Towards Optimal Use of Exception Handling
Information for Function Detection

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Abstract—Function entry detection is critical for security of binary code. Conventional methods heavily rely on patterns, inevitably missing true functions and introducing errors. Recently, call frames have been used in exception-handling for function start detection. However, existing methods have two problems. First, they combine call frames with heuristic-based approaches, which often brings error and uncertain benefits. Second, they trust the fidelity of call frames, without handling the errors that are introduced by call frames.

In this paper, we first study the coverage and accuracy of existing approaches in detecting function starts using call frames. We found that recursive disassembly with call frames can maximize coverage, and using extra heuristic-based approaches does not improve coverage and actually hurts accuracy. Second, we unveil call-frame errors and develop the first approach to fix them, making their use more reliable.

I. INTRODUCTION

Function detection is the process of identifying code regions in binary software that are compiled from source-level functions. Accurate function detection is critical for guaranteeing the correctness and effectiveness of mainstream applications of binary security, ranging from binary code similarity detection [22, 29], legacy-code patching [6, 38–40], shadow stack protection [8], coarse-grained [16, 25, 36, 45] or fine-grained [15, 17, 30, 37, 44] control flow integrity, to code layout randomization [10, 18–21, 28, 41, 42, 44].

The first step of function detection is to identify function entry points, or function starts and this is, however, very challenging. First, symbols in a binary provide the true identity of function starts, but those symbols are normally stripped. Second, binary code is often riddled with complex constructs (e.g., jump tables, tail calls, etc) for performance optimization. Mainstream conventional approaches for function start detection [7, 24, 27] first recursively disassemble a given binary from known function starts (e.g., program entry) and add the targets of call instructions as new function starts. They then scan the non-disassembled code to further detect function starts with common function prologues [32, 34] or data-mining models [7, 24], followed by recursive disassembly again. Beyond such a hybrid approach, there are also solutions that either (i) use data-mining models or neural networks to detect function starts [5, 33] or (ii) aggregate basic blocks connected by intra-procedural control flows into groups and consider the target of each call instruction or the first instruction in each group as a function start [4].

Although the above approaches have demonstrated some effectiveness in detecting function starts, they still share a fundamental drawback: they all attempt to recover function information using a pattern-driven principle, explicitly or implicitly. This drawback impedes the adoption of those approaches in the context of security applications. In fact, the patterns used by them are usually incomplete (missing true function starts) and/or inaccurate (introducing false function starts). Unlike symbols whose reliability is guaranteed by compilers, the patterns collected by these approaches do not build on any reliable source. Inevitably, those approaches lead to errors or omissions, which in turn reduces the confidence of users and even leads to cascading effects.

Recent advances [35, 43] have leveraged a new source to detect function starts in x64 binaries: call frames in the exception handling segment. To support exception handling, compilers emit call frames in x64 binaries as mandated by the ABI, giving information such as the start location for functions wherever possible. Mainstream binary analysis tools, in particular GHI DRA [2] and ANGR [34], already use call frames to facilitate function start detection. However, we observe two common, critical problems. First, the tools try to improve coverage by mixing the use of call frames with additional approaches that are sometimes safe and sometimes unsafe. Safe approaches leverage knowledge from the binary (e.g., symbols), the machine (e.g., instruction set), and/or the ABI (e.g., calling conventions) to provide correctness assurances. However, unsafe approaches are also involved, which try to use common patterns but typically do not offer assurances of correctness. These unsafe approaches inevitably introduce errors, sabotaging the reliability of call frames and the safe approaches. Moreover, the benefits from unsafe approaches (e.g., whether they can really improve coverage) remain unclear. Second, the tools fully trust the fidelity of call frames. They do not realize that call frames by themselves can also introduce errors and, not surprisingly, do not include any solutions to fix those errors.

In this paper, we inspect the above two problems, aiming to bring new insights towards optimal strategies of using call frames for function start detection.

First, we study the coverage of existing tools, when combining call frames with other methods, and the accuracy of the results produced. To perform the study, we collected 1,395 binaries from both real-world application and the popular benchmarks, and we separately measured the coverage and accuracy of detecting function starts detected by each combination of
approaches. Our key findings are (i) running safe recursive disassembly with call frames can already provide nearly full coverage; (ii) additionally running unsafe approaches from existing tools does not provide meaningful improvement to the coverage but, can introduce plenty of false positives. These bring insights towards both optimal coverage and better reliability in the use of call frames for function start detection.

