Rule-Based Static Analysis of Network Protocol Implementations

Octavian Udrea, Cristian Lumezanu, and Jeffrey S. Foster
{udrea, lume, jfoster}@cs.umd.edu
University of Maryland, College Park

Abstract

Today's software systems communicate over the Internet using standard protocols that have been heavily scrutinized, providing some assurance of resistance to malicious attacks and general robustness. However, the software that implements those protocols may still contain mistakes, and an incorrect implementation could lead to vulnerabilities even in the most well-understood protocol. The goal of this work is to close this gap by introducing a new technique for checking that a C implementation of a protocol matches its description in an RFC or similar standards document. We present a static (compile-time) source code analysis tool called Pistachio that checks C code against a rule-based specification of its behavior. Rules describe what should happen during each round of communication, and can be used to enforce constraints on ordering of operations and on data values. Our analysis is not guaranteed sound due to some heuristic approximations it makes, but has a low false negative rate in practice when compared to known bug reports. We have applied Pistachio to implementations of SSH and RCP, and our system was able to find many bugs, including security vulnerabilities, that we confirmed by hand and checked against each project's bug databases.

1 Introduction

Networked software systems communicate using protocols designed to provide security against attacks and robustness against network glitches. There has been a significant body of research, both formal and informal, in scrutinizing abstract protocols and proving that they meet certain reliability and safety requirements [24, 18, 6, 14, 25]. These abstract protocols, however, are ultimately implemented in software, and an incorrect implementation could lead to vulnerabilities even in the most heavily-studied and well-understood protocol.

In this paper we present a tool called Pistachio that helps close this gap. Pistachio is a static (compile-time) analysis tool that can check that each communication step taken by a protocol implementation matches an abstract specification. Because it starts from a detailed protocol specification, Pistachio is able to check communication properties that generic tools such as buffer overflow detectors do not look for. Our static analysis algorithm is also very fast, enabling Pistachio to be deployed regularly during the development cycle, potentially on every compile.

The input to our system is the C source code implementing the protocol and a *rule-based* specification of its behavior, where each rule describes what should happen in a "round" of communication. For example, the IETF current draft of the SSH connection protocol specifies that "When either party wishes to terminate the channel, it sends *SSH_MSG_CHANNEL_CLOSE*. Upon receiving this message, a party *must* send back a *SSH_MSG_CHANNEL_CLOSE*..." This statement translates into the following rule (slightly simplified):

```
recv(_, in, _)
in[0] = SSH_MSG_CHANNEL_CLOSE
⇒
send(_, out, _)
out[0] = SSH_MSG_CHANNEL_CLOSE
```

This rule means that after seeing a call to `recv()` whose second argument points to memory containing *SSH_MSG_CHANNEL_CLOSE*, we should reply with the same type of message. The full version of such a rule would also require that the reply contain the same channel identifier as the initial message.

In addition to this specification language, another key contribution of Pistachio is a novel static analysis algorithm for checking protocol implementations against

their rule-based specification. Pistachio performs an *abstract interpretation* [10] to simulate the execution of program source code, keeping track of the state of program variables and of *ghost variables* representing abstract protocol state, such as the last value received in a communication. Using a fully automatic theorem prover, Pistachio checks that whenever it encounters a statement that triggers a rule (e.g., a call to `recv`), on all paths the conclusion of the rule is eventually satisfied (e.g., `send` is called with the right arguments). Although this seems potentially expensive, our algorithms run efficiently in practice because the code corresponding to a round of communication is relatively compact. Our static analysis is not guaranteed to find all rule violations, both because it operates on C, an unsafe language, and because the algorithm uses some heuristics to improve performance. In practice, however, our system missed less than 5% of known bugs when measured against a bug database.

We have applied Pistachio to two protocol implementations: the LSH implementation of SSH2 and the RCP implementation from Cygwin. Analysis took less than a minute for each of the test runs, and Pistachio detected a multitude of bugs in the implementations, including many security vulnerabilities. For example, Pistachio found a known problem in LSH that causes it to leak privileged information [22]. Pistachio also found a number of buffer overflows due to rule violations, although Pistachio does not detect arbitrary buffer overflows. We confirmed the bugs we found against bug databases for the projects, and we also found two new unconfirmed security bugs in LSH: a buffer overflow and an incorrect authentication failure message when using public key authentication.

In summary, the main contributions of this work are:

- We present a rule-based specification language for describing network protocol implementations. Using pattern matching to identify routines in the source code and ghost variables to track state, we can naturally represent the kinds of English specifications made in documents like RFCs. (Section 2)

- We describe a static analysis algorithm for checking that an implementation meets a protocol specification. Our approach uses abstract interpretation to simulate the execution of the program and an automatic theorem prover to determine whether the rules are satisfied. (Section 3)

- We have applied our implementation, Pistachio, to LSH and RCP. Pistachio discovered a wide variety of known bugs, including security vulnerabilities, as well as two new unconfirmed bugs. Overall Pistachio missed about 5% of known bugs and had a 38% false positive rate. (Section 4)

```
0. int main(void) {
1.   int sock, val = 1, recval;
2.   send(sock, &val, sizeof(int));
3.   while(1) {
4.     recv(sock, &recval, sizeof(int));
5.     if (recval == val)
6.       val += 2;
7.     send(sock, &val, sizeof(int));
8.   }
9. }
```

Figure 1: Simple alternating bit protocol implementation

Based on our results, we believe that Pistachio can be a valuable tool in ensuring the safety and security of network protocol implementations.

2 Rule-Based Protocol Specification

The first step in using Pistachio is developing a rule-based protocol specification, usually from a standards document. As an example, we develop a specification for a straightforward extension of the alternating bit protocol [4]. Here is a straw-man description of the protocol:

> The protocol begins with the current party sending the value $n = 1$. In each round, if n is received then the current party sends $n + 1$; otherwise the current party resends n.

Figure 1 gives a sample implementation of this protocol. Here `recv()` and `send()` are used to receive and send data, respectively. Notice that this implementation is actually flawed—on statement 6, `val` is incremented by 2 instead of by 1.

To check this protocol, we must first identify the communication primitives in the source code. In this case we see that the calls to `send()` in statements 2 and 7 and the call to `recv()` in statement 4 perform the communication. More specifically, we observe that we will need to track the value of the second argument in the calls, since that contains a pointer to the value that is communicated.

We use *patterns* to match these function calls or other expressions in the source code. Patterns contain *pattern variables* that specify which part of the call is of interest to the rule. For this protocol, we use pattern `send(_, out, _)` to bind pattern variable *out* to the second argument of `send()`, and we use pattern `recv(_, in,`

Rule					Description
(1)		$\emptyset$	$\Rightarrow$	`send(_, out, _)` $out[0..3] = 1$ $n := 1$	The protocol begins by sending the value 1
(2)	`recv(_, in, _)` $in[0..3] = n$		$\Rightarrow$	`send(_, out, _)` $out[0..3] = in[0..3] + 1$ $n := out[0..3]$	If n is received then send $n + 1$
(3)	`recv(_, in, _)` $in[0..3] \neq n$		$\Rightarrow$	`send(_, out, _)` $out[0..3] = n$	Otherwise resend n

Figure 2: Rule-based protocol specification

_) to bind *in* to the second argument of `recv()`. For other implementations we may need to use patterns that match different functions. Notice that in both of these patterns, we are already abstracting away some implementation details. For example, we do not check that the last parameter matches the size of `val`, or that the communication socket is correct, i.e., these patterns will match calls even on other sockets.

Patterns can be used to match any function calls. For example, we have found that protocol implementers often create higher-level functions that wrap send and receive operations, rather than calling low-level primitives directly. Using patterns to match these functions can make for more compact rules that are faster to check, though this is only safe if those routines are trusted.

2.1 Rule Encoding

Once we have identified the communication operations in the source code, we need to write rules that encode the steps of the protocol. Rules are of the form

$$(P_H, H) \Rightarrow (P_C, C, G)$$

where H is a *hypothesis* and C is a *conclusion*, P_H and P_C are patterns, and G is a set of assignments to ghost variables representing protocol state. In words, such a rule means: If we find a statement s in the program that matches pattern P_H, assume that H holds, and make sure that on all possible execution paths from s there is some statement matching P_C, and moreover at that point the conditions in C must hold. If a rule is satisfied in this manner, then the side effects G to ghost variables hold after the statements matching P_C.

