Towards Automatic Discovery of Deviations in Binary Implementations with Applications to Error Detection and Fingerprint Generation

David Brumley, Juan Caballero, Zhenkai Liang, James Newsome, and Dawn Song
Carnegie Mellon University
{dbrumley,jcaballero,zliang,jnewsome,dawnsong}@cmu.edu

Abstract

Different implementations of the same protocol specification usually contain *deviations*, i.e., differences in how they check and process some of their inputs. Deviations are commonly introduced as implementation errors or as different interpretations of the same specification. Automatic discovery of these deviations is important for several applications. In this paper, we focus on automatic discovery of deviations for two particular applications: error detection and fingerprint generation.

We propose a novel approach for automatically detecting deviations in the way different implementations of the same specification check and process their input. Our approach has several advantages: (1) by automatically building symbolic formulas from the implementation, our approach is precisely faithful to the implementation; (2) by solving formulas created from two different implementations of the same specification, our approach significantly reduces the number of inputs needed to find deviations; (3) our approach works on binaries directly, without access to the source code.

We have built a prototype implementation of our approach and have evaluated it using multiple implementations of two different protocols: HTTP and NTP. Our results show that our approach successfully finds deviations between different implementations, including errors in input checking, and differences in the interpretation of the specification, which can be used as fingerprints.

1 Introduction

Many different implementations usually exist for the same protocol. Due to the abundance of coding errors and protocol specification ambiguities, these implementations usually contain *deviations*, i.e., differences in how they check and process some of their inputs. As a result, same inputs can cause different implementations to reach semantically different protocol states. For example, an implementation may not perform sufficient input checking to verify if an input is well-formed as specified in the protocol specification. Thus, for some inputs, it might exhibit a deviation from another implementation, which follows the protocol specification and performs the correct input checking.

Finding these deviations in implementations is important for several applications. In particular, in this paper we show 1) how we can automatically discover these deviations, and 2) how we can apply the discovered deviations to two particular applications: *error detection* and *fingerprint generation*.

First, finding a deviation between two different implementations of the same specification may indicate that at least one of the two implementations has an error, which we call *error detection*. Finding such errors is important to guarantee that the protocol is correctly implemented, to ensure proper interoperability with other implementations, and to enhance system security since errors often represent vulnerabilities that can be exploited. Enabling error detection by automatically finding deviations between two different implementations is particularly attractive because it does not require a manually written model of the protocol specification. These models are usually complex, tedious, and error-prone to generate. Note that such deviations do not necessarily flag an error in one of the two implementations, since deviations can also be caused by ambiguity in the specification or when some parts are not fully specified. However, automatic discovery of such deviations is a good way to provide candidate implementation errors.

Second, such deviations naturally give rise to *fingerprints*, which are inputs that, when given to two different implementations, will result in semantically different output states. Fingerprints can be used to distinguish between the different implementations and we call the discovery of such inputs *fingerprint generation*. Fingerprinting has been in use for more than a decade [25] and is an important tool in network security for remotely identifying which implementation of an application or operating system a remote host is running. Fingerprinting tools [7, 10, 14] need fingerprints to operate and constantly require new fingerprints as new implementations, or new versions of existing implementations, become available. Thus, the process of automatically finding these fingerprints, i.e., the fingerprint generation, is crucial for these tools.

Automatic deviation discovery is a challenging task—deviations usually happen in corner cases, and discovering deviations is often like finding needles in a haystack. Previous work in related areas is largely insufficient. For example, the most commonly used technique is random or semi-random generation of inputs [20, 43] (also called fuzz testing). In this line of approach, random inputs are generated and sent to different implementations to observe if they trigger a difference in outputs. The obvious drawback of this approach is that it may take many such random inputs before finding a deviation.

In this paper, we propose a novel approach to automatically discover deviations in input checking and processing between different implementations of the same protocol specification. We are given two programs P_1 and P_2 implementing the same protocol. At a high level, we build two formulas, f_1 and f_2, which capture how each program processes a single input. Then, we check whether the formula $(f_1 \wedge \neg f_2) \vee (\neg f_1 \wedge f_2)$ is satisfiable, using a solver such as a decision procedure. If the formula is satisfiable, it means that we can find an input, which will satisfy f_1 but not f_2 or vice versa, in which case it may lead the two program executions to semantically different output states. Such inputs are good candidates to trigger a deviation. We then send such candidate inputs to the two programs and monitor their output states. If the two programs end up in two semantically different output states, then we have successfully found a deviation between the two implementations, and the corresponding input that triggers the deviation.

We have built a prototype implementation of our approach. It handles both Windows and Linux binaries running on an x86 platform. We have evaluated our approach using multiple implementations of two different protocols: HTTP and NTP. Our approach has successfully identified deviations between servers and automatically generated inputs that triggered different server behaviors. These deviations include errors and differences in the interpretation of the protocol specification. The evaluation shows that our approach is accurate: in one case, the relevant part of the generated input is only three bits. Our approach is also efficient: we found deviations using a single request in about one minute.

Contributions. In summary, in this paper, we make the following contributions:

- **Automatic discovery of deviations:** We propose a novel approach to automatically discover deviations in the way different implementations of the same protocol specification check and process their input. Our approach has several advantages: (1) by automatically building symbolic formulas from an implementation, our approach is precisely faithful to the implementation; (2) by solving formulas created from two different implementations of the same specification, our approach significantly reduces the number of inputs needed to find deviations; (3) our approach works on binaries directly, without access to the source code. This is important for wide applicability, since implementations may be proprietary and thus not have the source code available. In addition, the binary is what gets executed, and thus it represents the true behavior of the program.

- **Error detection using deviation discovery:** We show how to apply our approach for automatically discovering deviations to the problem of error detection—the discovered deviations provide candidate implementation errors. One fundamental advantage of our approach is that it does not require a user to manually generate a model of the protocol specification, which is often complex, tedious, and error-prone to generate.

- **Fingerprint generation using deviation discovery:** We show how to apply our approach for automatically discovering deviations to the problem of fingerprint generation—the discovered deviations naturally give rise to fingerprints. Compared to previous approaches, our solution significantly reduces the number of candidate inputs that need to be tested to discover a fingerprint [20].

- **Implementing the approach:** We have built a prototype that implements our approach. Our evaluation shows that our approach is accurate and efficient. It can identify deviations with few example inputs at bit-level accuracy.

The remainder of the paper is organized as follows. Section 2 introduces the problem and presents an overview of our approach. In Section 3 we present the different phases and elements that comprise our approach and in Section 4 we describe the details of our implementation. Then, in Section 5 we present the evaluation results of our approach over different protocols. We discuss future enhancements to our approach in Section 6. Finally, we present the related work in Section 7 and conclude in Section 8.