Second, we systematically unveil and quantify the errors that call frames can introduce. To be specific, we compared the function starts extracted from call frames and the ground truth in our benchmark binaries. We discovered that modern compilers keep separate call frames \( \text{(also separate symbols)} \) for distant parts in a non-contiguous function. When such call frames are directly used for function start detection, they can bring a significant group of false function starts. We also found that existing tools do not provide any solution to handle such false function starts. Following our findings, we develop a new algorithm to fix errors brought by call frames. Our key insight is that distant parts in a non-contiguous function are typically connected via a jump. By checking that the jump between two call frames cannot be a jump between two functions \( \text{(i.e., the jump cannot be a tail call)} \), we can decide that the two call frames belong to the same non-contiguous function and thus, merge them. Inspired by this insight, we incorporate well-founded, restrictive criteria to detect tail calls, minimizing the chance of reporting false tail calls and ensuring that all missed tail calls are harmless. According to our evaluation, our algorithm can eliminate nearly 95% of the false function starts introduced by call frames, without incurring harmful side effects. Further, all the missed false function starts are due to conservativeness of our implementation choices instead of the design of our algorithm.

Our main contributions are as follows.

- **New knowledge** - We investigate the coverage and accuracy of function starts detected by combing call frames with different approaches from existing tools. We bring insights towards using call frames to achieve optimal coverage of function starts with a minimal hurt to the reliability.
- **New approach** - We are the first to systematically study, classify, and quantify the errors that call frames can bring. We develop the first approach that can fix the errors in call frames, making them a better information source for function start detection.
- **New finding** - We unveil key problems in how existing tools use call frames and demonstrate their significance with quantitative evidence.
- **New tool** - We developed a tool incorporating all our strategies. Its source code is available at https://github.com/ruotongyu/FETCH.

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\[1\] False positive means the start of a function identified but it is actually not. False negative means the start of a function is not identified.
The use of exception handling information by existing tools (ANGR and GHIDRA) in function start detection has two problems. First, they combine the reliable information in call frames with unsafe approaches, i.e., approaches that do not offer assurances of correctness: ① both ANGR and GHIDRA run prologue matching to detect function starts in the non-disassembled code regions, followed by a round of recursive disassembly from each matched function start; ② both ANGR and GHIDRA leverage heuristics to detect tail calls and consider their targets as function starts (not enabled by default); ③ ANGR linearly scans the remaining code gaps and treats the beginning of each correctly disassembled code piece as a new function start [27]. The use of unsafe approaches often bring errors, but it may not increase the coverage achieved by call frames and safe approaches that provide correctness guarantees (e.g., recursive disassembly). Second, the existing tools fully trust the fidelity of call frames, without realizing and handling the errors that call frames can bring.

C. Research Scopes

In this paper, we focus on exploring the use of exception handling information for function-start detection. Our goal is not to develop a new approach from scratch. Instead, we aim to expose any shortcomings in how existing tools use exception handling information and identify the best strategies of using exception handling information for function start detection. Specifically, we have the following goals:

- **Goal 1**: We study the coverage of function starts by combining call frames with both safe and unsafe approaches from existing tools. This will bring insights towards optimal coverage with a minimal threat to reliability. § IV discusses how we achieve this goal in detail.
- **Goal 2**: We systematically study the errors that call frames can introduce and explore new solutions to fix the errors. This will help ensure the fidelity of call frames as an information source for function start detection. § V presents our approach to the second goal.

In accordance to our goals, we restrict our discussion in this paper on binaries with call frames. To this regard, we focus on System-V x64 binaries (e.g., x64 binaries running on Linux or other Unix variants) because the corresponding ABI [23]

![Fig. 1: An example of exception handling in C++ programs.](image)

mandates the existence of call frames while the other types of binaries may not have call frames.

## III. Demystifying Exception Handling

In this section, we describe the technical details of exception handling at the binary level and unveil the types of exception handling information that can help function start detection.

### A. Exception Handling at the High Level

Exception handling is the process of responding to the occurrence of exceptions during the execution of a program. Support of exception handling has become a standard feature of modern programming languages. For instance, C++ provides the `try`, `throw`, and `catch` clauses to facilitate handling of exceptions. To explain exception handling, we use the C++ example in Figure 1. Exception handling in other programming languages follows a similar format, although using different grammar.