For example, Figure 2 contains the rules for our alternating bit protocol. Rule (1) is triggered by the start of the program, denoted by hypothesis $\emptyset$. This rule says that on all paths from the start of the program, `send()` must be called, and its second argument must point to a 4-byte block containing the value 1. We can see that this rule is satisfied in statement 2 in Figure 1. As a side effect, the successful conclusion of rule (1) sets the ghost variable n to 1. Thus the value of n corresponds to the data stored in `val`. Notice that there is a call to `send()` in statement 7 that could match the conclusion pattern—but it does not, because we interpret patterns in rules to always mean the *first* occurrence of a pattern on a path.

Rule (2) is triggered by a call to `recv()`. It says that if `recv()` is called, then assuming that the value n is received in the first four bytes of in, the function `send()` must eventually be called with $in + 1$ as an argument, and as a side effect the value of n is incremented. Similarly to before, this rule matches the first occurrence of `send()` following `recv()`. In our example code this rule is not satisfied. Suppose rule (1) has triggered once, so the value of n is 1, and we trigger rule (2) in statement 4. Then if we assume n is received in statement 4, then statement 7 will send $n + 2$. Hence Pistachio signals a rule violation on this line.

Finally, rule (3) is triggered on the same call to `recv()` in statement 4. It says that if we assume the value of n is not received in in, then eventually `send()` is called with n as the argument. This rule will be satisfied by the implementation, because when we take the false branch in statement 5 we will resend `val`, which always contains n after rules (1) or (3) fire.

2.2 Developing Rule-Based Specifications

As part of our experimental evaluation (Section 4), we developed rule-based specifications for the SSH2 protocol and the RCP protocol. In both cases we started with a specification document such as an RFC or IETF standard. We then developed rules from the textual descriptions in the document, using the following steps:

1. *Identifying patterns*. The specification writer can either choose the low-level communication primitives as the primary patterns, as in Figure 2, or write rules in terms of higher-level routines. We have attempted both approaches when developing our specifications, but decided in favor of the first method for more future portability.

2. *Defining the rules*. The main task in constructing a rule-based specification is, of course, determin-

ing the basic rules. The specification writer first needs to read the standards document carefully to discover what data is communicated and how it is represented. Then to discover the actual rules they should study the sections of the specification document that describe the protocol's behavior. We found that phrases containing *must* are good candidates for such rules. (For a discussion of terms such as *must*, *may*, and *should* in RFC documents, see RFC 1111.)

For instance, as we read the SSH2 standard we learned that the message format for SSH user authentication starts with the message type, followed by the user name, service name, and method name. Furthermore, we found that the use of "none" as the authentication method is strongly discouraged by the specification except for debugging purposes. This suggested a potential security property: To prevent anonymous users from obtaining remote shells, we should ensure that *If we receive a user authentication request containing the* none *method, we must return SSH_MSG_USERAUTH_FAILURE*. Once we determine this rule, it is easy to encode it in Pistachio's notation, given our knowledge of SSH message formats.

3. *Describing state*. Finally, as we are constructing the rules, we may discover that some protocol steps are state-based. For instance, in the SSH2 protocol, any banner message has to be sent before the server sends *SSH_MSG_USERAUTH_SUCCESS*. To keep track of whether we have sent the success message, we introduce a new ghost variable called *successSent* that is initially 0 (here we assume for simplicity that we only have one client). We modify our rules to set *successSent* to 1 or 0 in the appropriate cases. Then the condition on banner messages can be stated as *Given that successSent is 1 and for any message received, the output message type is different from SSH_MSG_USERAUTH_BANNER*. Our experience is that coming up with the ghost variables is the least-obvious part of writing a specification and requires some insight. In the LSH and RCP protocols, the state of the protocol usually depends on the previous message that was sent, and so our rules use ghost variables to track the last message.

Section 4.1 discusses the actual rule-based specifications we developed for our experiments.

3 Static Analysis of Protocol Source Code

Given a set of rules as described in Section 2 and the source code of a C program, Pistachio performs a static analysis to check that the program obeys the specified rules. Pistachio uses abstract interpretation [10] to simulate the behavior of source code. The basic idea is to associate a set of *facts* with each point during execution. In our system, the facts we need to keep track of are the predicates in the rules and anything that might be related to them. Each statement in the program can be thought of as a *transfer function* [1], which is a "fact transformer" that takes the set of facts that hold before the statement and determines the facts that hold immediately after:

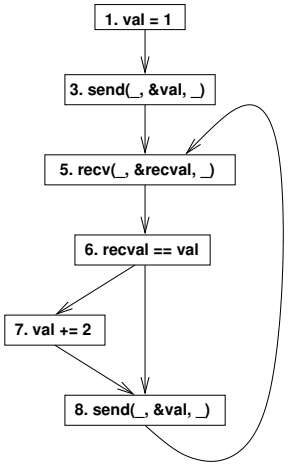
- After an assignment statement *var = expr*, we first remove any previous facts about *var* and then add the fact *var = expr*. For example, consider the code in Figure 1 again. If before statement 6 $\{val = n\}$ is the set of facts that hold, after the assignment in statement 6 the set $\{val = n + 2\}$ holds. Pointers and indirect assignments are handled similarly, as discussed below.

- If we see a conditional *if (p) s1 else s2*, we add the fact that p holds on the true branch, and that $\neg p$ holds on the false branch. For example, in statement 6 in Figure 1 we can always assume *recval = val*, since to reach this statement the condition in statement 5 must have been true.

- If we see a function call *f(x1, ..., xn)*, we propagate facts from the call site through the body of f and back to the caller. I.e., we treat the program as if all functions are inlined. As discussed below, we bound the number of times we visit recursive functions to prevent infinite looping, although recursive functions are rare in practice for network protocol implementations.

We perform our analysis on a standard *control-flow graph* (CFG) constructed from the program source code. In the CFG, each statement forms a node, and there is an edge from s_1 to s_2 if statement s_1 occurs immediately before statement s_2. For example, Figure 3(a) gives the CFG for the program in Figure 1.

Figure 4 presents our abstract interpretation algorithm more formally. The goal of this algorithm is to update *Out*, a mapping such that *Out*(s) is the set of facts that definitely hold just after statement s. The input to *FactDerivation* is an initial mapping *Out*, a set of starting statements S, and a set of ending statements T. The algorithm simulates the execution of the program from



(a) Control-Flow Graph

Rule (1)	**Hyp:** facts = $\emptyset$ **Concl:** stmt 2 matches, facts = $\{val = 1\}$ **Need to show:** $\{val = 1\} \wedge \{\&val = out\} \Rightarrow out[0..3] = 1$ **Action:** $n := 1$
Rule (3)	**Hyp:** stmt 4 matches, facts = $\{n = 1, val = 1, in = \&recval, in[0..3] \neq n\} = F$ **Branch:** Since assumptions $\Rightarrow$ $(recval \neq val)$, false branch taken **Concl:** stmt 7 matches, same facts F as above **Need to show:** $F \wedge \{\&val = out\} \Rightarrow out[0..3] = n$ **Action:** none
Rule (2)	**Hyp:** stmt 4 matches, facts = $\{n = 1, val = 1, in = \&recval, in[0..3] = n\}$ **Branch:** Since assumptions $\Rightarrow$ $(recval = val)$, true branch taken **Concl:** stmt 7 matches, facts are $F = \{n = 1, val = 3, in = \&recval, in[0..3] = n\}$ **Need to show:** $F \wedge \{\&val = out\} \Rightarrow (out[0..3] = in[0..3] + 1)$ **Fails** to hold; issue warning

(b) Algorithm Trace

Figure 3: Static Checking of Example Program

statements in S to statements in T while updating *Out*. Our algorithm uses an automatic theorem prover to determine which way conditional branches are taken. In this pseudocode, we write *pred*(s) and *succ*(s) for the predecessor and successor nodes of s in the CFG.

Our simulation algorithm uses a worklist Q of statements, initialized on line 1 of Figure 4. We repeatedly pick statements from the worklist until it is empty. When we reach a statement in T on line 6, we stop propagation along that path. Because the set of possible facts is large (most likely infinite), simulation might not terminate if the code has a loop. Thus on line 10 we heuristically stop iterating once we have visited a statement *max_pass* times, where *max_pass* is a predetermined constant bound. Based on our experiments, we set *max_pass* to 75. We settled on this value empirically by observing that if we vary the number of iterations, then the overall false positive and false negative rates from Pistachio rarely changed after 75 iterations in our experiments.