2 Problem Statement and Approach Overview

In this section, we first describe the problem statement, then we present the intuition behind our approach, and finally we give an overview of our approach.

Problem statement. In this paper we focus on the problem of automatically detecting deviations in protocol implementations. In particular, we aim to find inputs that cause two different implementations of the same protocol specification to reach semantically different output states. When we find such an input, we say we have found a candidate deviation.

The output states need to be externally observable. We use two methods to observe such states: (a) monitoring the network output of the program, and (b) supervising its environment, which allows us to detect unexpected states such as program halt, reboot, crash, or resource starvation. However, we cannot simply compare the complete output from both implementations, since the output may be different but semantically equivalent. For example, many protocols contain sequence numbers, and we would expect the output from two different implementations to contain two different sequence numbers. However, the output messages may still be semantically equivalent.

Therefore, we may use some domain knowledge about the specific protocol being analyzed to determine when two output states are semantically different. For example, many protocols such as HTTP, include a status code in the response to provide feedback about the status of the request. We use this information to determine if two output states are semantically equivalent or not. In other cases, we observe the effect of a particular query in the program, such as program crash or reboot. Clearly these cases are semantically different from a response being emitted by the program.

Intuition of our approach. We are given two implementations P_1 and P_2 of the same protocol specification. Each implementation at a high level can be viewed as a mapping function from the protocol input space I to the protocol output state space S. Let $P_1, P_2 : I \rightarrow S$ represent the mapping function of the two implementations. Each implementation accepts inputs $x \in I$ (e.g., an HTTP request), and then processes the input resulting in a particular protocol output state $s \in S$ (e.g., an HTTP reply). At a high level, we wish to find inputs such that the same input, when sent to the two implementations, will cause each implementation to result in a different protocol output state.

Our goal is to find an input $x \in I$ such that $P_1(x) \neq P_2(x)$. Finding such an input through random testing is usually hard.

However, in general it is easy to find an input $x \in I$ such that $P_1(x) = P_2(x) = s \in S$, i.e., most inputs will result in the same protocol output state s for different implementations of the same specification. Let $f(x)$ be the formula representing the set of inputs x such that $f(x) = true \iff P(x) = s$. When P_1 and P_2 implement the same protocol differently, there may be some input where f_1 will not be the same as f_2:

$$\exists x.(f_1(x) \wedge \neg f_2(x)) \vee (\neg f_1(x) \wedge f_2(x)) = \textit{true}.$$

The intuition behind the above expression is that when $f_1(x) \wedge \neg f_2(x) = \textit{true}$, then $P_1(x) = s$ (because $f_1(x) = \textit{true}$) while $P_2(x) \neq s$ (because $f_2(x) = \textit{false}$), thus the two implementations reach different output states for the same input x. Similarly, $\neg f_1(x) \wedge f_2(x)$ indicates when $P_1(x) \neq s$, but $P_2(x) = s$. We take the disjunction since we only care whether the implementations differ from each other.

Given the above intuition, the central idea is to create the formula f using the technique of weakest precondition [19, 26]. Let Q be a predicate over the state space of a program. The weakest precondition $wp(P, Q)$ for a program P and post-condition Q is a boolean formula f over the input space of the program. In our setting, if $f(x) = \textit{true}$, then $P(x)$ will terminate in a state satisfying Q, and if $f(x) = \textit{false}$, then $P(x)$ will not terminate in a state satisfying Q (it either "goes wrong" or does not terminate). For example, if the post-condition Q is that P outputs a successful HTTP reply, then $f = wp(P, Q)$ characterizes all inputs which lead P to output a successful HTTP reply. The boolean formula output by the weakest precondition is our formula f.

Furthermore, we observe that the above method can still be used even if we do not consider the entire program and only consider a *single* execution path (we discuss multiple execution paths in Section 6). In that case, the formula f represents the subset of protocol inputs that follow one of the execution paths considered and still reach the protocol output state s. Thus, $f(x) = true \Rightarrow P(x) = s$, since if an input satisfies f then for sure it will make program P go to state s, but the converse is not necessarily true—an input which makes P go to state s may not satisfy f. In our problem, this means that the difference between f_1 and f_2 may not necessarily result in a true deviation, as shown in Figure 2. Instead, the difference between f_1 and f_2 is a good candidate, which we can then test to validate whether it is a true deviation.

Overview of our approach. Our approach is an iterative process, and each iteration consists of three phases, as shown in Figure 1. First, in the *formula extraction* phase, we are given two binaries P_1 and P_2 implementing the same protocol specification, such as HTTP, and

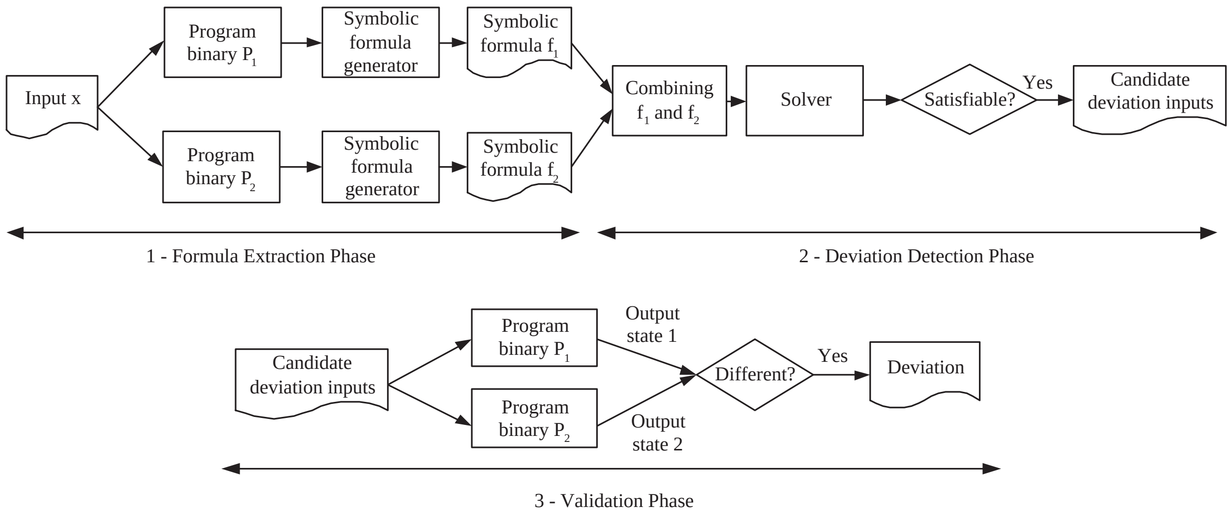


Figure 1: Overview of our approach.

an input x, such as an HTTP GET request. For each implementation, we log an execution trace of the binary as it processes the input, and record what output state it reaches, such as halting or sending a reply. We assume that the execution from both binaries reaches semantically equivalent output states; otherwise we have already found a deviation! For each implementation P_1 and P_2, we then use this information to produce a boolean formula over the input, f_1 and f_2 respectively, each of which is satisfied for inputs that cause the binary to reach the same output state as the original input did.