As shown in Figure 1, the `main` function receives two integers from the user and attempts to divide them by calling `div`. In normal cases, `div` returns the division result to `main`, but if the divisor is zero, it throws an exception which will then be caught and handled by `main`. To realize exception handling in this case, execution has to go through two key steps. First, it needs to find the proper handler for the exception. As shown in our example, the throwing of an exception and the suitable handler for that exception can lie in different functions. As such, exception handling may need to search in the call chain on the stack, including the current function where the exception is thrown and all the caller functions. Second, after finding the proper handler, execution is redirected to it.

The above two steps are mainly completed by a special procedure called `stack unwinding`. When an exception occurs, stack unwinding linearly searches every function on the call stack for the exception handler. While searching the exception handler, stack unwinding concurrently updates the stack by removing the stack frame of each searched function until the correct handler is identified. Following that, stack unwinding sets the stack pointer to the frame of the function with the correct handler, recovers the contexts in that function, and switches the execution to that handler.

In Figure 1, once `div` throws the exception at line 3, the execution will in turn search `div` and `main` to locate the right handler at line 12 in `main`. In this process, the execution will remove `div`'s stack frame and then set the stack pointer to `main`'s frame. Finally, the execution will recover the context of `main` and switches to the catch clause at line 12.
B. Exception Handling under the Hood

In this section, we further reveal the under-the-hood mechanism of exception handling and stack unwinding. We follow the same setting of our running example: exception handling in x64 binaries compiled from C++ programs.

Figure 2 shows the workflow of the exception handling procedure. We will focus on the part of stack unwinding since other parts are not related to function detection. Stack unwinding is mainly completed by the \_Unwind\_RaiseException function from C library (libgcc). We describe how \_Unwind\_RaiseException performs the stack unwinding procedure as follows. For simplicity, we abbreviate \_Unwind\_RaiseException as \( F_U \).

1. \( F_U \) first checks the program counter (PC), i.e., the \textit{rip} register, at the \textit{throw} statement and determines the current function (e.g., \texttt{div} in Figure 1) based on the PC.
2. \( F_U \) then checks if the current function has a proper handler. Specifically, it checks whether the current function has a catch block that can handle the \textit{throw}. If a proper catch block is found, \( F_U \) switches the PC to the catch block. Otherwise, \( F_U \) recovers the registers saved by the current function and destroys its stack frame by adjusting the stack pointer (SP). Then, \( F_U \) goes to the next step.
3. \( F_U \) finds the caller function on the stack (e.g., \texttt{main} in Figure 1) and repeats 2, using the return address as the new PC. However, if the stack frame is empty, \( F_U \) will invoke terminate to make the program exit abnormally.

As unveiled by the description above, 1-3 critically depend on three tasks: \( (T_1) \) given PC, finding the function containing the PC; \( (T_2) \) given PC and the corresponding SP, determining the call frame of the current function and its return address; \( (T_3) \) given PC and the corresponding SP, recovering the registers saved by the current function. To complete the three tasks, \( F_U \) leverages information from a special section called \texttt{eh\_frame}, which is also the key data empowering function detection. In the rest of this section, we will give a brief introduction of \texttt{eh\_frame} and then explain how it helps complete the three tasks.

C. \texttt{EH\_Frame}: Key Data Structure for Exception Handling

Overview of \texttt{EH\_Frame}: As illustrated in Figure 3, \texttt{eh\_frame} is a separate section in a binary file. It is structured as a list of Common Information Entries (CIE), each corresponding to an object file linked into the binary file. A CIE carries one or more Frame Description Entries (FDE), and typically, one FDE records the information of a unique function from the CIE’s object file.

Exception Handling with \texttt{EH\_Frame}: The major information in \texttt{eh\_frame} used by exception handling resides in the FDEs. An FDE record consists of a list of fields, among which PC Begin, PC Range, and Call Frame Instructions (CFIs) are indispensable to tasks \( T_1-T_3 \). In the following, we will follow the example in Figure 4 to explain how the three fields are used to complete \( T_1-T_3 \).

Figure 4a shows the assembly code of a function extracted from IDA-Pro 7.2 and Figure 4b shows the corresponding FDE. Line 2 and 3 in Figure 4b presents the PC Begin and the PC Range fields in the FDE. They explicitly give the start address and length of the function body. Using the PC information in the FDEs, exception handling can easily find the function containing a given PC, thus completing task \( T_1 \).

