**SPIDER: Enabling Fast Patch Propagation in Related Software Repositories**

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Abstract—Despite the effort of software maintainers, patches to open-source repositories are propagated from the main codebase to all the related projects (e.g., forks) with a significant delay. Previous work shows that this is true also for security patches, which represents a critical problem. Vulnerability databases, such as the CVE database, were born to speed-up the application of critical patches; however, patches associated with CVE entries (i.e., CVE patches) are still applied with a delay, and some security fixes lack the corresponding CVE entries. Because of this, project maintainers could miss security patches when upgrading software.

In this paper, we are the first to define safe patches (sp). An sp is a patch that does not disrupt the intended functionality of the program (on valid inputs), meaning that it can be applied with no testing; we argue that most security fixes fall into this category. Furthermore, we show a technique to identify sps, and implement SPIDER‡, a tool based on such a technique that works by analyzing the source code of the original and patched versions of a file. We performed a large-scale evaluation on 341,767 patches from 32 large and popular source code repositories as well as on 809 CVE patches. Results show that SPIDER was able to identify 67,408 sps and that most of the CVE patches are sps. In addition, SPIDER identified 2,278 patches that fix vulnerabilities lacking a CVE; 229 of these are still unmatched in different vendor kernels, which can be considered as potential unfixed vulnerabilities.

I. INTRODUCTION

The open-source software model revolutionized the software industry, and prior research shows that it is more secure [12], [33] than its closed-source counterpart. However, propagating changes and patches from the main repository of an open-source project to all the related projects (forks) is a major problem [66]. While related projects share a common “ancestry,” their code bases typically diverge over time, as different teams add different features and capabilities to each branch. As a result, when a problem is found and fixed in one branch, it is not always easy to directly apply this patch to another one [67]. For example, Android depends on a Linux kernel fork, and upgrading it with patches from the main kernel repository without thoroughly testing their effects could break Android.

To avoid this problem, and still be able to keep their software up-to-date, the maintainers of related projects need to carefully track other branches. When they see a fix that might be relevant for their codebase, they have to “cherry-pick” the patch: That is, they have to understand the patch and its behavior, adapt it to their own code base, and finally ensure that the whole system, after applying the patch, still works as expected. Not surprisingly, this is a manual and resource-intensive process [72], [17]. As a result, as shown in the Appendix D of our extended version [7], changes in the main code base of a project are usually applied to the code of dependent software with a significant delay [68]: Android 10, for example, is based on Linux kernel 4.19, while the latest release of the Linux kernel is version 5.3.8 [2].

This problem becomes critical when we consider security patches: in these cases, the fixes should propagate to all the codebases as soon as possible. Vulnerability databases such as the Common Vulnerabilities and Exposures (CVE) database were born to facilitate this process: project maintainers can take them as a reference to know which security-related patches they need to apply, without having to find them manually. Despite the existence of these databases, security patches still take a substantial amount of time to propagate to all the project forks [57], [53], [22], [41]. In the year 2016, the Android maintainers patched 76 publicly known vulnerabilities (i.e., CVEs) from the year 2014, two from 2013, and two from 2012, which means that 80 disclosed vulnerabilities remained unpatched in the Android code base for more than one year [1].

When this happens, maintainers of related projects are not aware that a patch actually addresses a security problem. This is a growing problem, as exemplified by the recent VLC security issue [16], which is caused because developers of libelmi failed to associate the corresponding security fix with a CVE ID [11], and the vulnerability existed for nearly two years after the fix was available. Unfortunately, hackers are known to scan source repository commits for fixes that might address vulnerabilities, and then check for the presence of these vulnerabilities in related repositories [74]. Therefore, the security fixes lacking a CVE ID provide a potential source of unfixed vulnerabilities as they are most likely not ported to related repositories.

Existing approaches that ease the process of cherry-picking relevant patches rely on commit-related information, such as code *diff* or commit messages [65], [76], [21], or they look for specific patterns [56]. These tools have the advantage of being fast, lightweight, scalable, and suitable to be used on large codebases. However, either they only match simple patches, or analyze commit messages, which are often not expressive enough to convey the scope and effect of a change [24], [69], [4]. Other techniques attempt to go a step further and analyze the semantic differences introduced by a patch using static analysis [44], [45], [25], [26], [64] and symbolic execution [52], [29], [62], [37]. Unfortunately, these techniques suffer from scalability issues. Moreover, some of these approaches also require the exact build environment [30] of the whole code base, restricting their practicality and applicability to complex software, such as the Linux kernel, the VLC player, the OpenBSD OS, etc., as these software have many possible configurations [12].

Intuitively, an ideal solution, which would help maintainers in selecting and applying important changes, would be a system that is capable of identifying those patches that do not affect the
intended functionality of the software. If the intended functionality of the software is not changed by a patch, this patch can be applied without the need for testing: we call these changes safe patches. In this paper, we argue that a significant portion of all security-related fixes falls under the category of safe patches [60]. Thus, a tool that can identify safe patches could be used to monitor the main repository and automatically alert or apply this kind of patches on a target forked repository. This observation is also confirmed by our anonymous survey (Appendix J) of maintainers and developers of various open-source software projects.

To be effective and usable on large codebases, a system to identify safe patches should at least satisfy the following requirements:

- **R1:** Only rely on the original and patched versions of the modified source code file, without any other additional information (e.g., commit message, build environment, etc.)
- **R2:** Be fast, lightweight and scalable.

In this work, we design and implement a static analysis approach that aims to identify safe patches and that satisfies both the requirements above. Our approach is designed specifically to target source code changes and to identify patches that could be applied with minimal testing, as they do not modify the program’s functionality. Specifically, we make the following contributions:

- We provide the first formal definition of safe patches, and design a general technique to identify them.
- We implement SPIDER, a system based on this technique, that takes as input only the source code of the original and patched file.
- We evaluate SPIDER on 341,767 commits taken from 32 source code repositories (Linux kernel repositories, Android kernel repositories, interpreters, firmware, utilities and various other repositories), as well as on 809 CVE patches.
- We identify 67,408 safe patches and show that SPIDER could help developers in the process of selecting and testing changes, resulting in a speed-up in the propagation of security fixes.
- We also provide the Security Patch mode of SPIDER that can precisely identify security patches. It identified 2,278 patches that most likely fix security vulnerabilities, despite the fact that they were not associated with any CVE entry. 229 of these issues are still unpatched in several kernel forks. As such, they can be considered unfixed vulnerabilities.
- We are releasing SPIDER and the corresponding git server-side hook configuration at github.com/usc-ssclab/spider.

Unlike previous work, our approach is the first that focuses on determining those patches that can be propagated to related projects with minimal effort, and without defining a priori specific types of changes or semantic characteristics that should be detected (i.e., we do not just target patches that fix a specific type of vulnerability). We envision our system to be part of the recently introduced Github forked repository. This observation is also confirmed by our anonymous survey (Appendix J) of maintainers and developers of various open-source software projects.

II. SAFE PATCHES

Our goal is to identify patches that can be applied without subsequent testing. We call such patches safe patches (sp).

Intuitively, for a patch to be considered an sp, it should satisfy the following two conditions:

- **Non-increasing input space (C1):** The patch should not increase the valid input space of the program. That is, the patched version should be more restrictive in the inputs that it accepts. The assumption is that some of inputs that the original program accepted resulted in security violations, and the patched version “removes” these inputs as invalid.
- **Output equivalence (C2):** For all the valid inputs that the patched program accepts, the output of the patched program must be the same as that of the original program.

The condition C1 ensures that there is no need to add new test cases, as there are no new inputs that are accepted by the patched program. Furthermore, the condition C2 ensures that there is no need to run the existing test cases as the output will be the same as that of the original program (for all the valid inputs). Consequently, if a patch satisfies the above two conditions then it can be applied without any effect on the existing test cases. Of course, the purpose of testing is to ensure that the program behaves as expected, so it is always a recommended step after applying a patch. In Section II-B, we define more formally the two conditions above.

A. Running Example

Listing 1 shows our running example, a C language example of a safe patch in the unified diff format (i.e., where + and − indicate inserted and deleted lines, respectively). In this example, the programmer decided that it was necessary to add an extra length check (Lines 3-5), presumably to protect against a buffer overflow later in the program. In addition, the patch also includes the length of the header (HDR) as part of a size check in Line 10.

This patch is safe. The inserted modifications to the variables len and tlen do not change the output of the function. Moreover, the extra conditional statement in Line 3 adds a missing length check, thereby restricting the input space. That is, all inputs where t->len is larger than MAX_LEN now lead to the function returning an error, while those inputs were accepted by the original function.

Figure 1 shows the control flow graph (CFG) after the application of this example patch: underlined text indicates the pieces of code inserted, while the left (blue) and right (red) children of each basic block are the true and false branches, respectively.