Next, in the *deviation detection* phase, we use a solver (such as a decision procedure) to find differences in the two formulas f_1 and f_2. In particular, we ask the solver if $(f_1 \land \neg f_2) \lor (f_2 \land \neg f_1)$ is satisfiable. When satisfiable the solver will return an example satisfying input. We call these inputs the *candidate deviation inputs*.

Finally, in the *validation* phase we evaluate the candidate deviation inputs obtained in the formula extraction phase on both implementations and check whether the implementations do in fact reach semantically different output states. This phase is necessary because the symbolic formula might not include all possible execution paths, then an input that satisfies f_1 is guaranteed to make P_1 reach the same semantically equivalent output state as the original input x but an input that does not satisfy f_1 may also make P_1 reach a semantically equivalent output state. Hence, the generated candidate deviation inputs may actually still cause both implementations to reach semantically equivalent output states.

If the implementations *do* reach semantically different output states, then we have found a deviation triggered by that input. This deviation is useful for two things: (1) it may represent an implementation error in at least one of the implementations, which can then be checked against the protocol specification to verify whether it is truly an error; (2) it can be used as a *fingerprint* to distinguish between the two implementations.

Iteration. We can iterate this entire process to examine *other* input types. Continuing with the HTTP example, we can compare how the two implementations process other types of HTTP requests, such as HEAD and POST, by repeating the process on those types of requests.

3 Design

In this section, we describe the details of the three phases in our approach, the formula extraction phase, the deviation detection phase, and the validation phase.

3.1 Formula Extraction Phase

3.1.1 Intuition and Overview

The goal of the formula extraction phase is that given an input x such that $P_1(x) = P_2(x) = s$, where s is the output state when executing input x with the two given programs, we would like to compute two formulas, f_1 and f_2, such that,

$$f_1(x) = true \Rightarrow P_1(x) = s$$

and

$$f_2(x) = true \Rightarrow P_2(x) = s,$$

This matches well with the technique of *weakest precondition* (WP) [19, 26]. The weakest precondition, denoted

$wp(P,Q)$, is a boolean formula f over the input space I of P such that if $f(x) = \textit{true}$, then $P(x)$ will terminate in a state satisfying Q. In our setting, the post-condition is the protocol output state, and the weakest precondition is a formula characterizing protocol inputs, which will cause the implementation to reach the specified protocol output state.

Unfortunately, calculating the weakest precondition over an entire real-world binary program can easily result in a formula that is too big to solve. First, there may be many program paths which can lead to a particular output state. We show that we can generate interesting deviations even when considering a single program path. Second, we observe that in many cases only a small subset of instructions operate on data derived from the original input. There is no need to model the instructions that do not operate on data derived from the original input, since the result they compute will be the same as in the original execution. Therefore we eliminate these instructions from the WP calculation, and replace them with only a series of assignments of concrete values to the relevant program state just before an instruction operates on data derived from the input.

Hence, in our design, we build the symbolic formula in two distinct steps. We first execute the program on the original input, while recording a trace of the execution. We then use this execution trace to build the symbolic formula.

3.1.2 Calculating the Symbolic Formula

In order to generate the symbolic formula, we perform the following steps:

1. Record the execution trace of the executed program path.
2. Process the execution trace. This step translates the execution trace into a program B written in our simplified intermediate representation (IR).
3. Generate the appropriate post-condition Q.
4. Calculate the weakest precondition on B by:
   (a) Translating B into a single assignment form.
   (b) Translating the (single assignment) IR program into the guarded command language (GCL). The GCL program, denoted B_g, is semantically equivalent to the input IR statements, but appropriate for the weakest precondition calculation.
   (c) Computing the weakest precondition $f = wp(B_g, Q)$ in a syntax-directed fashion on the GCL.

The output of this phase is the symbolic formula f. Below we describe these steps in more detail.

Step 1: Recording the execution trace. We generate formulas based upon the program path for a single execution. We have implemented a path recorder which records the execution trace of the program. The execution trace is the sequence of machine instructions executed, and for each executed instruction, the value of each operand, whether each operand is derived from the input, and if it is derived from the input, an identifier for the original input stream it comes from. The trace also has information about the first use of each input byte, identified by its offset in the input stream. For example, for data derived from network inputs, the identifier specifies which session the input came from, and the offset specifies the original position in the session data.

Step 2: Processing the execution trace. We process the execution trace to include only relevant instructions. An instruction is relevant if it operates on data derived from the input I. For each relevant instruction, we:

- Translate the x86 instruction to an easier-to-analyze intermediate representation (IR). The generated IR is semantically equivalent to the original instruction.

  The advantage of our IR is that it allows us to perform subsequent steps over the simpler IR statements, instead of the hundreds of x86 instructions. The translation from an x86 instruction to our IR is designed to correctly model the semantics of the original x86 instruction, including making otherwise implicit side effects explicit. For example, we insert code to correctly model instructions that set the `eflags` register, single instruction loops (e.g., `rep` instructions), and instructions that behave differently depending on the operands (e.g., shifts).

  Our IR is shown in Table 1. We translate x86 instruction into this IR. Our IR has assignments ($r := v$), binary and unary operations ($r := r_1 \Box_b v$ and $r := \Box_u v$ where $\Box_b$ and $\Box_u$ are binary and unary operators), loading a value from memory into a register ($r_1 := *(r_2)$), storing a value ($*(r_1) := r_2$), direct jumps (jmp ℓ) to a known target label (label ℓ_i), indirect jumps to a computed value stored in a register (ijmp r), and conditional jumps (if r then jmp ℓ_1 else jmp ℓ_2).

- Translate the information logged about the operands into a sequence of initialization statements. For each operand:
  - If it is not derived from input, the operand is assigned the concrete value logged in the execution trace. These assignments effectively model the sequences of instructions that we do not explicitly include.

Instructions	i	::=	$*(r_1) := r_2 \mid r_1 := *(r_2) \mid r := v \mid r := r_1 \square_b v$
			$\mid r := \square_u v$ $\mid$ `label` l_i $\mid$ `jmp` ℓ $\mid$ `ijmp` r
			$\mid$ `if` r `jmp` ℓ_1 `else jmp` ℓ_2
Operations	$\square_b$	::=	$+, -, *, /, \ll, \gg, \&, \mid, \oplus, ==, !=, <, \leq$ (Binary operations)
	$\square_u$	::=	$\neg, !$ (unary operations)
Operands	v	::=	n (an integer literal) $\mid$ r (a register) $\mid$ ℓ (a label)
Reg. Types	τ	::=	reg64_t $\mid$ reg32_t $\mid$ reg16_t $\mid$ reg8_t $\mid$ reg1_t (number of bits)

Table 1: Our RISC-like assembly IR. We convert x86 assembly instructions into this IR.