The rest part of Figure 4b (line 4-19) presents CFIs, a group of special instructions describing the unwinding rules. Due to historical reasons, the format of CFIs follows the DWA5F standard [9]. The core concept introduced by these unwinding rules is called “Canonical Frame Address (CFA)”. CFA is a universal variable that refers to the base address of the current stack frame (typically the highest address), which helps to uniform the various representations of the frame pointer introduced by compilers. There are four main types of instructions involved in the unwinding rules:

- \texttt{DW\_CFA\_def\_cfa} defines how CFA is represented, normally in the format of an offset to a designated register.
- \texttt{DW\_CFA\_advance\_loc} records the location of an instruction that changes the register used to represent the CFA or saves certain registers to the stack. The instruction location is represented by an offset to the function start.
- \texttt{DW\_CFA\_def\_cfa\_offset} describes the rule to calculate CFA when the value of the register representing CFA is changed. The rule typically follows the format of an offset relative to that register.
- \texttt{DW\_CFA\_offset} records the saving of certain registers to the stack, covering both the number and the location of the saved register.

We continue using the example in Figure 4 to explain how the above instructions describe concrete unwinding rules. At line 5 in Figure 4b, a \texttt{DW\_CFA\_def\_cfa} instruction defines that \texttt{rsp} is used to represent the CFA and initially, CFA = \texttt{rsp} + 8. Across the entire function, there are six instructions changing \texttt{rsp}, respectively marked as 1-6 in the comments in Figure 4a. Correspondingly, FDE records each change with a separate \texttt{DW\_CFA\_advance\_loc} instruction, also marked as 1-6 in the comments in Figure 4b. Following each \texttt{DW\_CFA\_advance\_loc} instruction, FDE appends a \texttt{DW\_CFA\_def\_cfa\_offset} instruction to describe how to re-calculate the CFA. Consider line 2 in Figure 4a as an example. The instruction pushes \texttt{rbp} to the stack, decreasing \texttt{rsp} by 8. Accordingly, line 6 in Figure 4b indicates that the instruction before address b1 makes a change to the register representing the CFA (i.e., \texttt{rsp}); line 7 in Figure 4b describes that now the offset between CFA and \texttt{rsp} is 16 bytes,
We will study the detection of function starts using FDEs with both safe and unsafe approaches from existing tools, and hence, understand which combination of approaches can bring the best balance between coverage and risks. To be more specific, we will center around three questions:

\[ Q_1 \] - Using only FDEs, how many function starts can be detected?

\[ Q_2 \] - Using FDEs and safe approaches, particularly recursive disassembly, how many function starts can be detected?

\[ Q_3 \] - Can unsafe approaches, such as the heuristics used by existing tools, help detect more function starts? What are their side effects?

To answer the above questions, we perform a set of empirical studies with a large corpus of x64 binaries as follows.

A. Setup of Studies

1) Preparation of Datasets: We collected two sets of x64 binaries, one from the wild and one built from source code.

Dataset 1: The first dataset are binaries collected from the wild, including 18 close-source binaries and 25 pre-built binaries from open-source programs. Details of the binaries are shown in Table I. The binaries cover nearly all the common types of software we use in our daily life, ranging from editors to browsers and conference clients. The binaries also cover both C programs and C++ programs.

Dataset 2: The second dataset is compiled from widely-used open source programs. As shown in Table II, the dataset includes 179 programs used by a recent study [27], covering both applications and libraries that are written in C/C++. These programs carry highly diverse functionality and complexity; they also contain both hand-written assembly code and hard-coded machine code. To further increase the diversity, we compiled the 179 programs into x64 binaries with both LLVM (version 6.0.0) and GCC (version 8.1.0), using optimization level O2, O3, Ofast, and Os. We omitted O0 and O1 since they are not widely used in practice. At the end, we produced 1,352 binaries in total.

IV. EXPLORING COVERAGE OF FUNCTION START DETECTION WITH CALL FRAMES

In this section, we aim at our first research goal — exploring the best strategies that use call frames towards optimal coverage of function starts with a minimal harm to the reliability. We will study the detection of function starts using FDEs with both safe and unsafe approaches from existing tools, and hence, understand which combination of approaches can bring the best balance between coverage and risks. To be more specific, we will center around three questions:

\[ Q_1 \] - Using only FDEs, how many function starts can be detected?

\[ Q_2 \] - Using FDEs and safe approaches, particularly recursive disassembly, how many function starts can be detected?

