TREKER: Tracing Error Propagation in Operating System Kernels

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***Abstract*—Modern operating systems (OSs) consist of numerous interacting components, many of which are developed and maintained independently of one another. In monolithic systems, the boundaries of and interfaces between such components are not strictly enforced at runtime. Therefore, faults in individual components may directly affect other parts of the system in various ways. Software fault injection (SFI) is a testing technique to assess the resilience of a software system in the presence of faulty components. Unfortunately, SFI tests of OSs are inconclusive if they do not lead to observable failures, as corruptions of the internal software state may not be visible at its interfaces and, yet, affect the subsequent execution of the OS beyond the duration of the test.**

In this paper we present TREKER, a fully automated approach for identifying how faulty OS components affect other parts of the system. TREKER combines static and dynamic analyses to achieve efficient tracing on the granularity of memory accesses. We demonstrate TREKER's ability to support SFI oracles by accurately tracing the effects of faults injected into three widely used Linux kernel modules.

***Index Terms*—Software Fault Injection, Robustness Testing, Test Oracles, Execution Tracing, Operating Systems**

I. INTRODUCTION

Complex modern software systems[1] generally consist of many interacting components. In larger systems, these components may be developed or maintained by different teams of developers and may differ in numerous aspects, including code quality and the amount of residual faults. In order to assess the resilience of the overall system, it is necessary to understand how it is affected by individual faulty components, a condition named *error propagation* in the Laprie taxonomy [1]. For this purpose, *software fault injection* (SFI), the deliberate introduction of faults in specific components to simulate their behavior in the presence of residual software faults, is an established approach [2]–[4].

In SFI tests, the *system under test (SUT)* is exposed to erroneous behavior of a component it is interacting with, the *injection target*. These fault injections are similar to mutations for mutation testing, but commonly based on different assumptions regarding the types and distributions of the introduced faults (see [5], [6] for an overview of common fault assumptions in either application). After the injection, interactions between the SUT and the injection target are triggered by a test *workload*. To assess error propagation from the injection target to the SUT, the behavior of the SUT is observed while it is processing the workload to identify behavioral deviations in response to the injection. Unfortunately, oracles of this type are generally insufficient to make any conclusions whenever no such behavioral deviations are observed. In such cases it is unknown whether the fault (1) has not been activated, (2) has been activated, but its effects have not propagated to the user interface, or (3) does generally not affect the system behavior.

[1]We will refer to software systems in the sense of software compositions from separately developed and compilable modules as "systems" in the following.

While the first case can be identified by additional code that logs the activation of injected faults, disinguishing the latter two requires introspection of the system during test execution. SFI test frameworks commonly use execution trace comparisons across setups with and without injected faults as a secondary oracle to distinguish between these cases [2], [7], [8].

A. The SFI Oracle Problem for OSs

While the usage of execution traces alleviates the aforementioned oracle problem, it is challenging for an important class of SUTs: Operating system (OS) kernel components, because all kernel components are interacting within the same address space and with the same privileges. Without memory protection between kernel components all memory is shared and directly accessible via pointers. This makes every memory operation in the system a potential cross-component interaction affecting the SUT that needs to be traced. Existing memory tracing approaches for user space applications (e.g., using Valgrind [9] or Pin [10]) are not applicable for OS kernels. Existing tracing approaches for OS kernels (e.g., SystemTap [11] or LTTng [12]), on the other hand, only provide tracing on the granularity of function calls instead of individual memory accesses. A naïve tracing of *all* memory operations is infeasible, as the kernel code base is large and some parts, such as hardware interrupt handling routines, are performance critical.

B. TREKER*: Solving the SFI Oracle Problem*

To correctly identify and characterize the effects of residual software faults in kernel components, we present TREKER, a scalable, fully automated approach for TRacing Error propagation in operating system KERnels that relies on a combination of static and dynamic analyses to infer error propagation from a faulty kernel component to other parts of the kernel. TREKER limits the trace points to the injection target and infers error propagation from deviations in the injection target's state and behavior that are visible to other parts of the kernel, thereby effectively improving the soundness of SFI tests for OSs at the cost of execution time overheads for trace collection and analysis.

We demonstrate TREKER's ability to trace the effects of faults in three widely used kernel components on the Linux kernel. We find that up to $\sim 10\,\%$ of seemingly successful runs in our fault injection experiments would be misclassified by conventional oracles.

The remainder of the paper is organized as follows: Section II gives an overview over related work. Our proposed approach is detailed in Section III. We discuss TREKER's implementation in Section IV and the experimental analysis in Section V. Concluding remarks can be found in Section VI.

II. Related Work

To classify the results of SFI tests on kernel code, TREKER traces the effects of injected software faults in OS kernels. We discuss existing trace-based approaches for user mode software in Section II-A, alternative approaches for kernel-level SFI tests in Section II-B and trace comparison in Section II-C.

A. Execution Trace Based Oracles for User Mode Software

Execution tracing has been widely adopted to determine the outcome of SFI tests [2], [6]–[8], [13]–[16], similar to our motivation for TREKER. Execution traces of the unmodified SUT are recorded and later used as a *golden run* oracle to compare executions with injected faults against. To record execution traces, three different techniques are used.

One class of approaches (e.g., [13], [14], [16]) uses debuggers to record execution traces. This imposes execution latencies that are not tolerable by most SUTs, among them OS kernels targeted by our work. Interrupt service routines, for instance, need to have short response times and exceeding those may result in unintended OS failures during test.

A second class of approaches (e.g., [17], [18]) uses full-system simulation for execution tracing. Full-system simulators implement the semantics of low-level hardware operations for a given platform in software. The SUT is executed on this simulated hardware model. Although the simulation of every single hardware operation in software imposes massive execution time overheads, this is not observable by the SUT. Any latencies observable by the SUT are based on the simulated hardware timer. Therefore, full-system simulators are generally suitable for tracing OS kernel executions, but massively impair test throughput due to the simulation overhead.