B. Formal Definition

We first define terminology used throughout the paper:

- **Input** i to a program: The input data with which the program is executed; f indicates the set of all the possible inputs to the program.
- **Function of a program:** The symbol f denotes the original function, and any subscript to it identifies its patched version. For example: f_p indicates the function f after applying the patch p.
- **Error-handling basic blocks:** The symbol BB_{err} denotes the basic blocks of a function that are part of its error-handling functionality. In Figure 1, BB_{err} is an

\footnote{However, for regression testing purposes, one may want to add a test case that checks that the inputs are indeed invalid and the corresponding security flaw is patched.}
error-handling basic block. We will explain later how error-handling basic blocks are identified.

- We use the notation \( i \rightarrow f \) to indicate that input \( i \) successfully executes through function \( f \). That is, starting from the entry basic block of \( f \), and given input \( i \), none of the error-handling basic blocks \( \{BB_{B_{err}}\} \) of \( f \) will be reached. In other words, \( i \) represent a valid input to the function \( f \).

- Output of a function: The output of a function \( f \) is its return value and all the externally visible changes to the program’s data. Specifically, the output includes the return value, all writes to heap and global variables, and the arguments to all function calls. For instance, the output of the function \( \text{get_read_size} \) in Listing 1 is its return value (line 19), and the value written to the pointer variable \( t \rightarrow \text{total} \) (line 17). Furthermore, \( \text{output}(i,f) \) indicates the output of the function \( f \) when run with input \( i \).

Now, we will use the definitions we introduced to formally define two conditions (\( C1 \) and \( C2 \)) introduced at the beginning of Section II.

1) Non-increasing input space (\( C1 \)): The non-increasing input space (\( C1 \)) condition requires that the patched program does not accept any inputs as valid that are not also accepted as valid by the original program. This condition can be defined at the granularity of functions; that is, for \( C1 \) to hold, we require that all patched functions, individually, do not accept any additional valid inputs. In other words, any valid input to a patched function must also be a valid input to the corresponding original function. More formally:

\[
\forall i \in I \ (i \rightarrow f_p) \rightarrow (i \rightarrow f) \quad \forall i \in I.
\]

In the case of Listing 1, the patch restricts the original input space by adding an additional constraint (i.e., \( t \rightarrow \text{len} > \text{MAX}_\text{LEN} \) in Line 3). As a result, all valid inputs to the patched program are also valid inputs to the original function (but not vice versa). This satisfies Equation 1.

2) Output correspondence (\( C2 \)): The output correspondence (\( C2 \)) condition requires that, for all valid inputs, the output of the patched program must be the same as the output of the original program. This condition, again, can be defined at the function granularity: For each patched function, for all corresponding valid inputs, the patched function must produce the same outputs as the original function. More formally:

\[
\forall i \in I \ (i \rightarrow f_p) \rightarrow (\text{output}(i,f_p) = \text{output}(i,f))
\]

In the case of Listing 1, although the patch inserts changes that modify the values of some variables (for example, \( \text{len} \)), the changes do not affect the externally visible data of the program, and thus, they do not change the output of the function, thereby satisfying Equation 2.

If all the patched functions satisfy both Equation 1 and Equation 2, then we can say that the patch satisfies the conditions \( C1 \) and \( C2 \). As a result, the patch can be considered as a safe patch (\( sp \)). Note that, as a trivial case, an empty patch \( (f_p = f) \) satisfies Equations 1 and 2, making it an \( sp \). Furthermore, there exist patches that do not satisfy the above conditions but still could be applied without testing, making our conditions sufficient but not necessary. We refer all the interested readers to Appendix A, where we explain our formalism with more examples.

III. IDENTIFYING SAFE PATCHES

In this section, we introduce a general technique to determine whether a given patch is an \( sp \).

A. Program Dependency Graph (PDG)

Our technique leverages the concept of a program dependency graph (PDG). A program dependency graph \( [36] \) captures both data and control dependencies in a single graph. Formally, the PDG of a function \( f \), denoted as \( PDG(f) = (V,C,D) \), is a directed graph where

- \( V = \{v_0, v_1, ..., v_n, E_n\} \) is a set of nodes, one for each instruction \( (v_n) \) of the function. The additional node, \( E_n \), represents the function entry.

- \( C \) is a set of directed, labeled edges, where each edge \( (v_i, v_j, T/F) \) represents the (direct) control dependency of \( v_j \) on \( v_i \). An instruction \( v_j \) is control-dependent on \( v_i \), and the edge is labeled as true \( (T) \) or false \( (F) \), when \( v_j \) is executed if and only if \( v_i \) evaluates to true \( \text{or false} \). To complete the PDG, if an instruction \( v \) is not control-dependent on any other instruction in the function (in other words, it does not have any incoming control flow edges), we connect it to the function entry node \( (E_n) \). That is, we add the edge \( (E_n,v,T) \) to \( C \). Note that all source nodes of control-flow edges are either conditional statements \( (if, \text{while}, \text{etc.}) \) or the function entry node.
Control dependency versus control flow: The concept of control dependency is different from the more commonly-used concept of control flow. Control flow captures possible flows of execution, while control dependency captures the necessary conditions that must hold for the execution to reach a particular statement. We refer all the interested readers to Appendix B, where we explain this in detail.

Control-Dependency Path: Given a $PDG(f) = (V, D, C)$ of a function $f$, we say that a control dependency path exists from instruction $x \in V$ to instruction $y \in V$, denoted as $x \rightarrow_c y$, if there exists a path in the $PDG$ from $x$ to $y$ that only follows control-dependency edges. Formally,

$$x \rightarrow_c y = \{<x,v_1,v_2,\ldots,v_n,y> | v_i \in V \land (x,v_1) \in C \land (v_n,y) \in C \land \forall 1 \leq i < n(v_i,v_{i+1}) \in C\}.$$ 

In the $PDG$ shown in Figure 2b, there exists a control-dependency path (a path along solid edges) from instruction at Line 8 to the instruction at Line 19: $\{8, 15, 19\}$. We say that a given data-dependency path $x \rightarrow_d y = <x,v_1,v_2,\ldots,v_n,y>$ is complete if there is no data dependency path to $x$. Formally, $(v_i, x) \notin D$. The data dependency path example from Line 8 to 19 is complete as there is no data dependency path to Line 8.

Also, note that although a data dependency path exists from the instruction at Line 8 to instruction at Line 19, there is no control-dependency path between these instructions. This is because the execution of the instruction at Line 19 is not controlled by the instruction at Line 8.

B. The Spider Approach

Our system is given as input a patch $p$, with $f$ and $f'_p$ being a function before and after applying the patch, respectively. The technique to detect whether $p$ is a safe patch works in four steps, as outlined in the following four sections.

1) Checking modified instructions: We first need to identify what statements are affected by a patch, and determine whether these modifications can be soundly analyzed given our requirement R1. Recall that R1 requires that the analysis operates directly on the original and patched versions of the modified source code file, without any other additional information (e.g., commit message, build environment, etc.).

Affected Statements: A statement can be affected either directly or indirectly by the patch. We call a statement directly affected if it is modified, inserted, deleted, or moved by the patch. A statement is indirectly affected if it is either control- or data-dependent on any of the directly affected statements. Given the set of directly affected statements $A_d$ and the $PDG$ of the corresponding function, all the instructions reachable from the statements in $A_d$, either through control flow or data flow edges, are indirectly affected.

Consider the patch for our running example in Listing 1. Here, the directly affected statements are at Lines 3, 4, 8, and 15. However, looking at the corresponding $PDG$ in Figure 2b, we can see that all instructions are reachable from the node that corresponds to the instruction at Line 3. Consequently, all statements are affected by the patch.
Locally analyzable statement: We call a directly affected statement *locally analyzable* if all the writes made by the statement can be captured *without* any interprocedural and pointer analysis. Specifically, the modifications made by the patch should not involve any new function calls or pointer manipulation. Consider the patch represented by Listing 2: The inserted statement at Line 4 is locally analyzable. However, the inserted statement at Line 5 is not locally analyzable, because it involves a new function call.

If a patch has any directly affected statements that are not locally analyzable, we *do not* consider it an *sp*. This is because we cannot soundly analyze the affected statements without analyzing the effects on the whole program. Moreover, performing whole-program analysis requires a static analysis tool (like LLVM), which in turn, requires access to the sources of the entire program, violating our requirement *R1*.  

```
int kthread_init()
{
    ...
    - total_size = file->size;
    + total_size = header + file->size;
    + init_cleanup();
    ...
    if(total_size > MAX_SIZE) {
        ...
    }
    ...
}
```

Listing 2: Patch illustrating locally analyzable statements.