– For operands derived from input, the *first* time we encounter a byte derived from a particular input identifier and offset, we initialize the corresponding byte of the operand with a *symbolic* value that uniquely identifies that input identifier and offset. On subsequent instructions that operate on data derived from that particular input identifier and offset, we do *not* initialize the corresponding operand, since we want to accurately model the sequence of computations on the input.

The output of this step is an IR program B consisting of a sequence of IR statements.

Step 3: Setting the post-condition. Once we have generated the IR program from the execution trace, the next step is to select a post-condition, and compute the weakest precondition of this post-condition over the program, yielding our symbolic formula.

The post-condition specifies the desired protocol output state, such as what kind of response to a request message is desired. In our current setting, an ideal post-condition would specify that "The input results in an execution that results in an output state that is semantically equivalent to the output state reached when processing the original input." That is, we want our formula to be true for exactly the inputs that are considered "semantically equivalent" to the original input by the modeled program binary.

In our approach, the post-condition specified the output state should be the same as in the trace. In order to make the overall formula size reasonable, we add additional constraints to the post-condition which constraint the formula to the same program path taken as in the trace. We do this by iterating over all conditional jumps and indirect jumps in the IR, and for each jump, add a clause to the post-condition that ensures that the final formula only considers inputs that also result in the same destination for the given jump. For example, if in the trace `if` e `then` ℓ_1 `else` ℓ_2 was evaluated and the next instruction executed was ℓ_2, then e must have evaluated to *false*, and we add a clause restricting $e =$ *false* to the post-condition.

In some programs, there may be multiple paths that reach the same output state. Our techniques can be generalized to handle this case, as discussed in Section 6. In practice, we have found this post-condition to be sufficient for finding interesting deviations. Typically, inputs that cause the same execution path to be followed are treated equivalently by the program, and result in equivalent output states. Conversely, inputs that follow a different execution path often result in a semantically different output state of the program. Although more complicated and general post-conditions are possible, one interesting result from our experiments is that the simple approach was all that was needed to generate interesting deviations.

Step 4: Calculating the weakest precondition. The weakest precondition (WP) calculation step takes as input the IR program B from Step 2, and the desired post-condition Q from Step 3. The weakest precondition, denoted $wp(B, Q)$, is a boolean formula f over the input space such that if $f(x) =$ *true*, then $B(x)$ will terminate in a state satisfying Q. For example, if the program is $B : y = x + 1$ and $Q : 2 < y < 5$, then $wp(B, Q)$ is $1 < x < 4$.

We describe the steps for computing the weakest precondition below.

Step 4a: Translating into single assignment form. We translate the IR program B from the previous step into a form in which every variable is assigned at most once. (The transformed program is semantically equivalent to the input IR.) We perform this step to enable additional optimizations described in [19, 29, 36], which further reduce the formula size. For example, this transformation will rewrite the program `x := x+1; x := x+1;` as `x1 := x0+1; x2 := x1+1;`. We carry out this transformation by maintaining a mapping from the variable name to its current incarnation, e.g., the original variable `x` may have incarnations `x0`, `x1`, and `x2`. We iterate through the program and replace each variable use with its current incarnation. This step is similar to computing the SSA form of a program [39], and is a widely used technique.

Step 4b: Translating to GCL. The translation to GCL takes as input the single assignment form from step 4a, and outputs a semantically equivalent GCL program B_g. We perform this step since the weakest precondition is calculated over the GCL language [26]. The resulting program B_g is semantically equivalent to the input single-assignment IR statements. The weakest precondition is calculated in a syntax-directed manner over B_g.

The GCL language constructs we use are shown in Table 2. Although GCL may look unimpressive, it is sufficiently expressive for reasoning about complex programs [24, 26, 28, 29] [1]. Statements S in our GCL programs will mirror statements in assembly, e.g., store, load, assign, etc. GCL has assignments of the form $lhs := e$ where lhs is a register or memory location, and e is a (side-effect) free expression. **assume** e assumes a particular (side-effect free) expression is true. An **assume** statement is used to reason about conditional jump predicates, i.e., we add "**assume** e" for the true branch of a conditional jump, and "**assume** $\neg e$" for the false branch of the conditional jump. **assert** e asserts that e must be true for execution to continue, else the program fails. In other words, Q cannot be satisfied if **assert** e is false. **skip** is a semantic no-op. $S_1; S_2$ denotes a sequence where first statement S_1 is executed and then statement S_2 is executed. $S_1 \Box S_2$ is called a choice statement, and indicates that either S_1 or S_2 may be executed. Choice statements are used for if-then-else constructs.

For example, the IR:

```
if  (x₀ < 0){
      x₁ := x₀ − 1;
} else {
      x₁ := x₀ + 1;
}
```

will be translated as:

$$(\textbf{assume}\ x_0 < 0; x_1 = x_0 - 1;)\Box$$
$$(\textbf{assume}\ \neg(x_0 < 0); x_1 := x_0 + 1;)$$

The above allows calculating the WP over multiple paths (we discuss multiple paths in Section 6). In our setting, we only consider a single path. For each branch condition e evaluated in the trace, we could add the GCL statement **assert** e if e evaluated to *true* (else **assert** $\neg e$ if e evaluated to *false*). In our implementation, using **assert** in this manner is equivalent to adding a clause for each branch predicate to the post-condition (e.g., making the post-condition $e \wedge Q$ when e evaluated to *true* in the trace).

Step 4c: Computing the weakest precondition. We compute the weakest precondition for B_g from the previous step in a syntax-directed manner. The rules for computing the weakest precondition are shown in Table 2. Most rules are straightforward, e.g., to calculate the weakest precondition $wp(A; B, Q)$, we calculate $wp(A, wp(B, Q))$. Similarly $wp(\textbf{assume}\ e, Q) \equiv e \Rightarrow Q$. For assignments $lhs := e$, we generate a let expression which binds the variable name lhs to the expression e. We also take advantage of a technical transformation, which can further reduce the size of the formula by using the single assignment form from Step 4a [19, 29, 36].

[1]The GCL defines a few additional commands such as a **do-while** loop, which we do not need.

3.1.3 Memory Reads and Writes to Symbolic Addresses

If the instruction accesses memory using an address that is derived from the input, then in the formula the address will be symbolic, and we must choose what set of possible addresses to consider. In order to remain sound, we add a clause to our post-condition to only consider executions that would calculate an address within the selected set. Considering more possible addresses increases the generality of our approach, at the cost of more analysis.