The third class of approaches (e.g., [7], [19]) relies on *dynamic binary instrumentation/translation* (DBI/T), e.g., using Pin [10] or Valgrind [20]. Similar approaches have been developed for OS kernels [21]–[24], but none of them has been used for execution tracing in SFI tests. As TREKER instruments kernel code during compilation, it is independent from kernel modules that need to co-evolve with changing kernel interfaces. In this respect it differs from the work of Feiner et al. [22] or Kedia et al. [24]. Moreover, approaches based on binary translation only work for a specific hardware architecture and require adjustment for others. PinOS [21], for instance, is limited to IA-32. The applicability of TREKER, in contrast, is not limited to any specific OS kernel or hardware architecture, as long as the instrumentation target can be compiled for that architecture with Clang/LLVM. As both PinOS and DECAF [23], [25] rely on virtualization, they cannot be applied for hardware-specific kernel code, such as device drivers, if that hardware cannot be emulated by the underlying hypervisors.

B. Oracles for Kernel-Level SFI Tests

Due to the SUT/architecture specificity of available kernel tracing tools, SFI tests for these SUTs commonly employ other, less accurate oracles.

Koopman et al. have introduced a classification of OS failure modes that they consider relevant and implemented corresponding detectors in the Ballista project [26]. Their classification comprises five different failure modes, collectively referred to as the "CRASH scale", where each letter of the acronym stands for a failure mode. **C**atastrophic failures are failures that render the entire system unusable, e.g., kernel panics. **R**estart failures denote cases where the OS silently stops serving requests made by the executing test case. Cases where the OS detects a problem and notifies the executing test (e.g., by signaling a segmentation fault) are called **A**bort failures. **S**ilent failures denote the violation of the kernel's specified behavior without corresponding notification to the executing test. **H**indering failures, on the other hand, are failures that mislead debugging efforts, e.g., by returning a wrong error code. Arguing that these are the most critical failure classes, Ballista and similar approaches to OS robustness testing limit their oracles to the detection of the first three classes of the CRASH scale [27]–[31].

TREKER focuses on the detection of silent or "non-crashing" failures, such as *silent data corruption* (SDC), which constitute a significant threat to reliability [32]–[35] and have been mostly ignored by existing work on OS level SFI tests. The reliable detection of *restart* failures requires kernel execution traces containing every single executed instruction. While TREKER is capable of implementing such a tracing policy, the required heavy-weight instrumentation may result in performance degradation similar to the approaches discussed in Section II-A. We, therefore, limit the scope of our approach to the detection of error propagation in the case of terminating test executions and employ existing timeout-based detectors for *restart* failures.

While a number of tools (e.g. SystemTap [11] and LTTng [12]) exist to trace the execution of OS kernel code using probes (cf. [36], [37] for SFI tracing), they are only capable of tracing function invocations and not individual memory accesses. To identify how faults affect SUT state, i.e., the data the SUT operates on, TREKER selectively instruments memory operations that are invisible to these tools.

C. Trace Comparison

To detect error propagation, TREKER compares traces of executions with injected faults to golden run traces of the unmodified SUT. Trace comparison is also commonly used for fault localization. Wong et al. give an extensive overview [38].

Such approaches typically compare traces of the same version of the SUT with different inputs to identify the root causes of behavioral divergences. Therefore, they are not directly applicable to the scenario targeted by TREKER.

III. SYSTEM MODEL

We propose an approach for identifying how faults in components in a monolithic operating system affect the rest of the system. To that end, this section starts with a brief overview of the underlying fault taxonomy, followed by a discussion of the systems we consider and their component interactions.

A. Faults and their Consequences

As hinted at in Section I, we follow the Laprie taxonomy [1]. Any system or system component[2] is assumed to implement a *system function* according to a *functional specification*. The system implements the system function as a sequence of *states*. The fraction of a system state that is perceivable at the system's *interface* is called the *external state*. The sequence of external states implementing the system function is referred to as *service* and the deviation of service from the functional specification is called a *failure*. The deviation of an external state in the sequence that constitutes the service may be caused by a prior deviation of the system's internal state that is invisible at the interface from a correct implementation of the system function. Such a deviation of the system state is called an *error*. The cause of an error is termed as a *fault*. By these definitions, a fault is "something that possibly leads to an error", an error "something that possibly leads to a failure", and a failure "a deviation of observed behavior from specified behavior."

When a fault causes an error, this is referred to as *fault activation*, and the effect an error has on subsequent system states is called *error propagation*.

B. Monolithic Operating Systems and Composition

We assume that monolithic operating systems consist of (a) a core part which provides essential functionality and is, therefore, always necessarily present and (b) an arbitrary number of modules implementing additional functionality.

Modules can interact with one another or the core kernel through function calls, thereby exchanging information via parameters and return values. Furthermore, the system does not enforce any memory isolation between its components. All modules and the core kernel share the same memory address space and can, in theory, freely access and modify each others' data structures. Finally, modules can also access and modify any global data structures in the system.

Although the implementation we describe in Section IV utilizes runtime loading and unloading of kernel modules, the fundamental approach described here does not conceptually rely on the availability of this functionality.

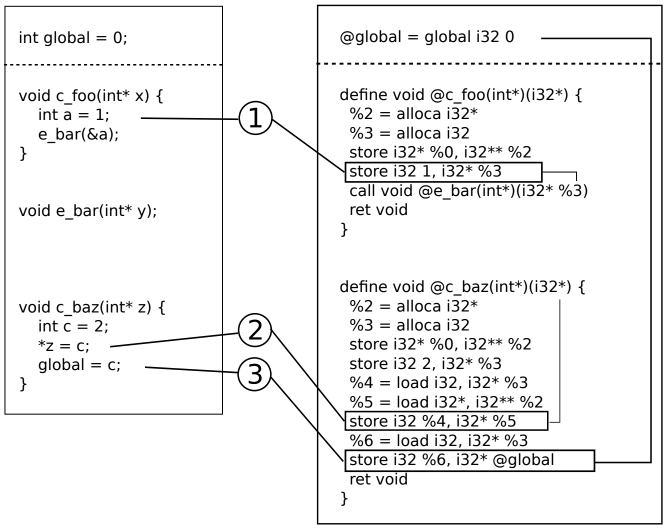
Due to the lack of runtime isolation or protection mechanisms, a faulty module can affect other modules or the core kernel in a variety of ways. In particular, tracing mechanisms that only consider parameters and return values of function calls cannot capture differences in communication through shared memory. However, due to the aforementioned lack of isolation, distinguishing between memory accesses that constitute potential shared memory communication, particularly write accesses by a faulty component, and those that do not is usually not straightforward without examining the entirety of all other modules and the core kernel. However, the result of such an analysis would be dependent on the particular modules present in the system in question and changes to this configuration might well yield different results. Therefore, we limit our analysis to the faulty component itself and analyze which fraction of its state can be expected to be accessible by *any* other component in the system, independent from the actual system configuration. We denote this fraction of expected externally visible behavior as the component's *interface*. The interface includes parameters of function calls from and return values of function calls to the component as well as memory accesses to locations that can reasonably be assumed to be used for transmitting data to other components via shared memory. We detail in the following what we do and do not consider such interface relevant memory accesses within a component targeted by our analysis.