2) Error-handling basic blocks: In the next step, we need to identify all the error-handling basic blocks ($BB_{err}$) in $f$ and $f_p$, so that all the changes to the statements within $BB_{err}$ are discarded and not considered in the next steps. This decision is based on the assumption that any changes to error basic blocks do not disrupt the original functionality (i.e., they just result in better or adjusted error-handling). The remaining statements affected by $p$ are then analyzed to check if Equations 1 and 2 can be proved. We leverage previous work [42, 73] to identify error-handling basic blocks, as discussed in more detail in Section IV-D.

3) Non-increasing input space (C1): To verify the non-increasing input space condition (C1), we need to ensure that the patch does not accept more inputs than the original function. In other words, the patch must not increase the valid input space for the modified function.

Intuitively, if a patch does not affect any control-flow statements (such as if, while, for, etc.), then it cannot change the input space of the function. However, if a patch affects one or more control-flow statements, we must verify that no additional inputs can successfully execute through the function.

This can be done by first identifying the valid exit points (VEP) of a function. The valid exit points of a function are those instructions that, if reached during the execution of an input, imply that the input successfully executed through the function. For instance, in the case of our running example in Listing 1, the return tlen instruction at Line 19 is a valid exit point.

We consider all return statements as possible valid exit points. However, a function might exit because of an error (for instance, Line 4 in Listing 1), and the corresponding return statement does not represent a valid exit point. Hence, to identify the VEP set, we need to filter out all the return statements that are part of error basic blocks ($BB_{err}$).

In summary, to identify the VEP set of a function $f$ with $PDG(f) = (V,D,C)$, we need to find all the exit points of $f$, i.e., $E_{x}(f)$, and filter out all the return instructions that belong to error basic blocks. More formally:

$$VEP(f) = \{r \mid (r \in E_{x}(f)) \land (BB(r) \notin BB_{err}(f))\}.$$  

where $BB(r)$ indicates the basic block of instruction $r$.

To ensure that a patch satisfies condition C1, we need to verify that all inputs that go through the valid exit points, i.e., $VEP$ of the patched function $f_p$, also go through the valid exit points of the original function $f$.

We observe that, in order for an input $i$ to be successfully executed by a function, the input must satisfy the path constraint (PC) of a valid exit point. Thus, all the inputs that are accepted as valid by a function, which we denote as $vinputs(f)$, are the union of all the inputs that satisfy the path constraints for *at least* one valid exit point. More formally, the constraints on the inputs that are successfully executed by the function $f$ are captured by the following disjunction:

$$vinputs(f) = \bigcup_{i \in VEP(f)} (PC(i)).$$  

If we have $vinputs(f_p) \rightarrow vinputs(f)$, which shows that all the inputs that can be successfully executed by the patched function $f_p$ are also successfully executed by the original function $f$, we have succeeded in proving condition C1.

For our running example in Listing 1, with the PDG of the patched function in Figure 2b, the valid exit point is at Line 19 (return tlen). By following the solid edges backwards and computing the path constraints for the patched function, we obtain $vinputs(f_p) = ((E_n \equiv T) \land (t \rightarrow ~ len > MAX_LEN \equiv F))$. For the original function, whose PDG is in Figure 2a, we obtain $vinputs(f) = (E_n \equiv T)$. We can easily see that $vinputs(f_p) \rightarrow vinputs(f)$, thus satisfying C1.

To perform this step, we use symbolic interpretation to convert the C language statements into symbolic expressions (as discussed in more detail below). Then, we prove the implications between the two symbolic expressions using a SAT solver [34] (more details are provided in Section IV-E).

4) Output equivalence (C2): To verify the output equivalence condition (C2), we need to verify that all externally visible changes (as described in Section II-B) in the patched function are the same as that of the original one. Specifically, we want to ensure that for any input that successfully executes through the patched and original function, the output of the two functions will be identical.

We first look at all the affected (non-control-flow) statements. First, we discard all the statements that modify local variables. While local variables can have an indirect effect on a function’s output (which we take into account, as explained below), the local variables themselves are not externally visible. Thus, we do not need to consider them in this step. In the next step, we need to verify that all the updates (writes) to non-local (global and pointer) variables, function call arguments, and return values in the patched function are the same as that of the original function. In other words, we aim to prove that all global and pointer variables have the same values after the patched function has executed (compared to the original function), the patched function returns the same value, and it calls the same functions with the same arguments (and in the same order). When we are able to prove this, we are sure that, for every valid input, the patch does not change the externally visible effect of executing this function.
Given a statement \( t \), we need to show that for all (valid) inputs that reach \( t \) in the patched and the original function, their outputs will be the same. More formally:

\[
\forall i \in I \{i \mapsto t_p\} \Rightarrow (\text{output}(t_p) = \text{output}(t))
\]

The output value of a statement depends on the values of the inputs (input variables). Consider, for example, the statement \( c = a + b \). Here, the output is assigned to the variable \( c \), and the value depends on the inputs \( a \) and \( b \). We can determine where these inputs come from by looking at the data-dependency graph for the statement. Of course, the inputs for a statement could come from multiple data-dependency paths. Consider again the PDG in Figure 2b. For the statement at Line 15, there are two complete data dependency paths: \(<8,15>\) and \(<8,11,15>\). The execution can take two different paths to reach this line, based on whether the function input satisfies the constraint on Line 10 or not.

For a given statement \( t \), and for each data-dependency path to this statement, we compute a symbolic expression for the possible output values (along these paths). The idea is that the union of the symbolic expressions (overall data-dependency paths) for \( t \) are the same for the patched function as for the original one. While this intuitively makes sense, there is one additional consideration. It is not enough to ensure that just the symbolic expressions are the same; they need to be the same under the same path constraints. Thus, we need to extend the symbolic expressions with their corresponding path constraints. We refer to these extended symbolic expressions as symbolic output-constraint pairs, which are computed as described hereinafter.

For a given statement \( t \) in a function \( f \) and the corresponding PDG \( (V, D, C) \), we can compute the output-constraint pairs from all the complete data dependency paths to \( t \). For each such path, we compute an output-constraint pair as:

\[
\Psi_s = (\text{interpret}(<x_1, x_2, ..., x_n, t>), \bigwedge_{1 \leq i \leq n} PC(x_i)).
\]

where interpret represents the symbolic expression that is computed by interpreting each of the instructions in sequence, and \( PC(\bullet) \) is the path constraint of the corresponding instruction in the PDG.

Let \( \Psi_s(t) \) and \( \Psi(t) \) be the symbolic output-constraint pairs for the statement \( t \) in the patched and original function, respectively. We say that the output of statement \( t \) is equivalent in the original and the patched function, denoted as \( \Psi_s(t) \equiv \Psi(t) \), if the following equation holds:

\[
\forall (o_x, c_x) \in \Psi_p(v) : \exists (o_y, c_y) \in \Psi(v) : (o_x == o_y) \land (c_x \rightarrow c_y).
\]

Note that \( o_\bullet \) are not concrete values but rather symbolic values.

It is possible that there is an infinite number of data dependency paths that lead to a statement. This happens when there are loops or cyclic dependencies in the data dependency graph (for example, when a value is updated inside the body of a loop and later used by an affected statement). We will show in Section IV-E how we resolve cycles in the data dependency graph. We will further argue that our approach is safe for a subset of instances, and we only consider these cases as safe patches.

Consider how we verify that condition C2 holds for our running example in Listing 1: The affected statements are at Lines 3, 8, 10, 11, 15, 17, and 19. Recall that we only consider non-control-flow statements. Thus, we can remove Line 3 and 10 from further consideration. Next, we can discard all statements that write to local variables, which removes Lines 8, 11, and 15. We end up with the statements at Lines 17 and 19, which write to a non-local variable through a pointer and return a value, respectively.

Looking at the PDG for the patched function (in Figure 2b), we see that there exist two complete data dependency paths for Line 17: \(<8, 15, 17>\) and \(<8, 11, 15, 17>\). The symbolic interpretation steps for both paths is shown in Table I. For every path, we first initialize each of the variables with a unique symbol, and then start interpreting each instruction according to its semantics. The symbolic output with corresponding path constraints along the path \(<8, 15, 17>\) is \((o_1, c_1) = (t->total = sym2(\text{En} == T) \land (\text{sym2} > \text{sym3}) \Rightarrow F) \land (((\text{sym2}+4)\%2) \neq 0 == F))\). For the path \(<8, 11, 15, 17>\), the result is \((u_2, c_2) = (t->total = sym2 + sym5, (\text{En} == T) \land (\text{sym2} > \text{sym3}) \Rightarrow F) \land (((\text{sym2}+4)\%2) \neq 0 == T))\).

For interpreting the original function, we start with the same initial symbols for the same variables that were used in the patched function. From the original function’s PDG in Figure 2a, for Line 17, there are also two data dependency paths: \(<7, 14, 17>\) and \(<7, 11, 14, 17>\). The symbolic output along with the corresponding path constraints are \((o_1, c_1) = (t->total = sym2, (\text{En} == T) \land (((\text{sym2}+2)\%2) \neq 0 == F))\) and \((u_2, c_2) = (t->total = sym2 + sym5, (\text{En} == T) \land (((\text{sym2}+2)\%2) \neq 0 == T))\).