Memory reads. When reading from a memory location selected by an address derived from the input, we must process the memory locations in the set of addresses being considered as operands, generating any appropriate initialization statements, as above.

We achieve good results considering only the address that was actually used in the logged execution trace and adding the corresponding constraints to the post-condition to preserve soundness. In practice, if useful deviations are not found from the corresponding formula, we could consider a larger range of addresses, achieving a more descriptive formula at the cost of performance. We have implemented an analysis that bounds the range of symbolic memory addresses [16], but have found we get good results without preforming this additional step.

Memory writes. We need not transform writes to memory locations selected by an address derived from the input. Instead we record the selected set of addresses to consider, and add the corresponding clause to the post-condition to preserve soundness. These conditions force the solver to reason about any potential alias relationships. As part of the weakest precondition calculation, subsequent memory reads that could use one of the addresses being considered are transformed to a conditional statement handling these potential aliasing relationships.

As with memory reads, we achieve good results only considering the address that was actually used in the logged execution trace. Again, we could generalize the formula to consider more values, by selecting a range of addresses to consider.

A,B $\in$ GCL stmt	::= $lhs := e$
	| A;B
	| **assume** e (e is an expression)
	| **assert** e (e is an expression)
	| A $\Box$ B
	| **skip**

GCL stmt	wp(stmt, Q)
assume e	$e \Rightarrow Q$
assert e	$e \wedge Q$
lhs := e	let $lhs = e$
A; B	wp(A, wp(B,Q))
A $\Box$ B	wp(A, Q) $\wedge$ wp(B,Q)

Table 2: The guarded command language (left), along with the corresponding weakest precondition predicate transformer (right).

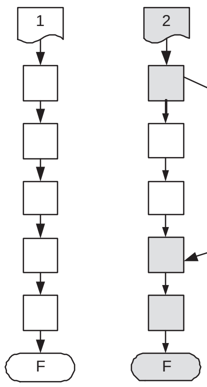


Figure 2: Different execution paths could end up in the same output states. The validation phase checks whether the new execution path explored by the candidate deviation input obtained in the deviation detection phase truly ends up in a different state.

3.2 Deviation Detection Phase

In this phase, we use a solver to find candidate inputs which may cause deviations. This phase takes as input the formulas f_1 and f_2 generated for the programs P_1 and P_2 in the formula extraction phase. We rewrite the variables in each formula so that they refer to the same input, but each to their own internal states.

We then query the solver whether the combined formula $(f_1 \wedge \neg f_2) \vee (\neg f_1 \wedge f_2)$ is satisfiable, and if so, to provide an example that satisfies the combined formula. If the solver returns an example, then we have found an input that satisfies one program's formula, but not the other. If we had perfectly and fully modeled each program, and perfectly specified the post-condition to be that "the input results in a semantically equivalent output state", then this input would be guaranteed to produce a semantically equivalent output state in one program, but not the other. Since we only consider one program path and do not perfectly specify the post-condition in this way, this input is only a *candidate deviation input*.

3.3 Validation Phase

Finally, we validate the generated candidate deviation inputs to determine whether they actually result in semantically different output states in the two implementations. As illustrated in Figure 2, it is possible that while an input does not satisfy the symbolic formula generated for a server, it actually does result in an identical or semantically equivalent output state.

We send each candidate deviation input to the implementations being examined, and compare their outputs to determine whether they result in semantically equivalent or semantically different output states.

In theory, this testing requires some domain knowledge about the protocol implemented by the binaries, to determine whether their outputs are semantically equivalent. In practice, we have found deviations that are quite obvious. Typically, the server whose symbolic formula is satisfied by the input produces a response similar to its response to the original input, and the server whose symbolic formula is not satisfied by the input produces an error message, drops the connection, etc.

4 Implementation

Our implementation consists of several components: a path recorder, the symbolic formula generator, the solver, and a validator. We describe each below.

Collecting the trace. The symbolic formula generator component is based on QEMU, a complete system emulator [9]. We use a modified version of QEMU, that has been enhanced with the ability to track how specified external inputs, such as keyboard or received network data are procesed. The formula generator monitors the execution of a binary and records the execution trace, containing all instructions executed by the program and the information of their operands, such as their value and whether they are derived from specified external inputs. We start monitoring the execution before sending requests to the server and stop the trace when we observe a response from the server. We use a no-response timer to stop the trace if no answer is observed from the server after a configurable amount of time.

Symbolic formula generation. We implemented our symbolic formula generator as part of our BitBlaze binary analysis platform [1]. The BitBlaze platform can parse executables and instruction traces, disassemble each instruction, and translate the instructions into the IR shown in Table 1. The entire platform consists of about 16,000 lines of C/C++ code and 28,000 lines of OCaml, with about 1,600 lines of OCaml specifically written for our approach.

Solver. We use STP [30, 31] as our solver. It is a decision procedure specialized in modeling bit-vectors. After taking our symbolic formula as input, it either outputs an input that can satisfy the formula, or decides that the formula is not satisfiable.

Candidate deviation input validation. Once a candidate deviation input has been returned by the solver, we need to validate it against both server implementations and monitor the output states. For this we have built small HTTP and NTP clients that read the inputs, send them over the network to the servers, and capture the responses, if any.

After sending candidate inputs to both implementations, we determine the output state by looking at the response sent from the server. For those protocols that contain some type of status code in the response, such as HTTP in the Status-Line, each different value of the status code represents a different output state for the server. For those protocols that do not contain a status code in the response, such as NTP, we define a generic *valid state* and consider the server to have reached that state, as a consequence of an input, if it sends any well-formed response to the input, independently of the values of the fields in the response.

In addition, we define three special output states: a *fatal state* that includes any behavior that is likely to cause the server to stop processing future queries such as a crash, reboot, halt or resource starvation, a *no-response state* that indicates that the server is not in the fatal state but still did not respond before a configurable timer expired, and a *malformed state* that includes any response from the server that is missing mandatory fields. This last state is needed because servers might send messages back to the client that do not follow the guidelines in the corresponding specification. For example several HTTP servers, such as Apache or Savant, might respond to an incorrect request with a raw message written into the socket, such as the string “IOError” without including the expected HTTP Status-Line such as “HTTP/1.1 400 Bad Request”.

Server	Version	Type	Binary Size
Apache	2.2.4	HTTP server	4,344kB
Miniweb	0.8.1	HTTP server	528kB
Savant	3.1	HTTP server	280kB
NetTime	2.0 beta 7	NTP server	3,702kB
Ntpd	4.1.72	NTP server	192kB

Table 3: Different server implementations used in our evaluation.