Read accesses are not generally considered part of the component interface. If the value that is read was previously written by the faulty module itself, the read access clearly does not constitute external communication. If, on the other hand, the value was written by another module, we do not consider the read access itself to be behavior visible to other components: While a faulty module may attempt to read from the wrong address, resulting in an unexpected value, this does not directly result in externally visible differences in behavior. Cases where it has indirect influence (for instance, if the faulty module proceeds to use the wrong value as a function parameter) will be captured under our notion of interface at the point where the behavior in question becomes externally visible.

Local write accesses are store operations to addresses that are not known to any components other than the faulty one. Most notably, this includes accesses to stack-allocated local variables unless their address is passed to another component (either directly, e.g., as a function parameter or implicitly by writing it to another externally visible memory location). Access to regions of memory that are allocated and freed without ever being referenced in an externally visible manner (that is, as with stack addresses, passed to external functions or written to externally visible addresses) in between also fall into this category. Such accesses are not considered externally visible for the purposes of our analysis and are therefore not deemed part of the component interface.

Externally visible write accesses are store operations to addresses that are known to components other than the faulty one. This includes all addresses that are passed to the module from another component, for instance as a parameter or return value, as well as globals and addresses belonging to memory that has been allocated by the module itself but then communicated to other components. As mentioned above,

[2]We mean "system or system component" whenever we refer to "system" in this subsection.



```
int global = 0;

void c_foo(int* x) {
    int a = 1;
    e_bar(&a);
}

void e_bar(int* y);

void c_baz(int* z) {
    int c = 2;
    *z = c;
    global = c;
}
```

```
@global = global i32 0

define void @c_foo(int*)(i32*) {
  %2 = alloca i32*
  %3 = alloca i32
  store i32* %0, i32** %2
  store i32 1, i32* %3
  call void @e_bar(int*)(i32* %3)
  ret void
}

define void @c_baz(int*)(i32*) {
  %2 = alloca i32*
  %3 = alloca i32
  store i32* %0, i32** %2
  store i32 2, i32* %3
  %4 = load i32, i32* %3
  %5 = load i32*, i32** %2
  store i32 %4, i32* %5
  %6 = load i32, i32* %3
  store i32 %6, i32* @global
  ret void
}
```

Fig. 1. Three different cases in which write accesses can be externally visible, in C and (simplified) LLVM IR.

it also includes all memory addresses that are reachable by following pointers from another externally visible address.

Of these three categories, the one most relevant for our analysis is the last one, externally visible write accesses. We distinguish between three different cases of external visibility of write accesses: 1) Writes to an address that the component passes to another component or to addresses that are reachable from such an address; 2) Writes to an address that was passed to the component by another component or to addresses that are reachable from such an address; 3) Writes to global variables or to addresses that are reachable from a global variable.

These three cases are illustrated in Figure 1. In the first case, a function in the component (`c_foo`) writes to a variable (`a`) and then passes the address of that variable to an external function (`e_bar`). Should the external function dereference that address, the result of the written value would be accessible to it. Note that we do not inspect whether such an access actually occurs, we just check whether it is possible. In the second case, a function in the component (`c_baz`) has received a pointer (`z`) as an argument and writes to that address. If the caller of `c_baz` is an external function (e.g., `e_bar`), that write access is visible to that caller. In the final case, a function in the component writes to a global variable (`global`).

In all of these examples, the external visibility of the stores in question is fairly straightforward to recognize, requiring at most one pointer dereference. However, more complicated cases exist, for which we introduce the following notion of reachability: An address `p` is *directly* reachable from an address `q` if `p` is stored at `q` (i.e. `*q = p`) or `q` is the base address of a data structure (e.g., an array or struct) and `p` is the address of a member of that data structure (e.g., `p = &(q->foo)`). An address `p` is *indirectly* reachable from an address `q` if there is an address `r` such that `p` is directly reachable from `r` and `r` is reachable (directly or indirectly) from `q`.

We consider the externally visible behavior of a component at its interface with the rest of the operating system to consist of the values of parameters passed to functions outside the component, the values returned to callers outside the component, the externally visible memory addresses it writes to and the values it writes to them.

Error propagation occurs when a faulty component exhibits externally visible behavior that a fault-free version of the same component will never exhibit under the same workload.

IV. TREKER: TRACING ERROR PROPAGATION IN OS KERNELS

The implementation work required to realize our proposed approach comprises two essential parts: An instrumentation tool capable of gathering the information required to fully capture the externally visible behavior of a target component and an analysis tool to perform the filtering and transformations required to distinguish between the cases described in Section III. We describe these parts in Section IV-A and Section IV-B, respectively. Trace comparison is described in Section IV-C.

A. Component Interface Identification and Instrumentation

The purpose of the instrumentation phase is to gather all the information required to reconstruct an accurate model of the externally visible behavior of the target component. To that end, it needs to capture the addresses and values of memory accesses as well as function calls, parameters and return values. Function call instrumentation needs to be performed both on the caller side, when the target component calls functions in other components, as well as the callee side, when other components invoke functions of the target component.

In order to avoid limiting TREKER to a specific OS or architecture, we have decided to implement compile time instrumentation as an LLVM [39] optimization pass, allowing us to support native execution on a various different architectures.

As an LLVM optimization pass, the instrumentation step operates on LLVM IR, a Static Single Assignment (SSA) representation. Unlike x86 assembly, only a small number of LLVM instructions operate on memory, most notably the `load` and `store` instructions. In addition to the memory accesses themselves, the instrumentation also needs to capture accesses to fields of data structures, or more specifically the computation of their addresses based on the base address of the data structure. In LLVM, this is typically modeled by the `getelementptr` instruction.