We can see that \( o_1 \equiv o_2 \land o_p \rightarrow c_1 \) and \( u_2 \equiv u_p \land u_p \rightarrow c_2 \). Hence, Equation 4 holds.

Similarly, we can show that the output at Line 19 is equivalent in both the patched and the original function. As a result, our system has verified that the patch satisfies condition C2, and the patch is safe. For a patch that affects multiple functions, the steps described above are performed for each function.

IV. SPIDER: DESIGN AND IMPLEMENTATION

In this section we show the details of SPIDER, a tool, that satisfies our requirements R1 and R2, uses the approach described in Section III to analyze a given C source code patch and determine if it is an sp. The steps that SPIDER performs are detailed in the remaining part of this section.

A. Preprocessing

SPIDER starts by handling the C preprocessor directives. File inclusions (i.e., #include) are ignored, since as a requirement we do not want to collect information outside of the two input source code files. Macro definitions are ignored as well: macro calls will be treated as regular function calls, as explained later. The system then uses the unifdef tool to handle conditional code inclusion directives (e.g., #ifdef, #ifndef, etc.): the output of unifdef is a valid C source file, without any of these constructs. Note that this step could exclude certain code segments. Section V explains this in detail. This first step outputs two C source files ready to be parsed.

B. Parsing

The preprocessed source files are parsed using the Jœrn [77] fuzzy parser, which provides an Abstract Syntax Tree (AST) for all the functions in the file. Although Jœrn also provides a Control Flow Graph (CFG), with nodes linked to the ones in the AST, we had to modify it to suite our needs. Specifically, we had to implement the reaching definitions analysis [58], simple type inference [63], control dependency analysis [18], and, finally, program dependency graph [36]. At the end of this phase, SPIDER has access to the AST, CFG, and PDG for each of the functions affected by the patch.
C. Fine-grained diff

SPIDER uses function names to pair the functions in the original file with the corresponding ones in the new files, assuming patches that insert, delete, or rename one or more functions not to be file with the corresponding ones in the new files, assuming patches.

The ASTs are also associated to the corresponding nodes in the CFG. Gumtree maps the nodes that insert, delete, or rename one or more functions not to be considered to be an error-handling basic block if it satisfies any of the following conditions:

- If BB forces the function to return a constant negative value or a C standard error code (i.e., one of the constant symbols defined in errno.h, e.g., EINVVAL) prepended by a minus sign or NULL. For this, we do a basic reaching definition analysis and check that all paths through the basic block reach a function exit that returns a constant negative value or a C standard error code. This is based on the observation that functions use negative integers or values in errno.h or NULL to indicate error conditions. For the CFG of our running example in Figure 1, we detect BB2 as an error-handling basic block as it causes the function to return a negative integer (return -1). Similarly, in Figure 3, BB2 causes the function to return the value of the variable ret, which is a negative integer (-1) set in BB1. Hence, BB2 will be considered as a BBerr.

- If BB ends in a direct jump (a goto) to a label that might indicate an error condition. We maintain a set of 15 error-related labels (e.g., panic, error, fatal, err), and we check if the BB ends with a goto error-related-label; statement. We derived our labels from an existing survey [14] and our experience in working with system code. This is based on the observation that most of the system code, especially operating system kernels [15], use goto to handle error conditions [6], [14]. In Figure 3, BB3 has the goto error; statement, and since err is one of our labels, BB3 will be considered as a BBerr. Note that, BB3 also satisfies the first condition, similar to BB2, as it can also cause the function to return a negative integer.

Unlike the work by Tian et al. [73], we do not consider the post-dominators of a BBerr to be BBerr's, thus, in Figure 3, the post-dominoators of the error-handling basic blocks BB2 and BB3 (BB5 and BB6, respectively) will not be considered as BBerr's. This conservative approach improves precision by avoiding certain basic blocks to be wrongly identified as BBerr's (such as BB6). However, we may miss certain error-handling basic blocks (BB5). Note that, our approach for improving the precision by missing potential error-handling basic blocks is safe. We refer all the interested readers to Appendix K where we explain this in detail.

Table I: Symbolic interpretation of the data-dependency path <8,15,17> and <8,11,15,17> of the PDG in Figure 2b.

<table>
<thead>
<tr>
<th>Current Statement</th>
<th>Symbolic State</th>
<th>Output</th>
</tr>
</thead>
<tbody>
<tr>
<td>8: len = t-&gt;len + 4</td>
<td>len = sym2 + sym5, t-&gt;len = sym2, MAX_LEN = sym3</td>
<td>t-&gt;len = sym2 + sym5</td>
</tr>
<tr>
<td>15: tlen = len - 4</td>
<td>tlen = sym5 + sym6, DEF_SIZE = sym5, t-&gt;total = sym6</td>
<td>t-&gt;total = sym2</td>
</tr>
<tr>
<td>17: t-&gt;total = tlen</td>
<td>tlen = sym2 + sym5, t-&gt;total = sym5, MAX_LEN = sym5</td>
<td>t-&gt;total = sym2</td>
</tr>
</tbody>
</table>

Fig. 3: Control flow annotated listing where the greyed out blocks, i.e., BB2 and BB3, represent the error-handling basic blocks identified by our approach.

D. Identification of error-handling basic blocks

We use a technique similar to the ones proposed in the works by Kang et al. [42] and Tian et al. [73] in order to identify error-handling basic blocks.
To check that our error-block detection approach is accurate, we randomly sampled 100 patches, and we verified that all the error basic blocks that we identified are indeed valid $BB_{err,s}$.

As explained in Section III, SPIDER discards all changes that happen within the identified $BB_{err,s}$. In Appendix I, we run SPIDER in “not ignoring mode” (NoEB), in which we do not ignore changes within $BB_{err,s}$ and show that the detection rate does not materially change (a 0.79% decrease; see, (Default - NoEB) in Table IV). This result shows that discarding the changes within error-handling basic blocks does not significantly influence the effectiveness of SPIDER.

### E. Patch Analysis

In the remaining part of this section, we explain how SPIDER identifies $sp$s based on the general technique described in Section III.

Given the $PDG$, we remove all the data-dependency and control-dependency cycles in the $PDG$ by removing all the back edges [23]. Given a statement $t$, we consider an edge to be a back edge if it is originated from a statement that is dominated by $t$ in the $PDG$. We provide more details in Appendix F, and argue that this technique is safe, if the patch does not contain any directly affected statements within a loop. However, if a patch directly modifies any statements within the loop this may not be safe, as proving the condition $C2$ becomes undecidable [46]. To be safe, a patch that directly modifies a statement within a loop will not be considered as an $sp$.

Using the diff-annotated CFG of the patched function, first we find all the directly affected statements. As explained in Section III, these are the statements that are directly modified by the patch.

Second, given the $PDG$, we follow the edges from the nodes corresponding to the directly affected statements to identify all the statements that are reachable, which represent the indirectly affected statements. The union of the directly and indirectly affected statements is our total affected statements. As mentioned in Section III, we ignore the affected statements that belong to the error-handling basic blocks ($BB_{err,s}$).

### Verifying non-increasing input space (C1):

To verify condition C1, we first check if any of the affected statements is a conditional statement. By the definition of $PDG$ (Section III-A), these are the nodes that have an outgoing control dependency (solid) edge.

If there are affected conditional statements, then we find all the valid exit points, i.e., the valid return statements (or VEP). For each statement in the VEP, we identify the conditional statements that are part of the path constraint by following the solid edges backward until $E_n$.

Given a path constraint, we convert each of the conditional in the path constraint into a symbolic expression. As explained in Section III-B4, we start by initializing each of the variables with unique symbolic values in the original and patched function. Therefore, if a variable is not modified by the patch, it will have the same symbolic value in both the original and patched functions.

**Conversion to symbolic expression:** For a statement to be converted into symbolic expression, its data dependencies need to be first converted to symbolic expressions as well.

Therefore, given a statement $s$, we first check if it has any incoming data dependency edges, if this is the case, we go to the parent and try to repeat this process backward in a breadth-first manner until we find all the nodes with no incoming data dependency edges, i.e., the nodes from which all the data-dependency paths are complete (Section III-A).

We call the nodes with no incoming data dependency edges as free nodes. We first convert each of the free nodes into symbolic values by following the corresponding instruction semantics (as shown in Table I).

We then forward-propagate the values from the free nodes to the statements along the data dependency edges until we reach $s$.

To interpret function calls, we create a new symbolic value based on the hash of the function name and the symbolic values of its arguments. For instance, for the call strncpy(buf), we create a symbolic value with name equal to hash(strlen, sym(buf)), where sym(buf) is the symbolic value of the variable buf.