In line 5 of the algorithm, we compute the set *In* of facts from the predecessors of s in the CFG. If the predecessor was a conditional, then we also add in the appropriate guard based on whether s is on the true or false branch. Then we apply a transfer function that depends on what kind of statement s is: Lines 13–15 handle simple assignments, which kill and add facts as described earlier, and then add successor statements to the worklist. Lines 16–24 handle conditionals. Here we use an automatic theorem prover to prune impossible code paths. If the guard p holds in the current state, then we only add s_1 to the worklist, and if $\neg p$ holds then we only add s_2 to the worklist. If we cannot prove either, i.e., we do not know which path we will take, then we add both s_1 and s_2 to the worklist. Finally, lines 25–32 handle function calls. We compute a renaming *map* between the actual and formal parameters of f, and then recursively simulate f from its entry node to its exit nodes. We start simulation in state *map*(Out), which contains the facts in *Out* renamed by *map*. Then the state after the call returns is the intersection of the states at all possible exits from the function, with the inverse mapping map^{-1} applied.

C includes a number of language features not covered in Figure 4. Pistachio uses CIL [26] as a front-end, which internally simplifies many C constructs by introducing temporary variables and translating loops into canonical form. We unroll loops up to *max_pass* times in an effort to improve precision. However, as discussed in Section 3.2, we attempt to find a fixpoint during unrolling process and stop if we can do so, i.e., if we can find a loop invariant. C also includes pointers and a number of unsafe features, such as type casts and unions. Pistachio tracks facts about pointers during its simulation, and all C data is modeled as arrays of bytes with bounds information. When there is an indirect assignment through a pointer, Pistachio only derives a fact if the theorem prover can show that the write is within bounds, and otherwise kills all existing facts about the array. Note that even though a buffer overflow may modify other memory, we do not kill other facts, which is unsound but helps reduce false positives. Since all C data is represented as byte arrays, type casts are implicitly handled as well, as long we can determine at analysis time the allocation size for each type, which Pistachio could always do in our experiments. In addition, in order to reduce false positives

FactDerivation(*Out*, S, T)

1: $Q \leftarrow S$
2: **while** Q not empty **do**
3: $s \leftarrow$ *dequeue*(Q)
4: *visit*$(s) \leftarrow$ *visit*$(s) + 1$
5: $In \leftarrow \cap_{s' \in pred(s)} \begin{cases} Out(s') \cup \{C\} & s' \text{ is "if}(C) \text{ then } s \text{ else } s_2\text{"} \\ Out(s') \cup \{\neg C\} & s' \text{ is "if}(C) \text{ then } s_1 \text{ else } s\text{"} \\ Out(s') & \text{otherwise} \end{cases}$
6: **if** $s \in T$ **then**
7: *Out*$(s) \leftarrow In$
8: **continue**
9: **end if**
10: **if** *visit*$(s) >$ *max_pass* **then**
11: **continue**
12: **end if**
13: **if** s is assignment "*var=expr*" **then**
14: *Out*$(s) \leftarrow$ (*In* $-$ {facts involving *var*}) $\cup$ {*var=expr*}
15: $Q \leftarrow Q \cup$ *succ*(s)
16: **else if** s is "if(p) then s_1 else s_2" **then**
17: *Out*$(s) \leftarrow$ *In*
18: **if** *Theorem-prover*(*Out*$(s) \Rightarrow p) =$ *yes* **then**
19: $Q \leftarrow Q \cup \{s_1\}$
20: **else if** *Theorem-prover*(*Out*$(s) \Rightarrow \neg p) =$ *yes* **then**
21: $Q \leftarrow Q \cup \{s_2\}$
22: **else**
23: $Q \leftarrow Q \cup \{s_1, s_2\}$
24: **end if**
25: **else if** s is "$f(x_1, \ldots, x_n)$" **then**
26: *map* $\leftarrow$ mapping between actual and formal parameters
27: *start*$' \leftarrow$ entry statement of f
28: $T' \leftarrow$ exit statements of f
29: *FactDerivation*(*map*(*Out*), {*start*$'$}, T')
30: *Out*$(s) \leftarrow \cap_{s' \in T'} map^{-1}($*Out*$(s'))$
31: $Q \leftarrow Q \cup$ *succ*(S)
32: **end if**
33: **end while**

Figure 4: Fact derivation in Pistachio

Pistachio assumes that variables are initialized with their default values independently of their scope. In the next sections, we illustrate the use of *FactDerivation* during the process of checking the alternating bit protocol from Figure 2.

3.1 Checking a Single Rule

Given the *FactDerivation* algorithm, we can now present our algorithm for checking that the code obeys a single rule R of the form $(P_H, H) \Rightarrow (P_C, C, G)$. Assume that we are given a set of statements S that match P_H. Then to check R, we need to simulate the program forward from the statements in S using *FactDerivation*. We check that we can reach statements matching P_C along all paths and that the conclusion C holds at those statements. Figure 5 gives our formal algorithm *CheckSingleRule* for carrying out this process.

The input to *CheckSingleRule* is a rule R, an initial set of facts *Out*, and a set of starting statements S. For all statements in S, on line 3 we add to their facts the assumptions H and any facts derived from pattern-matching S against P_H; we denote this latter set of facts

CheckSingleRule(R, *Out*, S)

1: Let R be of the form $(P_H, H) \Rightarrow (P_C, C, G)$
2: **for** $s \in S$ **do**
3: *Out*$(s) \leftarrow$ *Out*$(s) \cup H \cup P_H(s)$
4: **end for**
5: If there is a path from S on which no statement matches P_C, return error
6: Let T be the set of statements that are the first matches to P_C on all paths from statements in S
7: *FactDerivation*(*Out*, S, T)
8: **if** $\forall t \in T$, *Theorem-prover*((*Out*$(t) \wedge P_C(t)) \Rightarrow C) =$ *yes* **then**
9: /* R is satisfied */
10: **for** $s' \in T$ **do**
11: Remove from *Out*(s') facts involving ghost variables modified in G
12: *Out*$(s') \leftarrow$ *Out*$(s') \cup G$
13: **end for**
14: Remove from *Out* all the facts involving pattern variables
15: Return *rule satisfied*
16: **else**
17: /* R is not satisfied */
18: Return error
19: **end if**

Figure 5: Algorithm for checking a single rule

by $P_H(s)$. If there is some path from S along which we cannot find a match to P_C, we report an error on line 5 and consider the rule unsatisfied. Otherwise on line 6 we search forward along all program paths until we first find the conclusion pattern P_C. Then on line 7 we perform abstract interpretation using *FactDerivation* to update *Out*. On line 8, we use the theorem prover to check whether the conclusion C holds at the statements that match P_C. If they do then the rule is satisfied, and lines 11–12 update *Out*(s') with facts for ghost variables. We also remove any facts about pattern variables (*in* and *out* in our examples) from *Out* (line 14).

We illustrate using *CheckSingleRule* to check rule (1) from Figure 2 on the code in Figure 1. The first block in Figure 3(b) lists the steps taken by the algorithm. We will discuss the remainder of this figure in Section 3.2.

In rule (1), the hypothesis pattern P_H is the start of the program, and the set of assumptions H is empty. The conclusion C of this rule is $out[0..3] = 1$, where out matches the second argument passed to a call to `send()`. Thus to satisfy this rule, we need to show that $out[0..3] = 1$ at statement 2 in Figure 1. We begin by adding H and $P_H(0)$, which in this case are empty, to *Out*(0), the set of facts at the beginning of the program, which is also empty. We trace the program from this point forward using *FactDerivation*. In particular, *Out*$(1) =$ *Out*$(2) = \{val = 1\}$. At statement 2 we match the call to `send()` against P_C, and thus we also have fact $\&val =$ *out*. Then we ask the theorem prover to show *Out*$(2) \wedge \{\&val =$ *out*$\} \Rightarrow C$. In this case the proof succeeds, and so the rule is satisfied, and we set ghost variable n to 1.

CheckRuleSet(W, *Out*, S)

```
1: while W not empty do
2:     R ← dequeue(W)
3:     visit(R) ← visit(R) + 1
4:     if visit(R) > max_pass then
5:         continue
6:     end if
7:     Let R be of the form (P_H, H) ⇒ (P_C, C, G)
8:     Let T be the set of statements that are the first matches to P_H on all paths
       from statements in S
9:     Let Out' = Out
10:    FactDerivation(Out', S, T)
11:    CheckSingleRule(R, Out', T)
12:    Let U be the set of statements computed in step 6 in Figure 5
13:    if R is satisfied then
14:        CheckRuleSet({R' | R' depends on R}, Out', U)
15:    end if
16: end while
```

Figure 6: Algorithm for checking a set of rules

3.2 Checking a Set of Rules

Finally, we develop our algorithm for checking a set of rules. Consider again the rules in Figure 2. Notice that rules (2) and (3) both depend on n, which is set in the conclusion of rules (1) and (2). Thus we need to check whether rules (2) or (3) are triggered on any program path after we update n, and if they are, then we need to check whether they are satisfied. Since rule (2) depends on itself, we in fact need to iterate. Formally, we say that rule R_i *depends on* rule R_j if R_j sets a ghost variable that R_i uses in its hypothesis. We can think of dependencies as defining a graph between rules, and we use a modified depth-first search algorithm to check rules in the appropriate order based on dependencies.