Furthermore, the instrumentation should capture basic tracing information, such as function entry and exit, arguments and return values. Therefore, it also handles function calls (caller-side), function entry and function exit (callee-side).

Finally, TREKER is designed to handle kernel code, necessitating a way to instrument inline assembly which is common in operating systems code. Attempting to parse and process inline assembly directly suffers from many of the same drawbacks that make binary instrumentation an unattractive choice for kernel tracing, including lack of portability across different architectures and significant added complexity. In practice, however, inline assembly is usually specified using extended inline assembly syntax. Such extended inline assembly statements take a list of input and output variables and clobbers. The instrumentation can rely on these arguments and constraints to extract which memory addresses may be read from or written to by the inline assembly without parsing it directly. Based on this information, instrumentation can be performed as it would be for `load` or `store` instructions.

For each of the instrumentation points identified above, the instrumentation pass inserts a function call with the first argument indicating its type. The subsequent arguments differ for the different types of instrumentation points. In addition to memory addresses and values, the information passed to the function also includes static type information (e.g., whether a value is of a pointer type) and hashes of global variable names where applicable. This way, later analysis steps (e.g., the trace analysis described in Section IV-B) can identify pointer values in the trace without having to rely on heuristics, such as checking whether a value belongs to a previously seen address range (as in [7]).

The instrumentation pass inserts calls to `inst_wrapper`. For our experiments on Linux kernel modules, we applied a patch to the Linux kernel that implements a stub for this function and a kernel module that, once loaded, handles the logging at instrumentation points. Prior to loading this "runtime" kernel module, the kernel stub is effectively a no-op, allowing the instrumented module to function even when the runtime has not been loaded. For other application scenarios, such as user-level code, different implementations of the runtime, for instance in a library, would be possible as well.

When the runtime module is loaded, it changes a function pointer in the `inst_wrapper` stub to point to the actual logging implementation. That implementation uses `printk` to output information at each instrumentation point in order to enable reliable tracing even in cases where the target may crash. For other use cases, a trivial performance optimization would involve caching trace data in memory to reduce the number of calls to `printk`.

B. Trace Analysis

We have implemented a trace analysis tool that is capable of performing the reachability analysis for externally visible write accesses that we have described in Section III as well as deriving symbolic values for the addresses of memory accesses in order to facilitate comparisons between traces. We first describe our implementation of the reachability analysis, followed by our symbolic address generation.

1) Reachability: We have introduced a notion of reachability that incorporates both reachability through pointers as well as through access to member fields of data structures in Section III. Our implementation of reachability analysis applies this notion to individual execution traces. First, we split the trace by dynamic function calls. For each function call, we extract the caller, arguments, return value and called functions. For calls to internal functions, we additionally extract the trace entries generated during that function call. This results in a tree structure in which nodes represent dynamic instances of function calls and edges represent a caller-callee relationship.

Next, we perform the aforementioned reachability analysis for each of the three different cases in which stores performed by the instrumented component may be externally visible.

For the first case, writes in the component that are reachable from arguments passed to an external function, we first identify each node representing a call to an external function taking at least one pointer argument in the aforementioned tree. Then, for each such node, we iterate backwards over the preceding trace entries until we encounter another node representing an external function call. During this traversal, we build up a separate graph which we term the *reachability graph* from the encountered trace entries as follows:

- For load or store entries, check if the address node has an outgoing edge representing a previously seen load or store from that node, and if so, skip this trace entry. Otherwise, if the read or written value is a pointer, add an edge from the address node to the value node.
- For data structure member access entries (i.e. `getelementptr` instructions in LLVM IR), add an edge from the source (i.e. base address) to the destination (member address) node.

Non-existent address nodes are created on demand during the construction of the reachability graph.

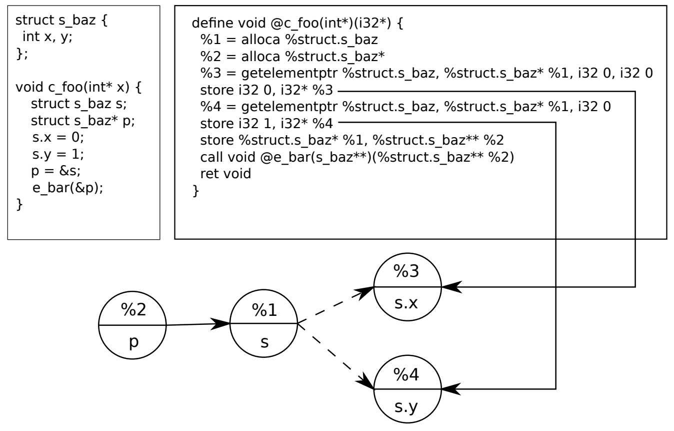
In this reachability graph, we identify the set of nodes (addresses) that are reachable from any of the nodes representing pointer arguments passed to the external function. This set of addresses is a subset of the addresses that are visible to the external function, and for each of these addresses, the last write access is deemed visible to the external function. An illustration of a graph for this case can be seen in Figure 2: The stack-allocated struct `s_baz` is accessible via the pointer `p` passed to the external function and both of the stores to its members are visible to the called function.

For the second case, writes in the component to global addresses or addresses reachable from them, we iterate over the trace, constructing a reachability graph as follows:

- For load or store entries, if the address node already has an outgoing edge representing a read or write access, remove it. Add an edge from the address node to the value node.
- For data structure member entries, add an edge from the source to the destination address.
- Mark global addresses when they are encountered and annotate the corresponding node.

In this reachability graph, we identify the set of nodes that are reachable from any node annotated as representing a global variable. As in the first case, write accesses operating on any of these addresses are deemed visible to the external function.