When multiple definitions of a variable reach an instruction, we use conditional symbolic variables based on the path constraint of the stricter path. For a variable $x$, if two definitions $d_1$ and $d_2$ from statements $v_1$ and $v_2$, respectively, reach a statement $v_3$. Then the symbolic value of $x$ at $v_3$ would be:

\[
v_3(x) = \begin{cases} 
Ite(PC(v_1), d_1, d_2) & \text{if } PC(v_1) \rightarrow PC(v_2) \\
Ite(PC(v_2), d_2, d_1) & \text{otherwise} 
\end{cases}
\]  

(5)

Where $Ite(c, a, b)$ represents an if-then-else symbolic value, which dictates to use the value $a$ if $c$ is satisfiable else $b$, $PC$ is the path constraint, and, from the rules of implication, $PC(c_1) \rightarrow PC(c_2)$ indicates that $PC(c_1)$ is a stricter condition than $PC(c_2)$. The Equation 5 correctly handles multiple definitions. We refer all the interested readers to Appendix H, where we explain this in detail.

Consider the statement at line 7 in the $PDG$ of Figure 4. Here, multiple definitions of the variable $total_mem$ reach line 7, i.e., from line 3 and 5. By using the initial symbolic values, for $strlen(buf) = sym1$, msg->len = sym2, MIN = sym3, and MAXMEM = sym4. The definitions of $total_mem$ at line 3 and 5 are $sym1 + sym2$ and $sym1 + sym3$, respectively. The path constraint for line 3 and 5 are $PC(3) = (En==T)$ and $PC(5) = (En==F)$.

```
1: max_len = strlen(buf);
2: + max_len = strlen(buf) + msg->len;
3: total_mem = max_len;
4: if (max_len < MIN) {
5: total_mem = MIN;
6: }
7: if (total_mem >= MAXMEM) {
8: return EINVAL;
9: }
10: return send_msg(msg, buf);
```

Listing 3: Patch affecting the control-flow of a function.
$PC(5) = (\text{(En==T)} \land ((\text{sym1} + \text{sym2}) < \text{sym3}))$, respectively. We can see that $PC(5) \rightarrow PC(3)$, as $PC(5)$ is a stricter condition, consequently the symbolic value of total_mem at line 7 will be: $Ite(PC(5), \text{sym3},(\text{sym1} + \text{sym2}))$.

The symbolic expression for the path constraint of the valid return (line 10) in the patched function from the PDG of Figure 4 would be $\left(E_n = R \land (Ite(PC(5), \text{sym3},(\text{sym1} + \text{sym2})) \geq \text{sym4})\right)$, for brevity we did not expand $PC(5)$, but the actual symbolic expression would be only in terms of initial symbolic values.

Following the steps described above, we convert the path constraints of each of the valid returns in the patched function to symbolic expressions. Then we obtain Equation 3 by the disjunction of the symbolic expressions. Finally, we convert the disjuncted symbolic expression into a Z3 [34] expression, i.e., $vinputs(f_p)$ (see Section III-B3).

We follow the same steps in the original function to compute $vinputs(f)$, then, using the Z3 tool once again, we verify the implication $vinputs(f_p) \rightarrow vinputs(f)$, thus proving that the patch satisfies condition C1.

Verifying output equivalence (C2): Given the list of affected non-control-flow statements, as explained in Section III-B4, we only consider the statements that update the non-local state of the function, i.e., the function output.

Consider the patch in Listing 1, where, although all the statements are affected by the patch, the only statements of interest are at line 17 and 19, as they update the heap and return value.

As explained in Section III-B4 and shown in Table I, we compute the symbolic expressions along each complete data dependency path along with the corresponding path constraints.

Finally, we convert the symbolic expressions into Z3 expression and verify Equation 4 using Z3. This verifies that the function affected by the patch satisfies condition C2. Note that the patch showed in Listing 3 changes only local variables and thus the output of the function remains the same as that of the original function for all valid inputs, thus satisfying condition C2.

We follow the above steps for each of the functions modified by the patch. We consider a patch to be a safe patch, only when C1 and C2 can be proved by following the steps described above.

Handling library functions: As explained in Section III, we consider patches that have only locally analyzable statements, i.e., patches that do not directly affect function calls and pointers. However, we noticed that there are certain library functions, whose effects can be easily summarized. Such as, memset. There are other print and logging library functions, like printf and printk, that do not affect the output of the patched function.

To handle this, we maintain a few categories of commonly used, well-known library functions (see Appendix G), whose effects can be either summarized or ignored.

V. Assumptions

Our implementation as specified in Section IV-E tries to guarantee that a patch is a safe patch. However, a careful reader might have noticed that there are certain assumptions made by our implementation. In this section, we explicitly describe the assumptions in our implementation:

Non-alias dependencies: As explained in Section IV-E, we use a PDG based on variables to compute all the affected statements. However, this ignores the data dependencies that could happen through pointers [19]. Handling this requires precise pointer analysis, which in turn require access to the whole program violating our requirement R1.

Pure functions: We consider all functions to be pure functions [75], i.e., the output of a function only depends on the input arguments. In other words, multiple calls to a function with the same arguments results in the same output. Furthermore, reordering function calls without any change to the arguments will also be treated as equivalent. That is, $f_1(\text{arg1}); f_2(\text{arg2})$ is equivalent to $f_2(\text{arg2}); f_1(\text{arg1})$. However, there could exist impure functions, whose output could also depend on the global state of the program. Soundly detecting whether a function is impure requires analyzing the function and its callees, which is not scalable and requires resolving function pointers.

Conditional compilation: The preprocessor conditional code directs (e.g., #ifdef, #ifndef, #else, etc.) allow different pieces of code to be be compiled depending on the values of certain preprocessor variables. We use the unifdef tool to handle these conditional compilation directives. unifdef attempts to obtain maximal code by enabling all preprocessor variables. However, for #ifdef- #else constructs, to be consistent, it has to select the code either under the if or the else directive. This could result in certain statements in the patch (which are controlled by preprocessor variables) to be invisible to SPIDER, and, in turn, this could lead to false positives. Handling conditional code compilation precisely requires analyzing the patch under all possible values of preprocessor variables and their combinations. This is not scalable for large codebases like the Linux kernel. To handle this, we allow users to enable the no preprocessor mode (NoPP). In NoPP mode, any patch that affects statements controlled by preprocessor variables will not be considered as an sp. We show in Appendix I that in NoPP mode, the detection rate of SPIDER does not vary much (a decrease of 1.15%, see (Default - NoPP) in Table IV). Furthermore, we also allow the user to specify the values of preprocessor variables, which can be used to get the correct source file instead of the conservative NoPP mode.

We consider the limitations above to be fundamental implications of our requirements R1 and R2. Nonetheless, we believe that our system provides a reasonable approach to identify safe patches. Moreover, if these assumptions are considered too strong, it is always possible to fall back to the more conservative Security Patch (SeP) mode (see Section VI for details). Finally, it is also possible to use our system to rank patches and prioritize those identified as safe for manually vetting (and testing).

VI. Security Patch mode

As explained in Section I, there could exist security patches without a corresponding CVE entry. To verify this, we have a configuration of SPIDER called Security Patch (SeP) mode that identifies security patches with no false positives, i.e., all the patches identified by this configuration are indeed security patches. SeP is based on the intuition that most of the security patches add additional input validation checks. Therefore, in SeP mode, we restrict ourselves to safe patches that affect only control-flow statements. Furthermore, when the commit message is available, we use the technique proposed by Zhou et al. [79] to filter out non-security related fixes. However, there can be false negatives, that is, potential security patches not detected as such.

Note that while SeP mode is more limited in the patches that it considers safe, it does not rely on any of the assumptions discussed.
in Section V. We believe that SeP mode of SPIDER is the first step towards a practical solution of automatically identifying security patches that could be easily integrated into any source-control system. We plan to integrate SeP mode of SPIDER into GitHub security alerts [8], which helps both the developers and maintainers to handle security patches. Note that our running example (shown in Listing 1), although being a security patch, is not detected by the SeP mode because it also affects non-control flow instructions.

VII. Evaluation

We evaluate the effectiveness of SPIDER in three different ways. First, we run it on a large dataset of 341,767 changes (i.e., commits) spanning over 32 repositories, collected from the year 2016 for a total of 32 months, in order to understand if it actually detects sps, according to our definition (see Section VII-A). Second, we run SPIDER on a set of security patches (i.e., CVE patching commits) to evaluate the usefulness of this tool in speeding the propagation of these critical fixes. Third, in Section VII-D, we show a way to use the SeP mode of SPIDER as a vulnerability finding tool by identifying non-CVE security patches that are missing in various active forks of the analyzed projects. Finally, we show in Section VII-E, that there are several non-CVE security patches in the Linux kernel and many of these are still unpatched, at the time of writing, on some of its Android-related forks: this provides real examples where SPIDER can be useful in fixing potential n-day vulnerabilities.