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To answer the above questions, we perform a set of empirical studies with a large corpus of x64 binaries as follows.
assembly functions in our dataset have incomplete types. More importantly, symbols can introduce a significant group of false positives, as we will show in § V. Thus, we only use symbols for the pre-compiled binaries in dataset 1 since we have no other options; while for dataset 2, we use a compiler-based approach to produce more complete and more accurate ground truth. Specifics are as follows.

Ground Truth for Dataset 1: As described above, we considered symbols as the ground truth of function starts for the binaries from the wild. Specifically, among the 25 binaries pre-built from open source projects, we found symbols in 1 of them and we successfully installed symbols for 8 others. For the closed-source binaries, we found symbols in 2 of them. In total, we obtained symbol-based ground truth for 11 wild binaries and our studies only considered them.

Ground Truth for Dataset 2: To generate a better ground truth than the symbols, we re-used the frameworks developed by [27] to intercept the end-to-end compiling and linking process to obtain all function starts.

B. Answering Question Q1

Comparing with Symbols: In our first study, we extracted the PC Begin fields from all FDEs and compared them with symbols. Not surprisingly, FDEs and symbols are highly overlapped. In the 11 wild binaries, FDEs cover 101,882 (99.99%) of the 101,891 symbols. In 9 out of the 11 binaries, FDEs cover all the symbols (see the column of FDE in Table I). The results with self-built binaries are similar. In the 1,352 self-built binaries, FDEs cover 1,138,601 (99.87%) of the 1,140,047 symbols. In 1,319 out of these binaries, FDEs cover all the symbols (see the column of FDE in Table II).

Comparing with Ground Truth: We further considered the PC Begin fields in our self-built binaries as function starts and compared them with the compiler-generated ground truth. In total, the FDEs cover 1,105,278 function starts. Despite the high overall coverage rate (99.87%), FDEs cover all the symbols (see the column of FDE in Table II). Of the 1,140,047 symbols, in 1,319 out of these binaries, FDEs cover all the symbols (see the column of FDE in Table II).
C. Answering Question $Q_2$

Following our first study, we then investigate whether recursive disassembly, a widely-used safe approach, can detect the missing function starts. Specifically, we ran the built-in recursive disassembly in both ANGR and GHIDRA, starting from addresses carried by FDEs and symbols. In the course of recursive disassembly, both ANGR and GHIDRA consider targets of call instructions as new function starts. As we focus on the effectiveness of recursive disassembly in this study, we disabled the extra heuristics used by ANGR and GHIDRA for function detection, including the tail call detection used by both tools, the function matching used by both tools, and the linear scan used by ANGR (more details can be found in [27]). To guarantee the accuracy of the experiment result, we only considered the self-built binaries since we have the precise ground truth for them.

Results with GHIDRA: GHIDRA can run all the 1,352 self-built binaries. However, the results are well below expectations. In comparison to solely using FDEs, recursive disassembly by GHIDRA significantly reduced the coverage: the total number of covered function starts dropped from 1,103,832 to 1,088,377; and the number of binaries with non-detected functions increased from 33 to 78. The reduction of coverage is mainly caused by a strategy — control-flow repairing — that examines the function start after a non-returning function. If the function start cannot be reached by other control flows, GHIDRA removes that function start. Due to inaccuracy in the detection of non-returning functions and incompleteness in the analysis of control flows [27], control-flow repairing often removes many true function starts, leading to reduced coverage as we observed.

We then conducted a follow-up test where we disabled the control-flow repairing. This time GHIDRA’s recursive disassembly demonstrated its effectiveness: in comparison to solely using FDEs, it increased the number of detected functions from 1,103,832 to 1,104,786 and dropped the number of binaries with non-detected functions increased from 33 to only 6 (see Figure 5a). While the recursive disassembly by GHIDRA indeed brings more coverage, we found that it is accompanied by another heuristic to detect thunk functions. The heuristic considers a function that starts with a jump to be a thunk function and takes the target of the jump as a new function start. In our test, the heuristic introduced over 400 new false positives and increased the number of binaries that have false positives from 488 to 542.

Results with ANGR: ANGR can only run 1,343 of the self-built binaries because it could not open the remaining 9. Before discussing the results, we want to note an observation that can make a significant difference. Specifically, ANGR marks a special group of functions (or precisely, functions that have a basic block solely consisting of padding instructions) as alignment. A recent study [27] suggests excluding the alignment functions for comparison. However, we found that doing so will reduce the coverage but not improve accuracy. Therefore, we preserved all the alignment functions.