For the third case, writes in the component that are reachable from arguments passed by an external function, we identify each node representing a call to an external function that in turn calls functions provided by the component. This corresponds to any external function node (including the root node) in the tree that has internal function child nodes. Then, for each component



```
struct s_baz {
  int x, y;
};

void c_foo(int* x) {
   struct s_baz s;
   struct s_baz* p;
    s.x = 0;
    s.y = 1;
    p = &s;
    e_bar(&p);
}
```

```
define void @c_foo(int*)(i32*) {
  %1 = alloca %struct.s_baz
  %2 = alloca %struct.s_baz*
  %3 = getelementptr %struct.s_baz, %struct.s_baz* %1, i32 0, i32 0
  store i32 0, i32* %3
  %4 = getelementptr %struct.s_baz, %struct.s_baz* %1, i32 0
  store i32 1, i32* %4
  store %struct.s_baz* %1, %struct.s_baz** %2
  call void @e_bar(s_baz**)(%struct.s_baz** %2)
  ret void
}
```

Fig. 2. An example of a reachability graph and the corresponding code snippet. Solid lines indicate values stored at an address, dashed lines indicate offset calculations. Writes to `s.x` and `s.y` are visible to `e_bar`.

function (that takes at least one pointer argument) called by such an external function, we iterate over all trace entries belonging to that function node and its child nodes, performing an in-order traversal of a sub-tree with the component function at its root. The traversal is stopped when we encounter another external function node. During this traversal, we once again build up a reachability graph, in the same manner as for global addresses, apart from annotating nodes representing global variables. We identify the set of nodes that are reachable from any node representing a pointer argument passed by the external function, and as in the previous cases, deem the last write accesses to any of these addresses visible to the external function.

2) Symbolic Addresses: To compare traces from different executions, where absolute addresses may differ, a mechanism to map concrete addresses to symbolic addresses is required. We generate symbolic addresses from reachability graphs similar to the ones described previously. A symbolic address consists of an *anchor point*, and a path starting from that anchor point. For writes in the component that are reachable from arguments passed by an external function and writes that are reachable from a global value (the second and third cases discussed above), symbolic addresses use the argument or the global variable as the anchor point and the shortest path from there to the address that was written to as the path. If, for instance, a pointer `x` is passed to the component, and the component writes to an address `y` that can be obtained by dereferencing `x` and adding an offset `k`, the resulting symbolic address is `x` $\xrightarrow{*}\xrightarrow{k}$. For writes in the component that are reachable from arguments passed to an external function, symbolic addresses are created using a similar mechanism. In this case, however, a set of anchor points consisting of return values of external functions, stack allocations, global variables and the results of pointer arithmetic is considered. If an address is reachable from several anchor points, we compare the lengths of the shortest paths from each anchor point to the address and pick the shortest one. The same symbolification is performed for values of pointer types.

C. Trace Comparison

Assessing the impact of faults on visible write accesses requires a mechanism for comparing traces of executions with activated faults to fault-free executions (golden runs). Moreover, in order to minimize the impact of non-deterministic runtime behavior, we need to compare a faulty execution to a set of fault free runs. While this allows us to more precisely extract those differences between traces that result from the activation of a fault (i.e. behavior that a fault-free implementation would never exhibit), it also complicates the comparison process. We compare traces using the following two-step approach:

1) Trace Merging: First, a set of traces from fault-free runs is processed in order to generate a merged trace structure containing information about the addresses *any* execution writes to as well as the adddresses *all* executions write to, along with the corresponding values: Let t_1 and t_2 be traces from two fault-free executions, both of which consist of the same sequence of function calls and write to address a_1, with the values being v_1 (t_1) and v_2 (t_2). The resulting merged structure then contains a write access $a_1 \leftarrow \{v_1, v_2\}$. Furthermore, let t_1 also write to address a_2. The merged structure then contains, separately, the set of addresses that all executions have written to ($A_{\text{all}} = \{a_1\}$) as well as the set of addresses that at least one trace has written to ($A_{\text{any}} = \{a_1, a_2\}$). Let t_3 be a trace from a third fault-free execution which consists of a different sequence of function calls. The addresses and values written by t_3 are stored separately from those of t_1 and t_2. In order to support workloads which exercise the target module using multiple threads or processes, merged structures are stored separately for different threads and processes.

2) Trace Comparison: Next, this merged structure is used in a comparison with a faulty execution. Let t_f be a trace from such an execution. First, the threads or processes in t_f need to be matched to their counterparts in the merged structure. Since absolute thread or process IDs may differ between executions, they do not form a reliable foundation for such a mapping. Instead, we perform the mapping by call sequence, looking first for exact matches. In cases where no exact match is found, the trace exhibiting the previously unknown call sequence can either be ignored so as to avoid introducing false positives, or a best effort comparison with the known call sequence with the longest common prefix can be performed. We call the former option *strict mode*. In the latter option, situations may arise in which several known call sequences have the same longest common prefix length with the new call sequence. In this case, we compare with all of them and report the results for the case in which we discover the fewest divergences. Best effort comparisons are only performed over the common prefix so that we never compare store visibility for different functions. For each address a_f that t_f writes to, the trace comparison checks if that address is also written to in at least one fault-free execution. In case it is not, the write to a_f is deemed an *additional* write access. Moreover, the comparison also checks if t_f writes to all addresses a_i that *every* fault-free execution writes to. If it does not, a write to such an a_i is deemed *missing*. Finally, for the set of addresses that both the faulty and at least one fault-free execution write to, the value v_f written by t_f is checked against the set of values written by the fault-free executions. If v_f is not in that set, the write access *differs* from the corresponding write accesses seen in fault-free runs. Non-pointer values are not assigned symbolic counterparts during trace processing but may in some cases take on different values even during most fault-free runs. This can be the case with, for instance, addresses that are written as non-pointer types, timestamps or random values. In order to minimize the number of false positives introduced by such cases, the comparison between faulty and fault-free runs ignores any values that differed in a majority of fault-free runs (i.e. for which the number of observed values is greater than half the number of fault-free runs).

The numbers of missing, additional and differing stores are gathered separately for the three cases of write access visibility.

V. Experimental Analysis

In this section, we evaluate our approach by performing experiments with real-world Linux kernel modules: a storage device driver and two file systems. The questions that we strive to answer in this evaluation are detailed in the following Section V-A. We describe our SUT in Section V-B. Section V-C covers the injection targets and Section V-D our choice of workload. We report on our experimental results in Section V-E.

A. Research Questions

Is TrEKer a sound detector for error propagation? To answer this question, we analyze if there are any spurious indications of error propagation by comparing memory traces of SFI tests for which the injected mutations have not been activated. As the injected faults cannot have an effect on the correct execution of the workload in this case, any differences in the memory traces are false positives.

Does TrEKer improve the soundness of SFI tests? Even if TrEKer is a sound detector, it only improves the *soundness of SFI tests* if silent error propagation actually occurs in these tests. To assess if silent error propagation goes unnoticed in conventional OS-level SFI tests, we analyze TrEKer's memory traces for SFI tests that complete without any obvious error indications.