The analysis that SPIDER performs, described in Section IV, is an intra-procedural static analysis that does not consider the interaction between different modified functions. For this reason, to isolate the effect of these interactions that represent a possible confounding factor, we evaluate SPIDER only on patches that affect a single C source file (i.e., .c format only). All the patches studied in our evaluation are real changes extracted from repositories of widely used open-source projects (see Section VII-A for more details).

Performance: On average SPIDER took 3.4 seconds to analyze a patch on a machine equipped with a two-core 2.40 GHz CPU, and 8GB RAM, demonstrating its speed and scalability.

Active forks: We noticed that most of the forks of repositories are inactive or dead, i.e., there are no new commits made to the repository since they are forked. Considering such inactive forks could exaggerate our results, and, therefore, we considered only active forks. We consider a fork to be active if it has at least ten new commits in the last six months, and using this filter, we were able to eliminate a number of forks. For instance, in the case of Linux kernel (ID 1), we consider only 269 active forks out of 23,854 forks.

A. Large-scale evaluation

We ran SPIDER on a large set of patches: we selected 32 open-source projects widely used by desktop, mobile, and embedded operating systems, and we collected from each of them all the single-C-file commits for the past 32 months from the time of writing (considering merges as single commits). All the details of the projects are shown in Table II.

B. Effectiveness of patch analysis

Table II also shows the number of sps identified by SPIDER in the dataset. Over the total 341,767 commits studied, SPIDER identified 67,408 (19.72%) safe patches (Column 6). Furthermore, 58.72% of these patches are missing in at least one of the active forks (MIAFs).

Checking for patch applicability: We use the following syntactic approach to identify whether a patch of a project is applicable to (or missing from) a fork or other projects. Given a patch, we extract the affected file’s source code before the patch (i.e., original file) and compare it to the latest version of the corresponding file in the fork. If the file is present in the fork and all the functions affected by the patch do not differ between the original file of the patch and the corresponding latest file in the fork, then it means that the patch can be applied to the fork. To perform the comparison, we use the git diff tool, and check that there are no modifications in the targeted functions.

It is interesting to note that, across all repositories, the percentage of sps mostly stays around 20%-25%, without much variation. There are certain projects where the percentage of detected sps is low, such as IDs 15 and 16. This low detection rate is mainly because of the inherently complex code and patches. We refer all the interested readers to Appendix C, where we explain this in detail.

Listing 6 shows a patch identified as an sp, where the patch modifies error basic blocks, which are ignored. Also, the patch moves certain function calls Py_INCREF and Py_DECREF. However, as the arguments to these calls (i.e., dll and ftuple) are not modified by the patch, the symbolic expressions of the arguments are proved to be equivalent by Z3, resulting in the patch being considered an sp. We show a few other sps in Appendix E.

Looking at these results, we argue that SPIDER would be helpful for project maintainers and could be directly used to port the fixes or to prioritize the changes that must be ported.

C. Evaluation on CVEs

We wanted to determine how many security patches are indeed sps, as claimed in Section I. To this end, we collected all the patching commits linked as reference fixes for kernels CVEs from the Android security bulletins [1], and, similar to the large-scale evaluation, we studied only the CVEs that patch a single C file. We also collected all the CVEs for the remaining repositories over the same amount of time. This resulted in the analysis of 809 CVE patches.

Table III shows the results obtained after running SPIDER on these patches, which show that 55.37% of the CVE-patching commits are non-disruptive, while on generic patches (i.e., Table II) the percentage was 19.72%. This finding shows that SPIDER could be useful not only to speed-up the process of selecting and applying a significant number of changes (as shown in Section VII-A) but also to apply more than half of the security patches in a faster way.

Listing 5 shows an example of CVE patching commit from Android security bulletin identified as a sp by SPIDER. Listing 5 is also one of the CVEs that we mentioned in Section I, which was patched in Android more than a year after the appearance of the corresponding entry in the database.

Looking at Table III, it is interesting to see that SPIDER performed relatively well with more than 50% success rate in all but OpenSSL and VLC CVEs. This is because the security fixes in these software packages are complex. More details can be found in Appendix D.

D. Security patches missing a CVE number

We used SPIDER in SeP mode on all the commits to identify security patches. We then checked if these patches have an associated CVE number. Listing 6 and 4 show examples of security patches missing CVE entries, which are detected by the SeP mode of SPIDER.
<table>
<thead>
<tr>
<th>ID</th>
<th>Linux Kernels</th>
<th>Android Kernels</th>
<th>Bootloader and Firmware</th>
<th>Trusted Operating Systems</th>
<th>OpenBSD</th>
<th>Windows Compatible OS</th>
<th>Interpreters</th>
<th>Graphical Subsystems</th>
<th>Multimedia</th>
<th>Distributed Databases</th>
<th>Utilities</th>
<th>Libraries</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Linux kernel mainline</td>
<td>Qualcomm MsM Android kernel</td>
<td>LK Embedded Kernel</td>
<td>nautilus-Gnome default graphical subsystem</td>
<td>OpenBSD</td>
<td>reactos-Open Source Windows Compatible OS</td>
<td>Python Interpreter</td>
<td>VLC Player</td>
<td>redis-In memory Database</td>
<td>Tmux-Terminal Multiplexer</td>
<td>libpng-PNG reference library</td>
<td></td>
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<tr>
<td>2</td>
<td>Linaro ARM Linux kernel</td>
<td>NVIDIA Tegra Android kernel</td>
<td>winfile-Windows File Manager</td>
<td>OpenVPN-Open source VPN daemon</td>
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<td>PHP Interpreter</td>
<td>FFmpeg-multimedia processing tools</td>
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<td>3</td>
<td>Raspberry Pi Linux kernel</td>
<td>Xiaomi Android kernel</td>
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**TABLE II**: Overall results of our large-scale evaluation. Active forks are computed for only GitHub hosted projects. The percentage for Total sps is over commits for the corresponding projects. MIAFs are percentage over total sps and non-CVE commits that are missing in at least one active fork.
The last two columns of Table II shows the complete results: Overall, SPIDER identified 2,278 security patches across all the repositories. After manual verification, we found these results to be correct. This shows that CVE IDs are not always used for security patches, and that relying on them is not an effective way to secure related repositories. The number of patches identified by the SeP mode is smaller compared to the total number of sps (i.e., 2,278 ≤ 67,408). This is because the SeP mode, as explained in Section VI, imposes strict requirements. Nonetheless, the SeP mode identified 2,278 security patches missing a CVE number.

Furthermore, 60.71% of these patches are missing in at least one of the active forks denoted as MIAFs. This is alarming, as these cases reveal unpatched security vulnerabilities in the forks, which could be exploited by a motivated attacker monitoring the patches. We observed a considerable number of patches (for example see Listing 10), where the commit message contains the vulnerability-triggering input, further reducing the effort for the attacker.

E. Missing patches in vendor kernels

To identify missing patches in vendor kernels, we check how many of the Linux Kernel mainline commits identified as sps still have to be applied to one or more of the eight vendor kernel repositories that we studied (i.e., projects 2 - 9 in Table II), at the time of writing. To do that, given a commit identified as an sp, we extract the affected file’s source code before the change, and we compare it to the same file, if present, in all the listed kernel repositories (Table II show the git branch or tag that we studied) using the git diff technique described in Section VII-B.

The stripe bars in Figure 5 shows the percentage of missing sps in different vendor kernels. We found that 9.427 of the 20,171 Linux kernel identified sps (i.e., 46.74%) are still not applied in at least one of the considered vendor kernels. A significant portion of these changes not considered useful by the maintainers (e.g., removals of unused code, small refactoring, etc.), and therefore, not imported. However, we found out that 297 of them are CVE patching commits (i.e., the ones that we linked to the corresponding CVEs, as shown in Section VII-C) that still have to be imported by the maintainers of some repositories: this supports the findings of previous studies [57], [53], [22], [41] that report that vulnerability databases are not always effective in speeding the propagation of security fixes.

Unified vulnerabilities in vendor kernels: We also checked the security patches (which do not have a CVE number) identified by the SeP mode in the Linux Kernel mainline that still have to be applied to one or more of the eight Linux Kernel repositories that we studied (i.e., projects 2 - 9 in Table II). The plain bars in Figure 5 show the percentage of missing non-CVE security patches in different vendor kernels. There are in total 229 security patches that do not have a corresponding CVE number and are missing on different kernel repositories, including the ARM Linux kernel main repository (i.e., project 2 in Table II): these can be seen as potential unfixed or n-day vulnerabilities. Given their potential severity, we manually verified them to assess their impact. For a few of these vulnerabilities, the impact is less severe because of the variation in kernel configurations. However, we found several missing patches

```
Listing 5: Real integer overflow patch identified as sp by SPIDER
(CVE-2014-9795 from July 2016 Android security bulletin).