Figure 6 gives our algorithm for checking a set of rules. The input is a set of rules W that need to be checked, a mapping *Out* of facts at each program point, and a set of statements S from which to begin checking the rules in W. To begin checking the program, we call *CheckRuleSet*(R_0, Out_0, S_0), where R_0 is the rule with hypothesis $\emptyset$ (we can always create such a rule if it does not exist), S_0 is the initial statement in the program, and Out_0 maps every statement to the set of all possible facts.

Then the body of the algorithm removes a rule R from the worklist W and checks it. Because rule dependencies may be cyclic, we may visit a rule multiple times, and as in Figure 5 we terminate iteration once we have visited a rule *max_pass* times (line 5). On line 8 we trace forward from S to find all statements T that match P_H. Then we copy the current set of facts *Out* into a new set *Out*$'$, simulate the program from S to T (line 10), and then on line 11 check the rule R with facts *Out*$'$. Notice that the call to *FactDerivation* on line 10 and the call to *CheckSingleRule* on line 11 modify the copy *Out*$'$ while leaving the original input *Out* unchanged. This means that in the next iteration of the loop, when we pick another rule from the worklist and check it starting from S, we will again check it using the initial facts in *Out*, which is the intended behavior: A call to *CheckRuleSet* should check all rules in W starting in the same state. Finally, on line 14, if the rule R was satisfied, we compute the set of all rules that depend on R, and then we recursively check those rules, starting in our new state from statements that matched the conclusion pattern.

We illustrate the algorithm by tracing through the remainder of Figure 3(b), which describes the execution of *CheckRuleSet* on our example program. Observe that rule (1) can be checked with no assumptions, hence we use it to begin the checking process. We begin with the initial statement in the program and call *CheckSingleRule*. As described in Section 3.1, we satisfy rule (1) at statement 2, and we set ghost variable n to 1. Thus after checking rule (1), we can verify rules that depend on n's value. For our example, either rule (2) or rule (3) might fire next, and so W will contain both of them.

Checking rule (3). Suppose we next choose rule (3). We continue from statement 2, since that is where we set ghost variable n, and we perform abstract interpretation forward until we find a statement that matches the hypothesis pattern of rule (3), which is statement 4. Now we add the hypothesis assumption $in[0..3] \neq n$ to our set of facts and continue forward. When we reach statement 5, the theorem prover shows that the false branch will be taken, so we only continue along that one branch—which is important, because if we followed the other branch we would not be able to prove the conclusion. Taking the false branch, we fall through to statement 7, and the theorem prover concludes that rule (3) holds.

Checking rule (2). Once we are done checking rule (3), we need to go back and start checking rule (2) where we left off after rule (1), namely just after we set $n := 1$ after statement 2. The set of facts contains $n = 1$ and $val = 1$, both set during the checking of rule (1). We continue forward from statement 2, match the hypothesis of rule (2) at statement 4, and then this time at the conditional we conclude that the true branch is taken, hence *val* becomes 3 at statement 7. Now the conclusion of the rule cannot be proven, so we issue a warning that the protocol was violated at this statement.

Finding a fixpoint. Suppose for illustration purposes that rule (2) had checked successfully, i.e., in statement 6, `val` was only incremented by one. Then at statement 7

we would have shown the conclusion and set ghost variable $n := out[0..3]$. Then since we changed the value of n, we need to re-check rules (2) and (3) starting from this point, since they depend on the value of n. Of course, if we follow the loop around again we would need to check rules (2) and (3) yet again, leading to an infinite loop, cut off after *max_pass* times.

In order to model this case more efficiently, Pistachio's implementation of *CheckRuleSet* includes a technique for finding a fixpoint and safely stopping abstract interpretation early. Due to lack of space, we omit pseudocode for this technique and illustrate it by example. During the first check of rule (2), we would have that $Out^0(2) = \{n = val, val = 1\}$, where the superscript of *Out* indicates how many iterations we have performed. After rule (2) succeeds at statement 7, we set n to *val*, and hence $Out^1(7) = \{n = val, val = 2\}$. Since rule (2) depends on itself, we need to check it once again. After simulating the loop in statements 3–8 another time, we would check rule (2) with facts $Out^2(7) = \{n = val, val = 3\}$. Rather than continuing until we reach *max_pass*, we instead try to intersect the facts we have discovered to form a potential loop invariant. We look at the set of facts that hold just before rule (2) is triggered and just after rule (2) is verified:

$Out^0(2) = \{n = val, val = 1\}$	Initial entry to loop
$Out^1(7) = \{n = val, val = 2\}$	Back-edge from the first iteration
$Out^2(7) = \{n = val, val = 3\}$	Back-edge from the second iteration

Generally speaking, at step k we are interested in the intersection $Out^0(2) \cap \bigcap_{i \in [1,k]} Out^i(7)$. In our case, the only fact in this intersection is $n = val$. We then set $Out^{k+1} = \{n = val\}$ (thus ignoring the particular value of *val* for step k) and attempt to verify rule (2) once more. Rule (2) indeed verifies, which means we have reached a fixpoint, and we can stop iterating well before reaching *max_pass*. We found this technique for finding fixpoints effective in our experiments (Section 4).

4 Implementation and Experiments

Our tool Pistachio is implemented in approximately 6000 lines of OCaml. We use CIL [26] to parse C programs and Darwin [5] as the automated theorem prover. Darwin is a sound, fully-automated theorem prover for first order clausal logic. We chose Darwin because it performs well and can handle the limited set of Horn-type theorems we ask it to prove. Since Darwin is not complete, it can return either "yes," "no," or "maybe" for each theorem. Pistachio conservatively assumes that a warning should be generated if a rule conclusion cannot be provably implied by the facts derived starting from the hypothesis.

In order to analyze realistic programs, Pistachio needs to model system libraries. When Pistachio encounters a library call, it generates a skeleton rule-based specification for the function that can be filled in by the user. Rules for library functions are assumed correct, rather than checked. For our experiments we added such specifications for several I/O and memory allocation routines. There are some library functions we cannot fully model in our framework, e.g., *geterrno*(), which potentially depends on any other library call. In this case, Pistachio assumes that conditionals based on the result of *geterrno*() may take either branch, which can reduce precision.

4.1 Core Rule Sets

We evaluated Pistachio by analyzing the LSH [21] implementation of SSH2 and the RCP implementation from Cygwin's inetutils package. We chose these systems because of their extensive bug databases and the number of different versions available.

We created rule-based specifications by following the process described in Section 2.2. Our (partial) specification for SSH2 totaled 96 rules, and the one for RCP totaled 58 rules. Because the rules describe particular protocol details and are interdependent, it is difficult to correlate individual rules with general correctness or security properties. In Figure 7, we give a rough breakdown of the rules in our SSH2 specification, and we list example rules with descriptions. These rules are taken directly from our experiments—the only changes are that we have reformatted them in more readable notation, rather than in the concrete grammar used in our implementation, and we have used `send` and `recv` rather than the actual function names.

The categories we chose are based on functional behavior. The first category, *message structure and data transfer*, includes rules that relate to the format, structure, and restrictions on messages in SSH2. The example rule requires that any prompt sent to keyboard interactive clients not be the empty string. The second category, *compatibility rules*, includes rules about backwards compatibility with SSH1. The example rule places a requirement on sending an identification string in compatibility mode. The third category, *functionality rules*, includes rules about what abilities should or should not be supported. The example rule requires that the implementation not allow the "none" authentication method.