What are the overheads resulting from TrEKer's instrumentation? Static code instrumentation always imposes a certain overhead at both compile-time and run-time. We compare both compilation and execution times of TrEKer against native SFI test compilation and execution.

Does TrEKer's instrumentation affect SFI test results? As code instrumentation modifies the SFI target's binary code and thereby potentially its behavior, it is conceivable that the results of SFI tests are affected or even invalidated by the instrumentation. In order to assess if such an effect is observable for our approach, we compare the results of SFI tests with and without instrumentation of the injection target using Fisher's exact test for independence.

B. SUT

Although TrEKer supports native execution, we perform our evaluation in a virtualized environment to avoid frequent hard machine restarts due to system crashes resulting from the tests. The toolchain we use in the experiments is illustrated in Figure 3. The guest system is Debian 8.6 running in QEMU 2.6.0. It is configured with one CPU and 1 GiB of RAM and has virtual SCSI and NVMe devices attached. KVM is enabled. The guest kernel is Linux 4.4.25, patched to support compilation with Clang/LLVM (using a modified version of the patch set created by the LLVMLinux[3] project) and compiled with Clang/LLVM 3.9.1. The host system is Debian 8.5 running the distribution-provided 3.16 kernel. All experiments are performed using four parallel QEMU instances running on a host system equipped with an i7-4790 CPU and 16 GiB of RAM. Experiment control and timeout detection are handled by a controller running on the same host. The timeout value for all tests is 45 seconds, excluding boot and setup time. In addition to the timeout mechanism, we employ detectors operating on the serial output of the guest system to detect error messages from the kernel. Our detectors distinguish between five different classes of kernel error messages (Call Trace, GPF, BUG, Oops and Panic). We also check exit codes during the workload execution to detect workload failures that did not result in kernel error messages, resulting in a total of eight different experiment result classes.

C. Injection Targets and Faultload Selection

We apply our proposed approach to three different, widely used Linux kernel modules: (1) `f2fs`, the Flash-Friendly File System, a file system specifically designed for NAND Flash-based storage devices; (2) `btrfs`, a copy-on-write file system implementing various advanced features; and (3) `nvme`, the kernel module providing support for NVMe devices.

For each of these modules, we perform the following series of steps: (1) We inject software faults using the SAFE tool[4] [4] with default settings, (2) build the resulting module using our compile time instrumentation tool (Section IV-A), (3) execute a workload that utilizes functionality provided by the module, and (4) observe the resulting effects during execution and via memory trace comparison.

SAFE performs fault injection at the source code level using the G-SWFIT [3] fault operators. We build and instrument the target modules with Clang/LLVM 3.9.1.

We use prefix matching for `btrfs` and `f2fs` to maximize the usage of recorded memory traces (see Section IV-C). As `nvme` directly interfaces with the system hardware and, thus, has a higher exposure to non-determinism, we use the strict mode to limit false positives resulting from this.

D. Workload Selection

All three modules in our study provide functionality related to file I/O. Two of them (`btrfs` and `f2fs`) are file systems

[3]http://llvm.linuxfoundation.org

[4]http://wpage.unina.it/roberto.natella/tools.html

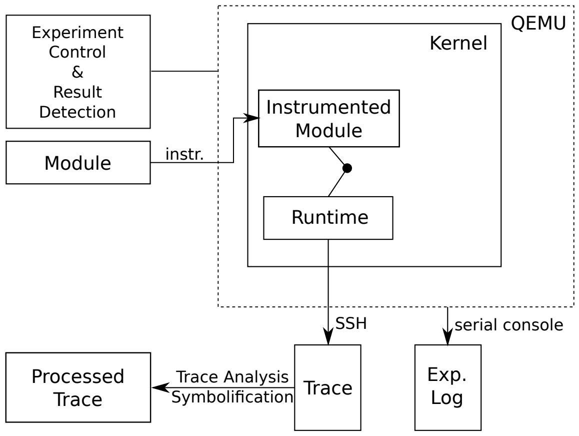


Fig. 3. The QEMU-based virtualized test environment and toolchain

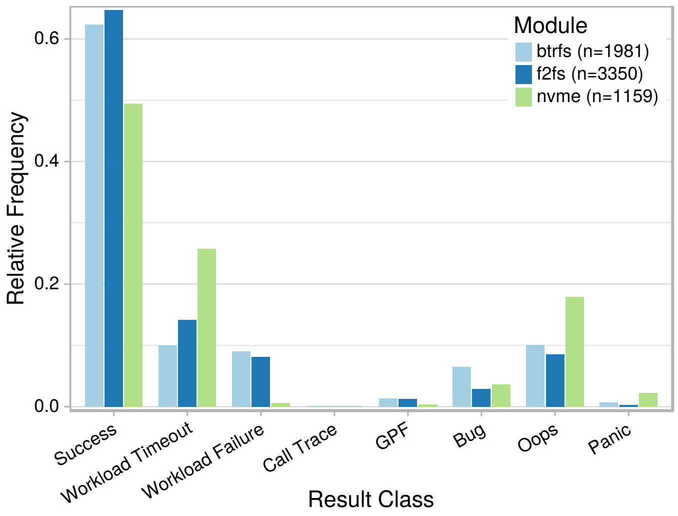


Fig. 4. Result distribution for runs with activated mutation

and the third one (`nvme`) provides support for an interface standard for storage devices. Consequently, we apply the same workload to all three modules. Specifically, the workload consists of the following sequence of steps:

1) Loading the target module and any other required modules; 2) Creating a filesystem (F2FS for the `f2fs` and `nvme` modules, BTRFS for the `btrfs` module) on either an NVMe (`nvme`, `f2fs`) or SCSI (`btrfs`) device; 3) Mounting that filesystem; 4) Creating a new file and writing to it; 5) Creating a new directory; 6) Reading the file; 7) Removing the directory; 8) Removing the file; 9) Unmounting the filesystem; 10) Removing the target module and all other modules that were loaded in the first step.

The instrumentation is active throughout the execution of the workload (that is, the runtime module is loaded prior to the first step and removed after the last step).

This workload exercises most commonly used filesystem features and, through module insertion, device registration, I/O activity and removal, also exercises the essential functionality of the `nvme` module.