5 Evaluation

We have evaluated our approach on two different protocols: HTTP and NTP. We selected these two protocols as representatives of two large families of protocols: text protocols (e.g. HTTP) and binary protocols (e.g. NTP). Text and binary protocols present significant differences in encoding, field ordering, and methods used to separate fields. Thus, it is valuable to study both families. In particular, we use three HTTP server implementations and two NTP server implementations, as shown in Table 3. All the implementations are Windows binaries and the evaluation is performed on a Linux host running Fedora Core 5.

The original inputs, which we need to send to the servers during the formula extraction phase to generate the execution traces, were obtained by capturing a network trace from one of our workstations and selecting all the HTTP and NTP requests that it contained. For each HTTP request in the trace, we send it to each of the HTTP servers and monitor its execution, generating an execution trace as output. We proceed similarly for each NTP request, obtaining an execution trace for each request/server pair. In Section 5.1, we show the deviations we discovered in the web servers, and in Section 5.2, the deviations we discovered in the NTP servers.

5.1 Deviations in Web Servers

This section shows the deviations we found among three web server implementations: Apache, Miniweb, and Savant. For brevity and clarity, we only show results for a specific HTTP query, which we find to be specially important because it discovered deviations between different server pairs. Figure 3 shows this query, which is an HTTP GET request for the file `/index.html`.

Deviations detected. For each server we first calculate a symbolic formula that represents how the server han-

Original request:

```
0000:   47 45 54 20  2F 69 6E 64  65 78 2E 68  74 6D 6C 20  GET /index.html
0010:   48 54 54 50  2F 31 2E 31  0D 0A 48 6F  73 74 3A 20  HTTP/1.1..Host:
0020:   31 30 2E 30  2E 30 2E 32  31 0D 0A 0D  0A           10.0.0.21....
```

Figure 3: One of the original HTTP requests we used to generate execution traces from all HTTP servers, during the formula extraction phase.

	$\neg f_A$	$\neg f_M$	$\neg f_S$
f_A	N/A	Case 1: unsatisfiable	Case 2: 5/0
f_M	Case 3: 5/5	N/A	Case 4: 5/5
f_S	Case 5: unsatisfiable	Case 6: unsatisfiable	N/A

Table 4: Summary of deviations found for the HTTP servers, including the number of candidate input queries requested to the solver and the number of deviations found. Each cell represents the results from one query to the solver and each query to the solver handles half of the combined formula for each server pair. For example Case 3 shows the results when querying the solver for $(f_M \wedge \neg f_A)$ and the combined formula for the Apache-Miniweb pair is the disjunction of Cases 1 and 3.

dled the original HTTP request shown in Figure 3. We call these formulas: f_A, f_S, f_M for Apache, Savant and Miniweb respectively. Then, for each of the three possible server pairs: Apache-Miniweb, Apache-Savant and Savant-Miniweb, we calculate the combined formula as explained in Section 3. For example, for the Apache-Miniweb pair, the combined formula is $(f_A \wedge \neg f_M) \vee (f_M \wedge \neg f_A)$. To obtain more detailed information, we break the combined formula into two separates queries to the solver, one representing each side of the disjunction. For example, for the Apache-Miniweb pair, we query the solver twice: one for $(f_A \wedge \neg f_M)$ and another time for $(f_M \wedge \neg f_A)$. The combined formula is the disjunction of the two responses from the solver.

Table 4 summarizes our results when sending the HTTP GET request in Figure 3 to the three servers. Each cell of the table represents a different query to the solver, that is, half of the combined formula for each server pair. Thus, the table has six possible cells. For example, the combined formula for the Apache-Miniweb pair, is shown as the disjunction of Cases 1 and 3.

Out of the six possible cases, the solver returned unsatisfiable for three of them (Cases 1, 5, and 6). For the remaining cases, where the solver was able to generate at least one candidate deviation input, we show two numbers in the format X/Y. The X value represents the number of different candidate deviation inputs we obtained from the solver, and the Y value represents the number of these candidate deviation inputs that actually generated semantically different output states when sent to the servers in the validation phase. Thus, the Y value represents the number of inputs that triggered a deviation.

In Case 2, none of the five candidate deviation inputs returned by the solver were able to generate semantically different output states when sent to the servers, that is, no deviations were found. For Cases 3 and 4, all candidate deviation inputs triggered a deviation when sent to the servers during the validation phase. In both cases, the Miniweb server accepted some input that was rejected by the other server. We analyze these cases in more detail next.

Applications to error detection and fingerprint generation. Figure 4 shows one of the deviations found for the Apache-Miniweb pair. It presents one of the candidate deviation inputs obtained from the solver in Case 3, and the responses received from both Apache and Miniweb when that candidate input was sent to them during the validation phase. The key difference is on the fifth byte of the candidate deviation input, whose original ASCII value represented a slash, indicating an absolute path. In the generated candidate deviation input, the byte has value 0xE8. We have confirmed that Miniweb does indeed accept any value on this byte. So, this deviation reflects an error by Miniweb: it ignores the first character of the requested URI and assumes it to be a slash, which is a deviation from the URI specification [15].

Figure 5 shows one of the deviations found for the Savant-Miniweb pair. It presents one of the candidate deviation inputs obtained from the solver in Case 4, including the responses received from both Savant and Miniweb when the candidate deviation input was sent to them during the validation phase. Again, the candidate deviation input has a different value on the fifth byte, but in this case the response from Savant is only a raw “File not found” string. Note that this string does not include the HTTP Status-Line, the first line in the response that includes the response code, as required by the HTTP spec-

Candidate deviation input:

```
0000:   47 45 54 20  E8 69 6E 64  65 78 2E 68  74 6D 6C 20  GET .index.html
0010:   B4 12 02 12  90 04 02 04  0D 0A 48 6F  A6 4C 08 20  ..........Ho.L.
0020:   28 D0 82 91  12 E0 84 0C  35 0D 0A 0D  0A           (.......5....
```

Miniweb response:

```
HTTP/1.1 200 OK
Server: Miniweb
Cache-control: no-cache
[...]
```

Apache response:

```
HTTP/1.1 400 Bad Request
Date: Sat, 03 Feb 2007 05:33:55 GMT
Server: Apache/2.2.4 (Win32)
[...]
```

Figure 4: Example deviation found for Case 3, where Miniweb's formula is satisfied while Apache's isn't. The figure includes the candidate deviation input being sent and the responses obtained from the servers, which show two different output states.

Candidate deviation input:

```
0000:   47 45 54 20  08 69 6E 64  65 78 2E 68  74 6D 6C 20  GET .index.html
0010:   09 09 09 09  09 09 09 09  0D 0A 48 6F  FF FF FF 20  ..........Ho...
0020:   09 09 09 09  09 09 09 09  09 0D 0A 0D  0A           .............
```

Miniweb response:

```
HTTP/1.1 200 OK
Server: Miniweb
Cache-control: no-cache
[...]
```

Savant response:

```
File not found
```

Figure 5: Example deviation found for Case 4, where Miniweb's formula is satisfied while Savant's isn't. The output states show that Miniweb accepts the input but Savant rejects it with a malformed response.

ification and can be considered malformed [27]. Thus, this deviation identifies an error though in this case both servers (i.e. Miniweb and Savant) are deviating from the HTTP specification.