Category	Example rule(s)	Description
Message structure and data transfer	recv(*in_sock*, *in*, _) *in.msgid* = *SSH_MSG_USERAUTH_REQUEST* *in.authtype* = *"keyboard-interactive"* ⇒ send(*out_sock*, *out*, _) *in_sock* = *out_sock* *out.msgid* = *SSH_MSG_USERAUTH_INFO_REQUEST* *len*(*out.prompt*) > 0	In keyboard interactive authentication mode, the prompt field(s) [the server sends to the interactive client] MUST NOT be empty.
Compatibility	recv(*sock*, *in*, _) *in*[*len*(*in*) − 2] = *CR* *in*[*len*(*in*) − 1] = *LF* *connected*[*sock*] = 0 ⇒ send(*sock*, *out*, _) *out*[*len*(*out*) − 2] = *CR* *out*[*len*(*out*) − 1] = *LF* *connected*[*sock*] := 1	In compatibility mode, after receiving the client identification string, the server MUST NOT send any additional messages before its identification string. [Note: The message with the identity string is distinguished by ending in a CR/LF combination]
Functionality	recv(_, *in*, _) *in*[0] = *SSH_MSG_USERAUTH_REQUEST* *isOpen*[*in*[1..4]] = 1 *in*[21..25] = *"none"* ⇒ send(_, *out*, _) *out*[0] = *SSH_MSG_USERAUTH_FAILURE*	It is STRONGLY RECOMMENEDED that the "none" authentication method not be supported.
Protocol logic	recv(*in_sock*, *in*, _) *in*[0] = *SSH_MSG_GLOBAL_REQUEST* *in*[1..14] = *"tcpip-forward"* *in*[15] = 1 *in*[(*len*(*in*) − 4)..(*len*(*in*) − 1)] = 0 ⇒ send(*out_sock*, *out*, _) *in_sock* = *out_sock* *out*[0] = *SSH_MSG_REQUEST_SUCCESS*	The server MUST respond to a TCP/IP forwarding request in which the *wantreply* flag [byte 15] is set to 1 and the *port* [last 4 bytes] is set to 0 with a *SSH_MSG_REQUEST_SUCCESS* containing the forwarding port.
	recv(*in_sock*, *in*, _) *in*[0] = *SSH_MSG_GLOBAL_REQUEST* *in*[15] = 1 ⇒ send(*out_sock*, *out*, _) *in_sock* = *out_sock*	The server MUST respond to all global requests with the *wantreply* flag [byte 15] set to 1.

Figure 7: Categorization and example rules for the SSH2 protocols

The last category, *protocol logic rules*, contains the majority of the rules. These rules require that the proper response is sent for each received message. The first example rule requires that the server provide an adequate response to TCP/IP forwarding requests with a value of 0 for *port*. The second rule requires that the server replies to all global requests that have the *wantreply* flag set.

Based on our experience developing rules for SSH and RCP, we believe that the process does not require any specialized knowledge other than familiarity with the rule-based language grammar and the specification document. It took the authors less than 7 hours to develop each of our SSH2 and RCP specifications. The rules are generally slightly more complex than is shown in Figure 7, containing on average 11 facts in the hypothesis and 5 facts in the conclusion for LSH, and 9 facts for the hypothesis and 4 for the conclusion for RCP. Originally, we started with a rule set derived directly from specification documents, which was able to catch many but not all bugs, and then we added some additional rules (a little over 10% more per specification) to look for some specific known bugs (Section 4.4). These additional rules produced about 20% of the warnings from Pistachio. Generally, the rules written from the specification document tend to catch missing functionality and message format related problems, but are less likely to catch errors relating to compatibility problems or unsafe use of library functions. The process of extending the initial set of rules proved fairly easy, since specific information about the targeted bugs was available from the respective bug databases.

4.2 Results for Core Rule Sets

We started with initial specifications for the SSH2 protocols (87 rules) and the RCP protocol (51 rules), with "core rules" based only on specification documents. In Section 4.4 we discuss extending these rules to target particular bugs. Using these specifications, we ran our tool against several different versions of LSH, ranging from 0.1.3 to 2.0.1, and several different versions of RCP, ranging from 0.5.4 to 1.3.2. We used the same specification for all versions of the code, and we ran Pistachio with *max_pass* set to 75.

Version	0.1.3	0.2.1	0.2.9	0.9.1	1.0.1	1.1.1	1.2.1	1.3.1	1.4.1	1.5.1	1.5.5	2.0.1
Analyzed code size (lines)	8745	8954	9145	9267	9221	10431	10493	10221	12585	12599	12754	13689
Running time (s)	23.96	25.24	24.99	25.89	25.21	26.85	28.91	30.1	29.74	31.45	36.3	38.91
Bugs in database	91	83	69	65	81	80	82	82	51	40	31	13
Warnings from Pistachio	118	123	110	97	91	93	92	82	78	74	33	25
False positives	40	57	43	43	22	27	24	16	38	38	7	12
False negatives	5	5	3	4	3	3	2	2	1	1	0	1

(a) LSH implementations

Version	0.5.4	0.6.4	0.8.4	1.1.4	1.2.3	1.3.2
Analyzed code size (lines)	4501	4723	4813	4865	4891	5026
Running time (s)	16.13	18.34	19.13	18.56	21.65	25.43
Bugs in database	51	46	47	51	28	23
Warnings from Pistachio	73	89	58	70	48	39
False positives	30	30	17	25	27	19
False negatives	2	2	1	2	0	1

(b) RCP implementations

Figure 8: Analysis Results with Core Rule Sets

Figure 8 presents the results of our analysis. We list the lines of code (omitting comments and blank lines) analyzed by Pistachio. We only include code involved in the rules, e.g., we omit the bodies of functions our rules treat as opaque, such as cryptographic functions.

The third row contains the running time of our system. (The running times include the time for checking the core rules plus the additional rules discussed in the next section.) In all cases the running times were under one minute. The next four rows measure Pistachio's effectiveness. We list the number of bugs found in the project's bug database for that version and the number of warnings issued by Pistachio. We counted only bugs in the database that were reported for components covered by our specifications. For instance, we only include bugs in LSH's authentication and transport protocol code and not in its connection protocol code. We also did not include reports that appeared to be feature requests or other issues in our bug counts. The last two rows report the number of false positives (warnings that do not correspond to bugs in the code) and false negatives (bugs in the database we did not find).

We found that most of the warnings reported by Pistachio corresponded to bugs that were in the database. We also found two apparently new bugs in LSH version 2.0.1. The first involves a buffer overflow in buffers reserved for passing environment variables in the implementation of the SSH Transport protocol. The second involves an incorrectly formed authentication failure message when using PKI. We have not yet confirmed these bugs; we sent an email to the LSH mailing list with a report, but it appears that the project has not been maintained recently, and we did not receive a response.

```
// Code is extracted from a function handling connection initialization
......
1. fmsgrecv(clisock,inmsg,SSH2_MSG_SIZE);
2. if(!parse_message(MSGTYPE_PROTOVER,inmsg,len(inmsg),&protomsg))
3.     return;
......
4. if(protomsg.proto_ver < 1) {
5.     payload.msgid = SSH_DISCONNECT;
6.     payload.reason = SSH_DISCONNECT_PROTOCOL_ERROR;
......
7.     sz = pack_message(MSGTYPE_DISCONNECT,payload,
                         outmsg,SSH2_MSG_SIZE);
8. } else {
9.     sprintf(outstr,"%.1f%c%s%c%c",2,SP,SRV_COMMENTS,CR,LF);
10.    sz = pack_message(MSGTYPE_PROTOVER,outstr,
                         outmsg,SSH2_MSG_SIZE);
......
11. }
12. fmsgsend(clisock,outmsg,sz);
```

Figure 9: Sample compatibility bug

To determine whether a warning is a bug, we trace the fact derivation process in reverse, using logs produced by Pistachio that give *Out* for each analyzed statement. We start from a rule failure at a conclusion, and then examine the preceding statements to see whether they directly contradict those facts. If so, then we have found what we think is a bug, and we look in the bug database to judge whether we are correct. If the preceding statements do not directly contradict the facts, we continue tracing backward, using *Out* to help understand the results, until we either find a contradiction or reach the hypothesis, in which case we have found a false positive. If the conclusion pattern is not found on all program paths, we use the same process to determine why those paths were not pruned from the search during fact derivation.

As a concrete example of this process, consider the second rule in Figure 7. This rule is derived from sec-

tion 5 of the SSH2 Transport Protocol specification, and Pistachio reported that this rule was violated for LSH implementation 0.2.9, since it could not prove that $out[len(out) - 2] = CR$ and $out[len(out) - 1] = LF$ at a conclusion. Figure 9 shows the code (slightly simplified for readability) where the bug was reported. Statement 12 matches the conclusion pattern (here *fmsgsend* is a wrapper around *send*), and so that is where we begin. Statement 12 has two predecessors in the CFG, one for each branch of the conditional statement 4. Looking through the log, we determined that the required facts to show the conclusion were in $Out(10)$ but not in $Out(7)$. We examined statement 7, and observed that if it is executed (i.e., if the conditional statement 4 takes the true branch), then line 10 will send the a disconnect message, which is incorrect. Thus we backtracked to statement 4 and determined that *protomsg.proto_ver<1* could not be proved either true or false based on $In(4)$, which was correctly derived from the hypothesis (asserted in $Out(1)$). Thus we determined that we found a bug, in which the implementation could send an *SSH_DISCONNECT* message for clients with versions below 1.0, although the protocol specifies that the server must send the identification first, independently of the other party's version. We then confirmed this bug against the LSH bug database.