E. Results

We report on the experimental results obtained with TREKER and how they answer the research questions posed in Section V-A. The overall result distribution for runs with activated mutation according to the simple detectors discussed in Section V-B is shown in Figure 4.

1) Soundness of TREKER*:* In mutation-based SFI, there is a risk that the mutated code fraction does not get executed during the test and, obviously, no error propagation should occur in these cases. To reliably identify these tests, we track the execution of mutated code by dedicated log instructions. We then use TREKER to analyze their memory traces. Any error propagation indicated by TREKER are false positives. Figure 5 shows the number of trace deviations detected by TREKER for different numbers of golden runs used as comparison basis for runs with and without mutation activation, with the latter case representing false positives indicated by the dashed lines. For all three modules, we observe a false positive rate below $1\,\%$. From Figure 5, we see that the number of detected trace deviations does not change beyond 800 golden runs. Consequently, we use this number as a comparison basis in our further experiments to keep the false positive rate in the presented results below $1\,\%$ and the comparison stable.

2) Soundness of SFI tests with TREKER*:* To assess the suitability of the proposed approach for detecting divergences in mutant behavior during apparently successful runs, we examine the sets of SFI test traces with mutant activations which finished without any obvious error indication, i.e. the runs that are marked as successful in Figure 4. We show the trace deviations found by TREKER in Figure 6 with overall rates ranging from $2.75\,\%$ (`btrfs`) to $10.1\,\%$ (`nvme`). From the analysis of different visibility types we observe instances of at least two different types of visibility for all modules. However, store visibility via a global variable only occurs for `nvme`. We conclude that, although the different types of visibility occur with different frequencies, analysis of all three is needed to obtain a complete picture of differences in memory access behavior between executions. The significantly higher rate of propagation to the callee rather than the caller is an interesting observation, as it indicates that errors tend to not propagate directly to components that invoke functionality of the targeted modules (i.e., their callers), but rather tend to spread further in the system. While a detailed study is needed to substantiate such a result, this finding illustrates the insights that TREKER fosters and that traditional SFI oracles cannot provide.

3) Instrumentation Overhead: To assess the overhead associated with our instrumentation, we compare the durations for compiling and executing mutated modules in different instrumentation modes.

Compile-time Overhead: We measure the user time[5] that `make` needs for building instrumented and uninstrumented versions of our mutants from a clean work space. Table I summarizes the median and the median absolute deviation

[5]We employ the GNU `time` utility to collect user times.

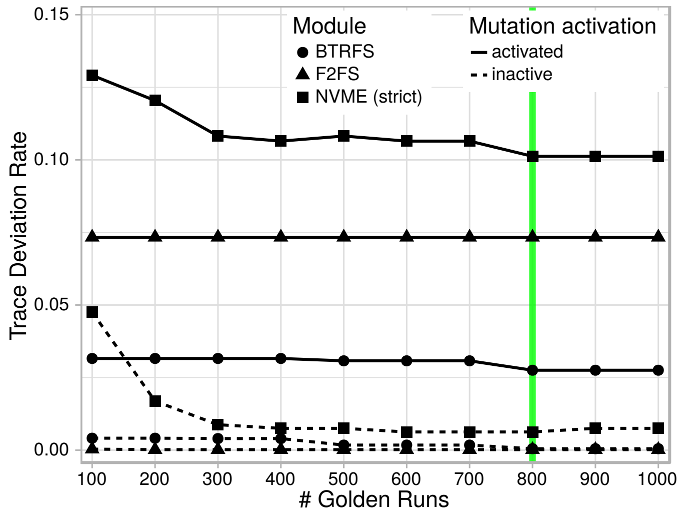


Fig. 5. Result stability with increasing number of golden runs.

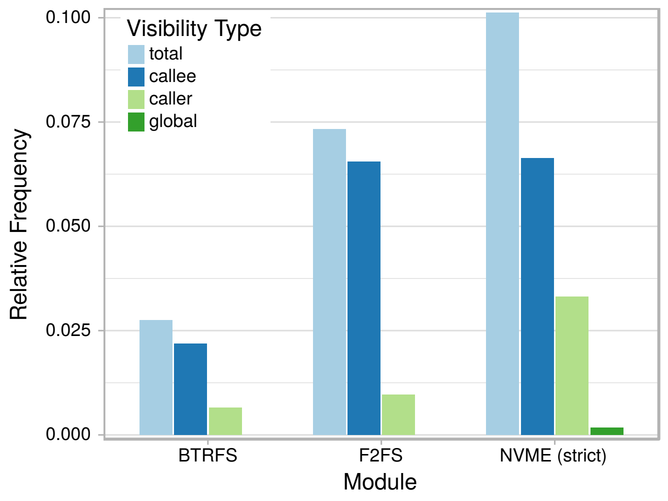


Fig. 6. Trace deviation rates for the three modules and different types of store visibility when compared with 800 golden runs.

(MAD) of user times. Column *OH* reports the overhead factors (between median values) for compilation with instrumentation for all modules. In the median, the compile-time overhead ranges from a factor of 1.4 for `f2fs` to a factor of 1.7 for `btrfs`. We deem these overheads as manageable in practice, especially since compilation is often a one-time effort and the actual needed real-time for compilation is much smaller than accumulated user time due to parallel compilation capabilities of build tools like `make`.

Run-time Overhead: We run the same SFI tests using the full set of mutants in three different modes: without instrumentation, with instrumentation compiled into the mutants but disabled during runtime, and with active instrumentation. We measure the durations of all workload executions that complete in all three modes. Table II summarizes the median and the median absolute deviation (MAD) of workload durations in seconds of real-time. Column *OH* reports the overhead factors (between

TABLE I
COMPILE-TIME OVERHEAD (OH) OF INSTRUMENTATION. USER TIMES ARE REPORTED IN SECONDS.

Module	Buildtype	Median	MAD	OH
btrfs	instr	71.86	0.21	1.7
	uninstr	43.62	0.11	
f2fs	instr	14.07	0.14	1.4
	uninstr	10.07	0.06	
nvme	instr	2.43	0.02	1.5
	uninstr	1.62	0.02	

TABLE II
RUN-TIME OVERHEAD (OH) OF INSTRUMENTATION. WORKLOAD DURATIONS REPORTED IN SECONDS.