```
in critical components like netfilter, which applies to all kernel configurations. The snippet of a non-CVE security patch that is missing in the msm kernel (ID 4) is shown in Listing 11, this patch, as mentioned before also contains the triggering input.

We are in the process of reporting all of these patches to the corresponding project maintainers and vendors, and submit all the necessary requests for CVEs.

VIII. LIMITATIONS

Along with the assumptions described in Section V, SPIDER comes with several limitations. Specifically,

Small patches: As we can see from Figure 6, the majority (57.1%) of the patches detected as sps are small (0-5 lines). Furthermore, SPIDER cannot verify patches that modify statements within a loop. These limitations are mainly because SPIDER tries to verify a patch to be safe in a sound way. We believe it is important to have a system with no false positives, that provides stronger guarantees, and that can be used by the maintainers safely.

Syntactic approach for patch applicability check: We use a syntactic approach to check for patch applicability in the related repositories. However, a patch although syntactically applicable to a file in a project may not be semantically applicable because the condition fixed by the patch could be impossible to occur in the project [40]. This limitation is induced by our requirement R1, as checking for semantic applicability of patches require sound static analysis techniques which require build environment and access to all source files, thus violating our requirement R1.

Heuristic approach for error-handling basic blocks detection: As explained in Section IV-D, we use a heuristic approach to identify error-handling basic blocks. However, these heuristics may not hold for other projects resulting in cases where a basic block matching our heuristics is not a true error-handling basic block. Consequently, we could have unsafe patches being identified as safe. To handle this, we provide the NoEB mode of SPIDER (Appendix I) where we do not ignore the changes in the error-handling basic blocks. This mode provides a safer version of SPIDER, albeit with a slight decrease in detection rate.

Susceptible to adversarial evasion: As a consequence of our assumptions (Section V), SPIDER is susceptible to adversarial evasion. For instance, as we treat macros as function calls, an adversarial developer or contributor could use macro calls to make SPIDER consider otherwise safe patches as unsafe. However, as we explained in Section I, the main use case of SPIDER is for developers and maintainers. Furthermore, we assume developers to be non-malicious users who want to ensure that their applications are as secure as possible.

Tool dependencies: The current implementation of SPIDER works only on C source code; however, the parser that we use should be easily extensible to other languages. The fine-grained diff step is language agnostic, thus, to extend the tool to other languages, we would only need to add language-specific heuristics and preprocessing. A good solution would be to have a configurable front end for different languages, similar to LLVM [47]. As our implementation is based on Joern and Gumtree, we also share the same limitations that these tools have.

IX. RELATED WORK

Source code changes and patches as research topics received a lot of attention in the past decade. This section covers a comprehensive portion of prior work on these topics (Section I already covered state-of-the-art code analysis techniques that were used in the field, thus they will not be covered here).

Vulnerability finding and exploitation: In Section VII-E we show how SPIDER can be used to find instances of unpatched code starting from the identified sps, including vulnerabilities. Finding unpatched code clones is the focus of most of the prior research on patches in the security field [50], [41], [49]. In this work, we do not look for code clones but for instances where the function affected by a patch is still equal to the unpatched version. Brumley et al. [28], instead, show how to generate exploits for a vulnerability starting from the corresponding patch.

Easing the patching process: Prior research has been very active in designing approaches and building tools to ease and speedup the process of patching [59], [71], [20]. However, most of these techniques target only specific bug classes [55]. Other studies concentrate on helping developers in applying systematic changes [78], [54]. Long et al. [51], in contrast with the previously mentioned studies, use machine learning to model correct code and generate generic defects fixes, but do not focus on propagating existing patches as we do in this study. Similar to what we do in this work, Kreutzer et al. [43] use AST differencing on changes to extract metrics to help cluster the changes by similarity.

Software evolution: Mining software repositories is a well-known technique to gain insights into the dynamics of software evolution [39], [38]. Perl et al. [61] built VCCFinder, a tool that leverages code metrics and patch features (e.g., keywords in commits) to identify vulnerability-contributing changes. However, in this work, we do not rely on the commit messages, and, instead perform a systematic analysis of the patches.

X. CONCLUSION AND FUTURE WORK

In this work, we designed, implemented, and evaluated SPIDER, a fast and lightweight tool (R2) based on our sp identification approach that can determine if a patch is safe using only the original and the patched source code of the affected file (R1), without the need for external information (e.g., build environment, commit message, etc.). Our large-scale evaluation on 341,767 commits extracted from 32 different open-source repositories, and on 809 CVE patches, demonstrates the effectiveness of SPIDER, and shows that a significant amount of security patches could have been automatically identified (i.e., 55.37%). Furthermore, we show how the SeP mode of SPIDER can be used to find unpatched security issues.

ACKNOWLEDGEMENTS

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REFERENCES


We manually checked a few of these large patches and verified that we ignore all the updates to local variables as they are not part of our conditions as explained in Section III. Investigation, we found certain interesting things, the patch changes the third argument to the function as shown in Listing 9, which removes a seemingly useless functionality as shown in Listing 7 is an sp.

A. Shortcomings of the sp formalism

According to our definition in Section II-B, a patch that removes all the functionality as shown in Listing 7 is an sp. This is because none of the inputs execute through the program or in other words all the inputs will end up in an error basic block. Equation 1 and 2 trivially hold as for all the inputs (i→fp) evaluates to false. We ignore all the updates to local variables as they are not part of the function output. Consider the patch as shown in Listing 9, which removes a seemingly useless memset. This is valid and commonly known as dead-store elimination [32]. However, on closer inspection, one can recognize that the memset may be required as it would potentially clean up some secret data to avoid information leaks. Our current definition of sp does not handle these cases.

Listing 7: A patch that removes all the functionalities

```c
int main(int argc, char **argv) {
    if (argc > 0) { return -1; }
    ...
}
```

Listing 8: Snippet from a sp patch (532c34b5bf1687df63b3fd5b2846312ac943c6) from mainline linux kernel (ID 1) that violates Equation 2.

```c
int decrypt(...) { char secret_buff[4096]; ...
    memset(secret_buff, 0, sizeof(secret_buff));
}
```

Listing 9: A non-CVE security patch (commit 4e7REDACTED) in FFmpeg (ID 21) that has triggering input in the commit message.

1) Patch sizes: The plot in Figure 6 shows the distribution of the size of the studied commits as well as those that SPIDER identified as sps. One can see that 42.9% of the patches identified as sps (i.e., 28,873 of them) affect more than five lines of code (the affected lines are the sum of the lines added and deleted according to the git difftool), and 5.6% of the patches affect more than 20 lines of code. We manually checked a few of these large patches and verified that these are in fact sps. Most of these patches fix a simple issue across multiple functions, resulting in large amounts of affected lines.

2) False negatives: One can imagine that SPIDER could have false negatives i.e., it could classify certain patches as non-sps where as they were in reality sp. This is not a major problem, as finding all sps is not the goal of SPIDER. However, during our manual investigation, we found certain interesting sps patches which violate our conditions as explained in Section III.

Listing 8 shows a patch which fixes a memory leak and ideally is an sp but does not satisfy the Equation 2. Here, among other things, the patch changes the third argument to the function copy_from_user to PAGE_SIZE (line 2) from sccb->length (line 10). Since we consider the arguments to a call to be the output of a function, the patch in Listing 8 changes the output of the function and thus will not be considered as a sp. However, a careful analysis of the patched function along with an understanding of the behavior of function copy_from_user would clarify that this patch doesn’t affect the output (for all valid inputs) and hence is a sp. In fact, this patch is a security fix for CVE-2016-6130.

```c
Listing 8: Snippet
```
B. Control dependency versus control flow

The concept of control dependency is different from the more commonly-used concept of control flow. Control flow captures possible flows of execution, while control dependency captures the necessary conditions that must hold for the execution to reach a particular statement. Consider the PDG of the patched function in Figure 2b. We can see a control dependency edge from the node (that corresponds to the instruction) at Line 3 to Line 15 with label F. This means that the condition at Line 3 must evaluate to false for the execution to reach Line 15. This is correct because if the condition at Line 3 evaluates to true, then the execution will immediately return from the function (Line 4). On the other hand, consider the control-flow graph of the patched function in Figure 1. There is no direct edge from BB1 (that contains Line 3) to BB5 (that contains Line 15). This is because the execution does not flow directly from BB1 to BB5 as there are other instructions in between (in BB3 and BB4).