While it is non-trivial to determine whether the reports issued by Pistachio correspond to bugs, we found it was generally straightforward to follow the process described above. Usually the number of facts we were trying to trace was small (at most 2-3), and the number of preceding statements was also small (rarely larger than 2). In the vast majority of the cases, it took on the order of minutes to trace through a Pistachio warning, though in some cases it took up to an hour (often due to insufficiently specified library functions that produced many paths). In general, the effort required to understand a Pistachio warning is directly proportional to the complexity of the code making up a communication round.

Figure 10 gives a more detailed breakdown of our results on LSH version 1.2.1. We divide the warnings and bugs into five main categories. The categories mostly but do not completely correspond to those in Figure 7.

Functionality errors correspond to missing functionality for which the implementation does not degrade gracefully, or conversely, to additional functionality that should not be present. The vast majority of these bugs were found as violations of rules in the *functionality* category from Figure 7. For example, the third rule in Figure 7 detected a functionality bug in LSH version 0.1.3, for the code in Figure 11. In this case, a message is received at statement 2, and Pistachio assumes the rule hypothe-

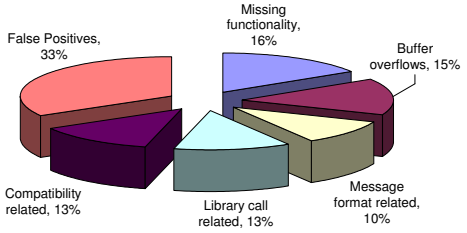


Figure 10: Error breakdown by type in LSH version 1.2.1

```
1. fmsgrecv(clisock,inmsg,SSH2_MSG_SIZE);
2. if(!parse_message(MSGTYPE_USERAUTHREQ,inmsg,len(inmsg),&authreq))
3.       return;
......
4. if(authreq.method==USERAUTH_PKI) {
......
5. } else if(authreq.method==USERAUTH_PASSWD) {
......
6. } else {
......
7. }
8. sz = pack_message(MSGTYPE_REQSUCCESS,payload,
                     outmsg,SSH2_MSG_SIZE);
9. fmsgsend(clisock,outmsg,sz);
```

Figure 11: Sample functionality bug

ses, which indicate that the message is a user authorization request. Then a success message is always sent in statement —but the rule specifies that the "none" authentication method must result in a failure response. Tracing back through the code, we discovered that the **else** statement on line 6 allows the "none" method to succeed. This statement should have checked for the "hostbased" authentication method, and indeed this corresponds to a bug in the LSH bug database.

Message format errors correspond to problems with certain message formats, and are found by violations of the *message format and data transfer* rules. For example, the first rule in Figure 7 detected a violation in LSH version 0.2.9 (code not shown due to lack of space). In this version of LSH, the server stores the string values of the possible prompts in an array terminated by the empty string. However, the implementation uses the array size and not the empty string terminator to determine the end of the array, which causes the implementation to potentially include the empty string terminator as one of the prompts, violating the rule.

Compatibility related errors correspond to problems in the implementation that cause it to work incorrectly with clients or servers that implement earlier versions of

```
0.  char laddr[17]; int lport;
. . . . . .
1. fmsgrecv(clisock,inmsg,SSH2_MSG_SIZE);
2. if(!parse_message(MSGTYPE_GLOBALREQ,inmsg,len(inmsg),&globreq))
3.     return;
. . . . . .
4. if(globreq.msgtype=MSGSUBTYPE_TCPIPFORWARD) {
5.     strcpy(laddr,getstrfield(globreq.payload,0));
6.     lport = getuint32field(globreq.payload,1);
. . . . . .
7.     if(!create_forwarding(clisock, laddr,lport))
8.       return debug_error();
9.     if((globreq.wantreply==1) && (lport == 0)) {
10.      payload.msgid = SSH_REQUEST_SUCCESS;
11.      payload.reason=lport;
12.      sz = pack_message(MSGTYPE_REQSUCCESS,payload,
                           outmsg,SSH2_MSG_SIZE);
13.      fmsgsend(clisock,outmsg,sz);
14.    }
15.}
```

Figure 12: Sample buffer overflow

the SSH protocol. These bugs correspond to violations of *compatibility* rules, and the earlier discussion of the code in Figure 9 illustrated one example.

Buffer overflows are detected by Pistachio indirectly during rule checking. Recall that when Pistachio sees a write to an array that it cannot prove is in-bounds, then it kills facts about the array. Thus sometimes when we investigated why a conclusion was not provable, we discovered it was due to an out-of-bounds write corresponding to a buffer overflow. For example, consider the code in Figure 12, which is taken from LSH version 0.9.1 (slightly simplified). While checking this code, we found a violation of the fourth rule in Figure 7, as follows. At statement 1, Pistachio assumes the hypothesis of this rule, including that the *wantreply* flag (corresponding to *in*[15]) is set, and that the message is for TCP forwarding. Under these assumptions, Pistachio reasons that the true branch of statement 4 is taken. But then line 5 performs a *strcpy* into laddr, which is a fixed-sized locally-allocated array. The function *getstrfield()* (not shown) extracts a string out of the received message, but that string may be more than 17 bytes. Thus at the call to *strcpy*, there may be a write outside the bounds of laddr, and so we kill facts about laddr. Then at statement 7, we call *create_forwarding()*, which expects laddr to be null-terminated—and since we do not know whether there is a null byte within laddr, Pistachio determines that *create_forwarding()* might return false, causing us to return from this code without executing the call to *fmsgsend* in statement 13.

In this case, if Pistachio had been able to reason at statement 5 that laddr was null-terminated, then it would not have issued a warning. Although the return statement 8 might seem be reachable in that case, looking inside of *create_forwarding()*, we find that can only occur

```
1. fmsgrecv(clisock,inmsg,SSH2_MSG_CHANNEL_REQUEST);
2. if(!parse_message(MSGTYPE_CHREQ,inmsg,len(inmsg),&chreq))
3.     return;
. . . . . .
4. if(chreq.msgtype==MSGSUBTYPE_SHELL) {
. . . . . .
      /* fmod was previously set to "rw" */
5.    if(!(clish = popen(make_clishell(clisock),fmod)))
6.       return debug_error();
. . . . . .
```

Figure 13: Sample library call bug

if LSH runs out of ports, and our model for library functions assumes that this never happens. (Even if an ill-formed address is passed to *create_forwarding()*, it still creates the forwarding for 0.0.0.0.) On the hand, if *create_forwarding()* had relied on the length of laddr, rather than it being null-terminated, then Pistachio would not have reported a warning here—even though there still would be a buffer overflow in that case. Thus the ability to detect buffer overflows in Pistachio is somewhat fragile, and it is a side effect of the analysis that they can be detected at all. Buffer overflows that do not result in rule violations, or that occur in code we do not analyze, will go unnoticed.

Library call errors correspond to unsafe use of library functions. These bugs are generally found the same ways buffer overflows are, as a side effect of rule checking. For example, Figure 13 contains code from LSH 0.9.1 that violated the last rule in Figure 7. In this case, we matched the hypothesis of the rule at statement 1, and then matched the request type at statement 2, and thus one possible path leads to the call to *popen* in statement 5. In this case, our model of *popen* requires that the second argument must be either "r" or "w," or the call to *popen* yields an undefined result. Since before statement 5 fmod was set to "rw," Pistachio assumes that *popen* may return any value, including null, and thus statement 6 may be executed and return without sending a reply message, thus violating the rule conclusion. Note that our model of *popen* always succeeds if valid arguments are passed, and thus if fmod were "r" or "w" a rule violation would not have been reported.