Module	Mode	Median	MAD	OH
btrfs	instr active	2.714	0.139	2.5
	instr inactive	1.113	0.012	1.0
	uninstr	1.109	0.008	
f2fs	instr active	1.951	0.061	19.3
	instr inactive	0.101	0.006	1.0
	uninstr	0.101	0.006	
nvme	instr active	2.133	0.082	3.3
	instr inactive	0.656	0.009	1.0
	uninstr	0.642	0.008	

median values) compared to the uninstrumented execution. The overhead for runs with active instrumentation ranges from a factor of 2.5 for `btrfs` to a factor of 19.3 for `f2fs`. We attribute the higher relative overhead for `f2fs` to the high concentration of logging output in its mount routine. We expect to achieve a lower overhead for such cases if data logging is changed to use a more efficient format rather than relying on the kernel's `printk` facilities. Execution with inactive instrumentation imposes a negligible overhead. We observe the highest overhead for `nvme` with 14 ms. By comparison, PinOS [21] overheads with inactive instrumentation range from a factor of 12 to 120. DECAF [25] incurs a 15.2 % overhead with disabled instrumentation in addition to the overheads incurred by QEMU emulation. TREKER, in contrast, can run on bare metal configurations to avoid this overhead. We conclude that, with TREKER, instrumented modules could even be used in production, but data logging should be enabled only for tests or execution periods of interest for trace analysis.

4) Instrumentation Impact on SFI Test Results: We examine the effect of our instrumentation on the results of SFI tests. We use the same set of tests with three instrumentation modes

TABLE III
p-VALUES OF FISHER'S TEST OF INDEPENDENCE OF OBSERVED RESULT DISTRIBUTION AND INSTRUMENTATION MODE

Module	p
btrfs	0.9834
f2fs	0.9978
nvme	0.8420

that we used to assess the run-time overhead in Section V-E3. We consider all tests with activated mutation and compare the obtained result distributions for each module. We use Fisher's exact test to test the null hypothesis (H_0) that "there is no association between observed result distributions and the instrumentation mode". Table III reports the p-values obtained from Fisher's test. With $p \gg 0.05$ for all three modules, we cannot reject the null hypothesis, i.e., there is no statistically significant evidence that the instrumentation systematically changes the result distribution.

Nonetheless, in pairwise comparisons of executions of the same mutant with different instrumentation modes, we observe a small number of differences in outcomes. We focus on the comparison between runs with activated instrumentation and uninstrumented runs and see a total of 79, 101 and 68 differences for `btrfs`, `f2fs` and `nvme`, respectively, amounting to $0.79\,\%$, $1.11\,\%$ and $2.46\,\%$. As it is the module that most frequently exhibits such divergences, we discuss the nature of the divergences seen for `nvme` in some more detail: In 26 of the 68 cases, we observe a timeout only for the run with activated instrumentation. We hypothesize that these are most likely cases of spurious timeout detection, potentially a result of the overheads we discuss in Section V-E3. In a further 21 cases, we observe neither a success nor a timeout but different failure modes. For instance, there are several cases in which the uninstrumented run results in a kernel panic whereas the run with activated instrumentation merely results in a kernel oops before reaching the execution time limit. These are, once again, likely related to longer test execution times due to the instrumentation. We also observe two cases in which the instrumented run completes successfully whereas the uninstrumented run does not, suggesting non-deterministic behavior by the mutant. Among the remaining 19 cases, we observe twelve in which the instrumented run fails shortly after activating a mutation whereas the uninstrumented run does not (our data does not reveal whether the mutation was activated during the uninstrumented run), six cases in which the instrumented run results in a failure after the end of the workload execution and after removal of the runtime but prior to system shutdown and finally one in which the uninstrumented execution times out but the instrumented run does not. We conclude that most of the differences in outcome we observe are related to timeout detection and execution time limits and could be tackled by adjusting the corresponding values at the cost of a lower test throughput, similar to what has been reported in [40].

5) Threats To Validity: We identify the following threats to validity: 1) Non-determinism in the memory access patterns of the target modules that can, even in the absence of faults, lead to divergences between execution traces for the same workload; 2) Limitations of the presented approach for identifying visible stores, assigning symbolic addresses and detecting divergences; 3) The choice of target modules, SUT and workload.

We take several measures to minimize the effects of non-determinism: We use a large number of golden runs as a comparison base, assign symbolic values to memory addresses (including pointers that are used as value rather than address operands in load or store operations) to avoid non-determinism introduced by concrete address values, and handle different processes and threads individually as opposed to explicitly tackling concurrency. The low false positive rates obtained in our evaluation demonstrate the effectiveness of these measures.

TREKER has several restrictions on the scope within which, for instance, store visibility is determined (e.g., only stores between the prior external function and the current one are considered) or symbolic values are assigned (pointer arithmetic that is not modeled by `getelementptr` instructions is not analyzed). These restrictions result from the deliberately limited scope of our instrumentation and from performance optimizations in the trace processing. Consequently, there may be visible stores outside of the range considered by TREKER or different memory addresses that are assigned the same symbolic address. Such instances may result in the proposed approach reporting fewer divergences than actually exist.

Finally, the evaluation targets three different kernel modules providing related functionality, running on one kernel version and one system setup. Other categories of kernel modules or other operating systems may behave in a significantly different manner, and our results may not generalize. Furthermore, different workloads could exercise different parts of the module. Long-running workloads, for instance, may be expected to spend less time executing parts of the module for which the instrumentation is particularly expensive, such as module insertion, potentially leading to lower mean overheads. Furthermore, the likelihood of error propagation may increase with longer workload running times. We believe that TREKER is applicable to a wide variety of usage scenarios and our evaluation demonstrates the viability of the approach.

VI. CONCLUSION

In this paper, we have presented TREKER, an approach for identifying how faulty OS components can affect other parts of the system. TREKER enables tracing memory accesses in a target module using compile-time instrumentation and achieves low instrumentation overheads. We have presented a method for utilizing TREKER to improve oracles for FI experiments targeting OS components. An evaluation with several widely used modules for the Linux kernel demonstrates the viability of the approach, finding that conventional oracles would misclassify up to $\sim 10\,\%$ of seemingly successful runs. The evaluation shows a false positive rate below $1\,\%$.

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