C. Reasons for low detection rate of sps

There are certain projects where the percentage of detected sps is low, such as IDs 15 and 16. After manual investigation of the subset of these patches, we found the following reasons:

**Complex code:** There are certain projects that mostly contain complex functions with data-dependencies inside nested loops. Specifically, the Python (ID 15) and PHP (ID 16) interpreters, and cURL (ID 24). Here, although the patches themselves are simple, the data dependencies increase the complexity of constraints, resulting in SPIDER failing to prove implication for the condition \( C1 \) (Section III-B3) resulting in a smaller sp detection rate.

**Complex patches:** In projects such as libpng (ID 30) and, OpenVPN (ID 28), the commits tend to be complex as they deal with media file formats and cryptographic protocols. Consequently, SPIDER fails to prove the equivalence for the condition \( C2 \).

D. Patches fixing cryptographic issues

Most of the CVEs in OpenSSL fix security issues related to cryptographic operations that affect the control flow in complex ways. A few OpenSSL CVEs fix cryptographic implementations against time side-channel attacks, which SPIDER is unable to reason about. For instance, the commit hash ae50d8270026edf5b3c7f8aaa0 c6677462b33d97 [13] for CVE-2016-0703 of the OpenSSL repository fixes SSLv2 implementation against the Bleichenbacher [27] attack. We fail to identify this as an sp because the changes do not satisfy our definition of sp (refer Section II-B).

E. Examples of sps

The Listing 12 shows a patch identified as sp, in this case, the patch just adds an error basic block through a case statement, satisfying conditions \( C1 \) and \( C2 \), as the valid input space (matching the case statement) is restricted, and the function output does not change for the valid inputs. Listing 13 shows a commit in Redis identified as an sp, where there are no conditions affected (condition \( C1 \) holds) and changes are made only to a local variable thus not affecting the function output (condition \( C2 \) holds).

Listing 12: An sp identified in OPTEE (commit 388302877d413) where the changes just add an error basic block.

```python
int HelloRepl1_ReplCommand (RedisModu
... RedisModuleCallReply *reply ;
... reply = RedisModule_Call (ctx, "INCR", "c!", "foo");
+ RedisModule_Call (ctx, "INCR", "c!", "foo");
... reply = RedisModule_Call (ctx, "INCR", "c!", "bar");
+ RedisModule_Call (ctx, "INCR", "c!", "bar");
RedisModule_ReplyWithLongLong (ctx , 0)
return REDISMODULE_OK;
```

Listing 13: An sp identified in Redis (commit 6798736909b7) where the changes are only to local variables and do not affect the output of the function.

F. Removing back edges in the PDG

In this section, we argue that removing back-edges is safe when a patch does not directly modify a statement within a loop.

In principle, removing back-edges in the PDG unrolls [31] the corresponding loop once. The symbolic expression of the values computed inside the loop will be as if the loop is executed once.

If the output of the function does not depend on the number of iterations of a loop then unrolling the loop once or multiple times does not affect our output equivalence checking, and hence it is safe.

As explained in Section III-B4, we use symbolic expressions (Table 1) to check the output equivalence of the functions. Now, consider the case where the output of the function depends on the number of iterations of a loop, and the symbolic expressions of the output are same in the original and the patched function. This means that the number of iterations of the loop will be the same in the original and patched function, and consequently, the output should be the same.

Hence, our approach of removing the back-edges and using symbolic expressions for output equivalence checking is safe when a patch does not directly modify a statement within a loop. However, if the patch directly modifies a statement within a loop, the removal of the back-edges prevents the back-propagation of this information resulting in computation of potentially wrong symbolic output-constraint pairs, thus is not safe.

---

**TABLE IV:** The summary of the number and percentage of sps detected by running SPIDER in various modes across all the projects listed in Table II. Detailed break down across each of the projects can be found in Table IV of our extended version [7].

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<tr>
<td>Total across all projects</td>
<td>341,767</td>
<td>64,682 (18.93%)</td>
<td>63,463 (18.57%)</td>
<td>60,378 (17.81%)</td>
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G. Summarizing library functions

As mentioned in Section IV-E, we maintain a list of well-known library functions which could be easily summarized. The categories of the function are:

- Print and logging functions (e.g., printf (without the \%n format specifier), printk), we ignore its affects as they are used for logging.
- Memory initialization and release functions (e.g., kmemset, memset, kfree, free), are considered as writes to the corresponding variables.
- Kernel synchronization function calls (e.g., spin_lock, spin_unlock, mutex_lock, mutex_unlock). Similar to the logging functions, these do not affect the output. However, improperly used synchronization functions could cause deadlocks. To avoid this, we need to check that any \_lock or \_unlock function should have corresponding \_unlock or \_lock respectively. To do this, for any inserted \_lock or \_unlock function in a basic block BB, we check that there exists corresponding \_unlock or \_lock function in one of the post-dominator or pre-dominator basic blocks of BB respectively.
- C security-sensitive function calls (e.g., strcpy, strncpy, strlcpy, memcp, sprintf, sscanf and their variants). We model these as assignments. For instance, the call strcpy(dst, src) will be treated as the assignment dst=src.

H. Handling multiple definitions

In principle, there are two basic cases when multiple definitions of a variable can reach a statement. We show in this section that both of the cases are handled by our Equation 5.

The first case is shown below. In this case, the definitions at both line 1 or 3 can reach the statement at line 5:

1. \( v = d_1; \)
2. \( \text{if}(c) \{ \)
3. \( \quad v = d_2; \)
4. \( \} \)
5. \( y = v + x; \)

All the executions that reach line 3 should have executed line 1. In other words, line 3 is guarded by a stricter condition. Furthermore, if the constraint represented by the condition \( c \) is satisfied, then the value defined at line 3 (i.e., \( d_2 \)) will reach line 5. This is captured by the first case of the Equation 5.

Consider the second case, where the definitions at line 2 or 3 can reach line 6:

1. \( \text{if}(c) \{ \)
2. \( \quad v = d_1; \)
3. \( \} \) else \( \{ \)
4. \( \quad v = d_2; \)
5. \( \} \)
6. \( y = v + x; \)

In this case, both statements are mutually exclusive, and, depending on whether the constraint represented by the condition \( c \) is true or false, the definitions at line 2 or line 4 reach line 6. This is captured by the second case of the Equation 5.

I. Impact of our assumptions

Although SPIDER tries to be sound in detecting \( sps \), it has a few assumptions (Section V) and uses heuristics (Section IV-D) which may not be desirable for certain users. In this section, we evaluate the effectiveness of our technique when each of these assumptions or heuristics is disabled. Specifically, we run SPIDER in following modes:

- \( NoEB \): As explained in Section IV-D, we ignore the affected statements that are part of a error-handling basic block (\( BB_{\text{err}} \)). The \( BB_{\text{err}} \)s are detected using certain heuristics that may not hold for certain projects. Incorrect identification of \( BB_{\text{err}} \)s might cause certain non-safe patches to be wrongly classified as \( sps \). In \( NoEB \) mode, we \( do not \) ignore any affected statements and analyze all the statements even if they belong to an \( BB_{\text{err}} \).
- \( NoPP \): We use the tool \texttt{unifdef} to handle preprocessor directives. However, as explained in Section V, this could cause some code to ignored if it is part of a \#if-then-else construct. In \( NoPP \) mode, if a patch affects a function which has any code controlled by a preprocessor directive it will \( not \) be considered as a \( sp \).

Table IV shows the overall effectiveness of SPIDER across all the projects with each of these modes turned on. The detection rate did not vary much across the projects. The detailed breakdown for each project is provided in Table IV of our extended version [7]. The column \( NoEB \cup NoPP \) shows the results when both the modes are enabled. We also show the effectiveness when all of these modes are turned off, i.e., the Default mode. The detection rate does not vary much across all the modes, which shows that the effectiveness of the techniques used by SPIDER does not largely depend on the assumptions and heuristics.

J. Anonymous survey on the requirement of SPIDER

To get a feeling for the utility of a tool like SPIDER, we performed an anonymous survey of maintainers and developers of various open-source software projects, including Ubuntu, OpenUSE, Linaro, OpenBSD, and VLC. 82% of those who completed the survey (32 out of 39 participants) agreed that such a tool would be very useful, and they were prepared to use it for their projects. Interestingly, only OpenBSD developers (the remaining 7 participants) expressed concerns, as such a system might also propagate bug-inducing patches like Apple’s goto fail [3], but they agree that it could still help expert developers to prioritize their efforts. This anonymous survey is exempted from IRB approval [9], as there is no collection or use of user private information.

K. Impact of not identifying all error-handling basic blocks

It is important to observe that the risky mistakes are those where we (incorrectly) identify non-error basic blocks as error blocks. In such cases, we could falsely identify a patch as an \( sp \). It is much less problematic or safer to misidentify an error-handling block as a non-error-handling block. The reason is that such a mistake might cause our system to analyze more statements than necessary which could result in discarding a safe patch as unsafe, but it does not introduce unsafe patches as safe. Thus, we consider our approach safely conservative.