Figure 6 shows another deviation found in Case 4 for the Savant-Miniweb pair. The HTTP specification mandates that the first line of an HTTP request must include a protocol version string. There are 3 possible valid values for this version string: "HTTP/1.1", "HTTP/1.0", and "HTTP/0.9", corresponding to different versions of the HTTP protocol. However, we see that the candidate deviation input produced by the solver uses instead a different version string, "HTTP/\b.1". Since Miniweb accepts this answer, it indicates that Miniweb is not properly verifying the values received on this field. On the other hand, Savant is sending an error to the client indicating an invalid HTTP version, which indicates that it is properly checking the value it received in the version field. This deviation shows another error in Miniweb's implementation.

To summarize, in this section we have shown that our approach is able to discover multiple inputs that trigger deviations between real protocol implementations. We have presented detailed analysis of three of them, and confirmed the deviations they trigger as errors. Out of the three inputs analyzed in detail, two of them can be attributed to be Miniweb's implementation errors, while the other one was an implementation error by both Miniweb and Savant. The discovered inputs that trigger deviations can potentially be used as fingerprints to differentiate among these implementations.

5.2 Deviations in Time Servers

In this section we show our results for the NTP protocol using two different servers: NetTime [6] and Ntpd [12]. Again, for simplicity, we focus on a single request that we show in Figure 7. This request represents a simple query for time synchronization from a client. The request uses the Simple Network Time Protocol (SNTP) Version 4 protocol, which is a subset of NTP [38].

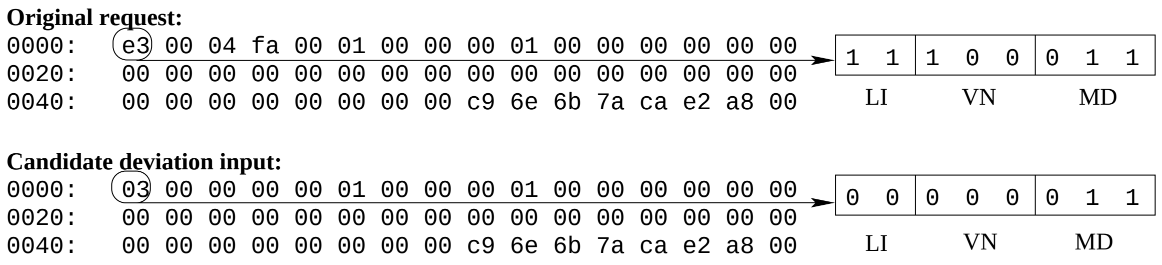
Deviations detected. First, we generate the symbolic formulas for both servers: f_T and f_N for NetTime and Ntpd respectively using the original request shown in Figure 7. Since we have one server pair, we need to query the solver twice. In Case 7, we query the solver for $(f_N \wedge \neg f_T)$ and in Case 8 we query it for $(f_T \wedge \neg f_N)$.

Candidate deviation input:
```
0000:   47 45 54 20  2F 69 6E 64  65 78 2E 68  74 6D 6C 20  GET /index.html
0010:   48 54 54 50  2F 08 2E 31  0D 0A 48 6F  FF FF FF 20  HTTP/..1..Ho...
0020:   09 09 09 09  09 09 09 09  09 0D 0A 0D  0A           .............
```

Miniweb response:
```
HTTP/1.1 200 OK
Server: Miniweb
Cache−control: no−cache
[...]
```

Savant response:
```
HTTP/1.1 400 Only 0.9 and 1.X requests supported
Server: Savant/3.1
Content−Type: text/html
[...]
```

Figure 6: Another example deviation for Case 4, between Miniweb and Savant. The main different is on byte 21, which is part of the Version string. In this case Miniweb accepts the request but Savant rejects it.



Original request:
```
0000:   e3 00 04 fa 00 01 00 00 00 01 00 00 00 00 00 00
0020:   00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
0040:   00 00 00 00 00 00 00 00 c9 6e 6b 7a ca e2 a8 00
```

Candidate deviation input:
```
0000:   03 00 00 00 00 01 00 00 00 01 00 00 00 00 00 00
0020:   00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
0040:   00 00 00 00 00 00 00 00 c9 6e 6b 7a ca e2 a8 00
```

NetTime response:
```
0000:   04 0f 00 fa 00 00 00 00 00 00 00 00 00 00 00 00
0020:   c9 6e 72 6c a0 c4 9a ec c9 6e 6b 7a ca e2 a8 00
0040:   c9 6e 72 95 25 60 41 5e c9 6e 72 95 25 60 41 5e
```

Ntpd response:
```
No response
```

Figure 7: Example deviation obtained for the NTP servers. It includes the original request sent in the formula extraction phase, the candidate deviation input output by the solver, and the responses received from the servers, when replaying the candidate deviation input. Note that the output states are different since NetTime does send a response, while Ntpd does not.

The solver returns unsatisfiable for Case 7. For Case 8, the solver returns several candidate deviation inputs. Figure 7 presents one of the deviations found for Case 8. It presents the candidate deviation input returned by the solver, and the response obtained from both NTP servers when that candidate deviation input was sent to them during the validation phase.

Applications to error detection and fingerprint generation. The results in Figure 7 show that the candidate deviation input returned by the solver in Case 8 has different values at bytes 0, 2 and 3. First, bytes 2 and 3 have been zeroed out in the candidate deviation input. This is not relevant since these bytes represent the "Poll" and "Precision" fields and are only significant in messages sent by servers, not in the queries sent by the clients, and thus can be ignored.

The important difference is on byte 0, which is presented in detail on the right hand side of Figure 7. Byte 0 contains three fields: "Leap Indicator" (LI), "Version" (VN) and "Mode" (MD) fields. The difference with the original request is in the Version field. The candidate deviation input has a decimal value of 0 for this field (note that the field length is 3 bits), instead of the original decimal value of 4. When this candidate deviation input was sent to both servers, Ntpd ignored it, choosing not to respond, while NetTime responded with a version number with value 0. Thus, this candidate deviation input leads the two servers into semantically different output states.

