a broken LLVM–JR. 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 obfus-
cated program. Programs protected with the Tigress virtualization

### Table 3: Results for datasets

| 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          | 0/07                      | Yes         | 0/6a                             | 0a                     | 110                     | 13/13                  | Yes            | 0.309s                        | -                            |
| cmp_test | 0.408s      | 0.342s          | 1/1                       | Yes         | 2/2                              | 7                      | 39                     | 8/8                    | Yes            | -                             | -                            |
| edges    | 0.129s      | 0.233s          | 2/2                       | Yes         | 1/1                              | 5                      | 16                     | 4/4                    | Yes            | -                             | -                            |
| edges2   | 0.428s      | 0.622s          | 0/0                       | Yes         | 2/3a                            | 11                     | 120                    | 10/10                  | Yes            | -                             | -                            |
| 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            | -                             | -                            |
| multiples| 0.405s      | 0.251s          | 0/0                       | Yes         | 1/1                              | 1                      | 41                     | 9/9                    | Yes            | -                             | -                            |
| op1      | 0.188s      | 0.010s          | 1/1                       | Yes         | 2/2                              | 5                      | 24                     | 3/3                    | Partially6      | 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                    | Yesf           | -                             | 0                            |

*Remill State struct was used 5Binary execution failed because of other protections like anti-tampering
Unknown amount of original basic blocks 4Dead argument was detected 6MBA formula was not optimized away 7Recovered integer arithmetic

3https://github.com/pgarba/Saturn_Results

4Obfuscator0 and Obfuscator1 are made up names
5Context 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 `opt` is only partially deobfuscated. The MBA based opaque predicate is removed but the recovered calculation is still based on the MBA formula \(^a\). 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 times\(^5\). 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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\(^a\)The comparison is available in the results’ repository

\(^b\)This is a data point observed in the results' repository.
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