In addition to warnings that correspond to bugs, Pistachio also issues a number of false positives. Figure 14 breaks down the causes of false positives found in LSH, averaged over all versions. The main cause of false positives is insufficient specification of library calls. This is primarily due to the fact that library functions sometimes rely on external factors such as system state (e.g., whether *getenv()* returns NULL or not depends on which environment variables are defined) that cannot be fully

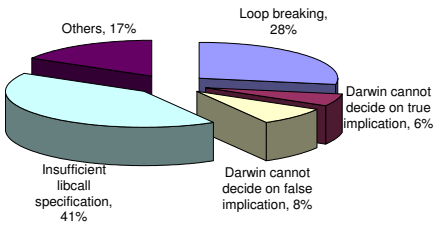


Figure 14: Causes for false positives in LSH

modeled using our rule-based semantics. For such functions, only partial specifications can be devised. The remaining false positives are due to limitations of the theorem prover and to loop breaking, where we halt iteration of our algorithm after *max_pass* times.

Besides false positives, Pistachio also has false negatives, as measured against the LSH and RCP bug databases. From our experience, these are generally caused by either assumptions made when modeling library calls, or by the fact that the rule sets are not complete. As an example of the first case, we generally make the simplifying assumption that on `open()` calls, there are sufficient file handles available. This caused a false negative for LSH version 0.1.3, where a misplaced `open()` call within a loop lead to the exhaustion of available handles for certain SSH global requests.

4.3 Security Implications

As can be seen from the previous discussion, many of the bugs found by Pistachio have obvious security implications. Even bugs that initially appear benign may introduce security vulnerabilities, depending on what constitutes a vulnerability in a particular circumstance. However, in order to measure our results we looked through the bug databases to identify which of the bugs are either clearly security-related by their nature or were documented as security-related. On average, we classified approximately 30% of the warnings (excluding false positives) as security-related for LSH and approximately 23% for RCP. Of these, buffer overflows account for approximately 53% of the security-related bugs. We consider all buffer overflows security-related. Access control warnings account for 20% of the total. These refer to the execution of functions for which the user does not have sufficient privileges. Finally, compatibility problems account for 18% of the total. These do not directly violate security, but do impede the use of a secure protocol. The remaining security-related bugs did not fall into any broader categories.

Our classification of bugs as security-related has some uncertainty, because the bug databases might incorrectly categorize some non-exploitable bugs as security holes. Conversely, some bugs that are not documented as being security-related might be exploitable by a sufficiently clever attacker. In general, any bug in a network protocol implementation is undesirable.

4.4 Results for Extended Rule Sets

In a second set of experiments, we were interested in estimating how easily the rule-based specification could be extended to catch specific bugs we found in the bug databases. Our goal was to study how Pistachio could be used during the development process. In particular, as a programmer finds bugs in their code, good software engineering practice is to write regression tests to catch the bug again if it appears in the future. In the same way, using Pistachio the programmer can write extra "regression rules" to re-run in the future.

We looked for bugs we missed using the core set of rules and added slightly over 10% more rules (9 new rules for LSH and 7 for RCP) to the initial specifications to cover most of the bugs. We found the rules we needed to add were typically for features that were strongly recommended but not required by the specification, because it turned out that violations of these recommendations were considered errors. One example is the recommendation that a proper disconnect message be sent by the SSH server when authentication fails.

Figure 15 shows the effect of the additional rules on the number of the errors detected. In each table we show the specific implementation version, the number of bugs in the database, the total number of warnings from Pistachio and the number of warnings generated from the 10% additional rules. The last two rows in each table in Figure 15 contain the number of false positives caused by the additional rules and the number of false negatives that remain after enriching the specification. We can see that the additional rules account for under 20% of the total number of warnings generated by Pistachio. From the set of new warnings produced by Pistachio after introducing the additional rules, approximately 18% had security implications according to our classification from Section 4.3, mostly related to access control issues and buffer overflows. Roughly half of the remaining false negatives are due to terminating iteration after *max_pass* times, and the other half are due to aspects of the protocol

Version	0.1.3	0.2.1	0.2.9	0.9.1	1.0.1	1.1.1	1.2.1	1.3.1	1.4.1	1.5.1	1.5.5	2.0.1
Bugs in database	91	83	69	65	81	80	82	82	51	40	31	13
Warnings from Pistachio	133	143	124	112	106	109	111	100	93	83	40	28
From 10% rules	15	20	14	15	15	16	19	18	15	8	7	3
False pos. from 10%	8	8	6	8	7	5	7	4	6	5	3	2
False neg. after 10%	1	0	1	0	2	0	0	0	1	0	1	0

(a) LSH implementations

Version	0.5.4	0.6.4	0.8.4	1.1.4	1.2.3	1.3.2
Bugs in database	51	46	47	51	28	23
Warnings from Pistachio	84	78	67	77	56	45
From 10% rules	11	9	10	7	8	6
False pos. from 10%	6	5	5	4	2	4
False neg. after 10%	1	1	1	0	1	0

(b) RCP implementations

Figure 15: Analysis Results for Extended Rule Sets

our new rules still did not cover.

For the extended rules, we also measured how often we are able to compute a symbolic fixpoint for loops during our analysis. Recall that if we stop iteration of our algorithm after *max_pass* times then we could introduce unsoundness, which accounts for approximately 27% of the false positives, as shown in Figure 14. We found that when *max_pass* is set to 75, we find a fixpoint before reaching *max_pass* in 250 out of 271 cases for LSH, and in 153 out of 164 cases for RCP. This suggests that our symbolic fixpoint computation is effective in practice.

5 Related Work

Understanding the safety and robustness of network protocols is recognized as an important research area, and the last decade has witnessed an emergence of many techniques for verifying protocols.

We are aware of only a few systems that, like Pistachio, directly check source code rather than abstract models of protocols. CMC [24] and VeriSoft [15] both model check C source code by running the code dynamically on hardware, and both have been used to check communication protocols. These systems execute the code in a simulated environment in which the model checker controls the execution and interleaving of processes, each of which represents a communication node. As the code runs, the model checker looks for invalid states that violate user-specified assertions, which are similar to the rules in Pistachio. CMC has been successfully used to check an implementation of the AODV routing protocol [24] and the Linux TCP/IP protocol [23].

There are two main drawbacks to these approaches. First, they potentially suffer from the standard state space explosion problem of model checking, because the number of program executions and interleavings is extremely large. This is typical when model checking is used for data dependent properties, and both CMC and VeriSoft use various techniques to limit their search. Second, these tools find errors only if they actually occur during execution, which depends on the number of simulated processes and on what search algorithm is used. Pistachio makes different tradeoffs. Because we start from a set of rules describing the protocol, we need only perform abstract interpretation on a single instance of the protocol rather than simulating multiple communication nodes, which improves performance. The set of rules can be refined over time to find known bugs and make sure that they do not appear again. We search for errors by program source path rather than directly in the dynamic execution space, which means that in the best case we are able to use symbolic information in the dataflow facts to compute fixpoints for loops, though in the worst case we unsafely cut off our search after *max_pass* iterations. Pistachio is also very fast, making it easy to use during the development process. On the other hand, Pistachio's rules cannot enforce the general kinds of temporal properties that model checking can. We believe that ultimately the CMC and VeriSoft approach and the Pistachio approach are complementary, and both provide increased assurance of the safety of a protocol implementation.

Other researchers have proposed static analysis systems that have been applied to protocol source code. MAGIC [7] extracts a finite model from a C program using various abstraction techniques and then verifies the model against the specification of the program. MAGIC has been successfully used to check an implementation of the SSL protocol. The SPIN [18] model checker has

been used to trace errors in data communication protocols, concurrent algorithms, and operating systems. It uses a high level language to specify system descriptions but also provides direct support for the use of embedded C code as part of model specifications. However, due to the state space explosion problem, neither SPIN nor MAGIC perform well when verifying data-driven properties of protocols, whereas Pistachio's rules are designed to include data modeling. Feamster and Balakrishnan [14] define a high-level model of the BGP routing protocol by abstracting its configuration. They use this model to build *rcc*, a static analysis tool that detects faults in the router configuration. Naumovich *et al.* [25] propose the FLAVERS tools, which uses dataflow analysis techniques to verify Ada pseudocode for communication protocols. Alur and Wang [2] formulate the problem of verifying a protocol implementation with respect to its standardized documentation as refinement checking. Implementation and specification models are manually extracted from the code and the RFC document and are compared against each other using reachability analysis. The method has been successfully applied to two popular network protocols, PPP and DHCP.