We check the specification for this case to find out that a zero value for the Version field is reserved, and according to the latest specification should no longer be supported by current and future NTP/SNTP servers [38]. However, the previous specification states that the server should copy the version number received from the client in the request, into the response, without dictating any special handling for the zero value. Since both implementations seem to be following different versions of the

Program	Trace-to-IR time	% of Symbolic Instructions	IR-to-formula time	Formula Size
Apache	7.6s	3.9%	31.87s	49786
Miniweb	5.6s	1.0%	14.9s	25628
Savant	6.3s	2.2%	15.2s	24789
Ntpd	0.073s	0.1%	5.3s	1695
NetTime	0.75s	0.1%	4.3s	5059

Table 5: Execution time and formula size obtained during the formula extraction phase.

	Input Calculation Time
Apache - Miniweb	21.3s
Apache - Savant	11.8s
Savant - Miniweb	9.0s
NetTime - Ntpd	0.56s

Table 6: Execution time needed to calculate a candidate deviation input for each server pair.

specification, we cannot definitely assign this error to one of the specifications. Instead, this example shows that we can identify inconsistencies or ambiguity in protocol specifications. In addition, we can use this query as a fingerprint to differentiate between the two implementations.

5.3 Performance

In this section, we measure the execution time and the output size at different steps in our approach. The results from the formula extraction phase and the deviation detection phase are shown in Table 5 and Table 6, respectively. In Table 5, the column "Trace-to-IR time" shows the time spent in converting an execution trace into our IR program. The values show that the time spent to convert the execution trace is significantly larger for the web servers, when compared to the time spent on the NTP servers. This is likely due to a larger complexity of the HTTP protocol, specifically a larger number of conditions affecting the input. This is shown in the second column as the percentage of all instructions that operate on symbolic data, i.e., on data derived from the input. The "IR-to-formula time" column shows the time spent in generating a symbolic formula from the IR program. Finally, the "Formula Size" column shows the size of the generated symbolic formulas, measured by the number of nodes that they contain. The formula size shows again the larger complexity in the HTTP implementations, when compared to the NTP implementations.

In Table 6, we show the time used by the solver in the deviation detection phase to produce a candidate deviation input from the combined symbolic formula. The results show that our approach is very efficient in discovering deviations. In many cases, we can discover deviation inputs between two implementations in approximately one minute. Fuzz testing approaches are likely to take much longer, since they usually need to test many more examples.

6 Discussion and Future Work

Our current implementation is only a first step. In this section we discuss some natural extensions that we plan to pursue in the future.

Addressing other protocol interactions. Currently, we have evaluated our approach over protocols that use request/response interactions (e.g. HTTP, NTP), where we examine the request being received by a server program. Note that our approach could be used in other scenarios as well. For example, with clients programs, we could analyze the response being received by the client. In protocol interactions involving multiple steps, we could consider the protocol output state to be the state of the program after the last step is finished.

Covering rarely used paths. Some errors are hidden in rarely used program paths and finding them can take multiple iterations in our approach. For each iteration, we need a protocol input that drives both implementations to semantically equivalent output states. These protocol inputs are usually obtained from a network trace. Thus, the more different inputs contained in the trace the more paths we can potentially cover. In addition, we can query the solver for multiple candidate deviation inputs, each time requiring the new candidate input to be different than the previous ones. The obtained candidate inputs often result in different paths. We have done work on symbolic execution techniques to explore multiple program paths and plan to apply those techniques here [16, 17].

Creating formulas including multiple paths. In this paper, we apply the weakest precondition on IR programs that contain a single program path, i.e., the processing of the original input by one implementation.

However, our weakest precondition algorithm is capable of handling IR programs containing multiple paths [19]. In the future, we plan to explore how to create formulas that include multiple paths.

On-line formula generation. Our current implementation for generating the symbolic formula works offline. We first record an execution trace for each implementation while it processes an input. Then, we process the execution trace by converting it into the IR representation, and computing the symbolic formula. Another alternative would be to generate the symbolic formulas in an on-line manner as the program performs operations on the received input, as in BitScope [16, 17].

7 Related Work

Symbolic execution & weakest precondition. Symbolic execution was first proposed by King [34], and has been used for a wide variety of problems including generating vulnerability signatures [18], automatic test case generation [32], proving the viability of evasion techniques [35], and finding bugs in programs [21, 47]. Weakest precondition was originally proposed for developing correct programs from the ground up [24, 26]. It has been used for different applications including finding bugs in programs [28] and for sound replay of application dialog [42].

Static source code analysis. Chen et al. [23] manually identify rules representing ordered sequences of security-relevant operations, and use model checking techniques to detect violations of those rules in software. Udrea et al. [45] use static source code analysis to check if a C implementation of a protocol matches a manually specified rule-based specification of its behavior.

Although these techniques are useful, our approach is quite different. Instead of comparing an implementation to a manually defined model, we compare implementations against each other. Another significant difference is that our approach works directly on binaries, and does not require access to the source code.

Protocol error detection. There has been considerable research on testing network protocol implementations, with heavy emphasis on automatically detecting errors in network protocols using fuzz testing [2–5, 8, 11, 13, 33, 37, 43, 46]. Fuzz testing is a technique in which random or semi-random inputs are generated and fed to the program under study, while monitoring for unexpected program output, usually an unexpected final state such as program crash or reboot.

Compared to fuzz testing, our approach is more efficient for discovering deviations since it requires testing far fewer inputs. It can detect deviations by comparing how two implementations process the same input, even if this input leads both implementation to semantically equivalent states. In contrast, fuzz testing techniques need observable differences between implementations to detect a deviation.

There is a line of research using model checking to find errors in protocol implementations. Musuvathi et.al. [40, 41] use a model checker that operates directly on C and C++ code and use it to check for errors in TCP/IP and AODV implementations. Chaki et al. [22] build models from implementations and checks it against a specification model. Compared to our approach, these approaches need reference models to detect errors.

Protocol fingerprinting. There has also been previous research on protocol fingerprinting [25, 44] but available fingerprinting tools [7, 10, 14] use manually extracted fingerprints. More recently, automatic fingerprint generation techniques, working only on network input and output, have been proposed [20]. Our approach is different in that we use binary analysis to generate the candidate inputs.

8 Conclusion

In this paper, we have presented a novel approach to automatically detect deviations in the way different implementations of the same specification check and process their input. Our approach has several advantages: (1) by automatically building the symbolic formulas from the implementation, our approach is precisely truthful to the implementation; (2) automatically identifying the deviation by solving formulas generated from the two implementations enables us to find the needle in the haystack without having to try each straw (input) individually, thus a tremendous performance gain; (3) our approach works on binaries directly, i.e., without access to source code. We then show how to apply our automatic deviation techniques for automatic error detection and automatic fingerprint generation.

We have presented our prototype system to evaluate our techniques, and have used it to automatically discover deviations in multiple implementations of two different protocols: HTTP and NTP. Our results show that our approach successfully finds deviations between different implementations, including errors in input checking, and differences in the interpretation of the specification, which can be used as fingerprints.

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