Many systems have been developed for verifying properties of abstract protocol specifications. In these systems the specification is written in a specialized language that usually hides some implementation details. These methods can perform powerful reasoning about protocols, and indeed one of the assumptions behind Pistachio is that the protocols we are checking code against are already well-understood, perhaps using such techniques. The main difficulty of checking abstract protocols is translating RFCs and other standards documents into the formalisms and in picking the right level of abstraction. $Mur\varphi$ is a system for checking protocols in which abstract rules can be extracted from actual C code [20]. The main differences between our approach and the $Mur\varphi$ system lies in how the rules are interpreted: in $Mur\varphi$ the rules are an abstraction of the system and are derived automatically, whereas in Pistachio rules specify the actual properties to be checked in the code. Uppaal [6] models systems (including network protocols) as timed automata, in which transitions between states are guarded by temporal conditions. This type of automata is very useful in checking security protocols that use time challenges and has been used extensively in the literature to that extent [28, 12]. In [12], Uppaal is used to model check the TLS handshake protocol. CTL model checking can also be used to check network protocols. In [9], an extension of the CTL semantics is used to model AODV.

Recently there has been significant research effort on developing static analysis tools for finding bugs in software. We list a few examples: SLAM [3] and BLAST [17] are model checking systems that have been used to find errors in device drivers. MOPS [8] uses model checking to check for security property violations, such as TOCTTOU bugs and improper usage of *setuid*. Metal [13] uses data flow analysis and has been used to find many errors in operating system code. ESP [11] uses data flow analysis and symbolic execution, and has been used to check sequences of I/O operations in gcc. All of these systems have been effective in practice, but do not reason about network protocol implementations, and it is unclear whether they can effectively check the kinds of data-dependent rules used by Pistachio.

Dynamic analysis can also be used to trace program executions, although we have not seen this technique used to check correctness of implementations. Gopalakrishna et al. [16] define an Inlined Automaton Model (IAM) that is flow- and context-sensitive and can be derived from source code using static analysis. The model is then used for online monitoring for intrusion detection.

Another approach to finding bugs in network protocols is online testing. Protocol fuzzers [27] are popular tools that look for vulnerabilities by feeding unexpected and possibly invalid data to a protocol stack. Because fuzzers can find hard-to-anticipate bugs, they can detect vulnerabilities that a Pistachio user might not think to write a rule for. On the other hand, the inherent randomness of fuzzers makes them hard to predict, and sometimes finding even a single bug with fuzzing may take a long time. Pistachio quickly checks for many different bugs based on a specification, and its determinism makes it easier to integrate in the software development process.

Our specification rules are similar to precondition/postcondition semantics usually found in software specification systems or design-by-contract systems like JML [19]. Similar constructs in other verification systems also include BLAST's event specifications [17].

6 Conclusion

We have defined a rule-based method for the specification of network protocols which closely mimics protocol descriptions in RFC or similar documents. We have then shown how static analysis techniques can be employed in checking protocol implementations against the rule-based specification and provided details about our experimental prototype, Pistachio. Our experimental results show that Pistachio is very fast and is able to detect a number of security-related errors in implementations of the SSH2 and RCP protocols, while maintaining low

rates of false positives and negatives.

Acknowledgements

This research was supported in part by NSF CCF-0346982 and CCF-0430118. We thank Mike Hicks, David Wagner, Nick Petroni, R. Sekar, and the anonymous reviewers for their helpful comments.

References

[1] A. V. Aho, R. Sethi, and J. D. Ullman. *Compilers: Principles, Techniques, and Tools*. Addison Wesley, 1988.

[2] R. Alur and B.-Y. Wang. Verifying network protocol implementations by symbolic refinement checking. In *Proceedings of International Conference on Computer-Aided Verification*, 2001.

[3] T. Ball and S. K. Rajamani. The SLAM Project: Debugging System Software via Static Analysis. In *Proceedings of POPL*, 2002.

[4] K. A. Bartlett, R. A. Scantlebury, and P. T. Wilkinson. A note on reliable full-duplex transmission over half-duplex links. *Communications of the ACM*, 12(5):260–261, 1969.

[5] P. Baumgartner, A. Fuchs, and C. Tinelli. Darwin: A Theorem Prover for the Model Evolution calculus. In *IJCAR Workshop on Empirically Successful First Order Reasoning*, 2004.

[6] J. Bengtsson, K. G. Larsen, F. Larsson, P. Pettersson, and W. Yi. UPPAAL - a Tool Suite for Automatic Verification of Real-Time Systems. In *Hybrid Systems*, pages 232–243, 1995.

[7] S. Chaki, E. Clarke, A. Groce, S. Jha, and H. Veith. Modular Verification of Software Components in C. In *Proceedings of the 25th International Conference on Software Engineering*, 2003.

[8] H. Chen and D. Wagner. MOPS: An Infrastructure for Examining Security Properties of Software. In *Proceedings of the 9th ACM Conference on Computer and Communications Security*, 2002.

[9] R. Corin, S. Etalle, P. H. Hartel, and A. Mader. Timed Model Checking of Security Protocols. In *Proceedings of the 2004 ACM Workshop on Formal Methods in Security Engineering*, 2004.

[10] P. Cousot and R. Cousot. Abstract Interpretation: A Unified Lattice Model for Static Analysis of Programs by Construction or Approximation of Fixpoints. In *Proceedings of the 4th Annual ACM SIGPLAN-SIGACT Symposium on Principles of Programming Languages*, pages 238–252, 1977.

[11] M. Das, S. Lerner, and M. Seigle. ESP: Path-Sensitive Program Verification in Polynomial Time. In *Proceedings of the 2002 ACM SIGPLAN Conference on Programming Language Design and Implementation*, pages 57–68, Berlin, Germany, June 2002.

[12] G. Diaz, F. Cuartero, V. Valero, and F. Pelayo. Automatic Verification of the TLS Handshake Protocol. In *Proceedings of the 2004 ACM Symposium on Applied Computing*, 2004.

[13] D. Engler, D. Y. Chen, S. Hallem, A. Chou, and B. Chelf. Bugs as Deviant Behavior: A General Approach to Inferring Errors in Systems Code. In *Proceedings of the 18th ACM Symposium on Operating Systems Principles*, Banff, Canada, Oct. 2001.

[14] N. Feamster and H. Balakrishnan. Detecting BGP Configuration Faults with Static Analysis. In *Proceedings of NSDI*, 2005.

[15] P. Godefroid. Model Checking for Programming Languages Using Verisoft. In *Proceedings of POPL*, 1997.

[16] R. Gopalakrishna, E. H. Spafford, and J. Vitek. Efficient intrusion detection using automaton inlining. In *Proceedings of the IEEE Symposium on Security and Privacy*, 2005.

[17] T. A. Henzinger, R. Jhala, R. Majumdar, and G. Sutre. Software Verification with BLAST. *Lecture Notes in Computer Science*, 2648:235–239, January 2003.

[18] G. J. Holzmann. The Model Checker SPIN. *Software Engineering*, 23(5):279–295, 1997.

[19] G. T. Leavens, K. R. M. Leino, E. Poll, C. Ruby, and B. Jacobs. JML: notations and tools supporting detailed design in Java. In *OOPSLA 2000 Companion*, 2000.

[20] D. Lie, A. Chou, D. Engler, and D. L. Dill. A Simple Method for Extracting Models for Protocol Code. In *Proceedings of the 28th Int'l Symposium on Computer Architecture*, 2001.

[21] A GNU implementation of the Secure Shell protocols. `http://www.lysator.liu.se/~nisse/lsh/`.

[22] N. Möller. lshd leaks fd:s to user shells, Jan. 2006. `http://lists.lysator.liu.se/pipermail/lsh-bugs/2006q1/000467.html`.

[23] M. Musuvathi and D. R. Engler. Model checking large network protocol implementations. In *Proceedings of NSDI*, 2004.

[24] M. Musuvathi, D. Y. W. Park, A. Chou, D. R. Engler, and D. L. Dill. CMC: A Pragmatic Approach to Model Checking Real Code. In *Proceedings of OSDI*, 2002.

[25] G. N. Naumovich, L. A. Clarke, and L. J. Osterweil. Verification of Communication Protocols Using Data Flow Analysis. In *Proceedings of the 4th ACM SIGSOFT Symposium on Foundations of Software Engineering*, 1996.

[26] G. C. Necula, S. McPeak, S. P. Rahul, and W. Weimer. CIL: Intermediate Language and Tools for Analysis and Transformation of C Programs. In *Proceedings of the 11th International Conference on Compiler Construction*, 2002.

[27] P. Oehlert. Violating assumptions with fuzzing. *IEEE Security & Privacy Magazine*, 3:58–62, 2005.

[28] S. Yang and J. S. Baras. Modeling Vulnerabilities of Ad Hoc Routing Protocols. In *Proceedings of the 1st ACM workshop on Security of Ad Hoc and Sensor Networks*, 2003.