In total, the group of 1,343 binaries contain 982,763 functions. By using FDEs alone, we detected 981,317 of those functions and achieved full coverage in 1310 binaries. However, the further recursive disassembly by ANGR decreased the number of binaries with full coverage to 1,303. The major cause is a heuristic that ANGR uses to merge functions. To be specific, ANGR merges two adjacent functions if the two functions are connected by a jump which is the only outgoing control-transfer from the first function and the only incoming control-transfer to the next function.

Following up the above test, we re-ran ANGR’s recursive disassembly without function merging. This time recursive disassembly demonstrated true effectiveness. It increased the number of detected functions from 981,317 to 982,195 and increased the number of binaries with full coverage from 1,310 to 1,337. However, similar to GHIDRA, ANGR’s recursive disassembly is coupled with a heuristic that introduces extra false positives. In an alignment function where the beginning instructions are considered padding, the heuristic will mark the first non-padding instruction a new function start, incurring 3,973 false positives.

Results with Safe Recursive Disassembly: As described above, the recursive disassembly by GHIDRA and ANGR is coupled with heuristics. In addition, the recursive disassembly itself in GHIDRA and ANGR also uses other unsafe strategies to handle complex constructs (e.g., indirect jumps) [27]. These indicate that the tests with GHIDRA and ANGR do not truly unveil the coverage of “safe” recursive disassembly on top of FDEs. This motivated us to run an extra test with error-free recursive disassembly. In general, recursive disassembly can run into errors only when handling indirect jumps, indirect calls, tail calls, and non-returning functions. We handle these complex constructs as follows to avoid errors.

1. **Indirect Jumps**: We only consider indirect jumps for jump tables. Specifically, we follow DYINST [24] to detect and solve jump tables which has proven high precision [27] and fixed some implementation defects in DYINST.
2. **Indirect Calls**: We skip all indirect calls.
3. **Tail Calls**: We do not detect tail calls.
4. **Non-returning Functions**: We reuse DYINST’s algorithm to detect non-returning functions, which has proven accurate [27]. We expanded the non-returning library functions used by DYINST to cover all the cases in our self-built binaries. In particular, we handled error and error_at_line as special cases since they are non-return only when the first argument is non-zero. Encountering either function, we run backward slices from the first argument and examine whether the argument always flows from 0. If so, we consider the function returning and non-returning otherwise.

Running the above error-free recursive disassembly, we achieved identical coverage as GHIDRA and ANGR, while more importantly, we introduced no false positives during the recursive disassembly, as illustrated by Figure 5.
After running our safe recursive disassembly with FDEs, we missed 568 functions in the 1,352 binaries and missed 568 functions in the 1,343 binaries that ANGR can run. All the missed functions are assembly functions, mainly belonging to two groups: (1) functions that are only reachable via tail calls and the successors of those functions (2) functions that are only reachable via indirect calls and the successors of those functions. In the last study, we aim to understand whether the other unsafe approaches used by GHIDRA and ANGR can help detect those functions and what harm they will incur.

Results with GHIDRA: GHIDRA uses two heuristic-based approaches, function matching and tail call detection,\(^3\) to further detect function starts. We tested the two approaches in turn. As indicated by Figure 5a the two approaches are not helpful to coverage. The function matching detected no new function starts, despite it neither brought false positives. The tail call detection found 16 new function starts, however, at the cost of 97,339 new false positives.

Results with ANGR: Besides using function matching and tail call detection, ANGR also detects function starts in its linear-scan process. In our study, we in turn tested function matching, tail call detection, and linear scan. Function matching helped detect 8 new function starts. However, it brought 4,128 false positives and it decreased the number of binaries with full accuracy from 845 to 13; The tail call detection found 211 new function starts at the cost of 4,686 false positives. Moreover, it dropped the number of binaries with full accuracy from 845 to 697; The linear scan detected 230 new function starts. However, it increased the number of false positives from 35,159 to 210,921 and more importantly, it eliminated all the binaries that have full accuracy.

E. Moving Towards Full Coverage

Recursive disassembly with FDEs can provide high coverage, but it does not guarantee full coverage for a specific binary. It would be very convenient if we could identify — or slightly over-approximate — the missing function starts, since

\(\text{this will enable the users to have full coverage and, with slight manual efforts on examining the functions we further identify, obtain a full accuracy (except the accuracy issues inherited from FDEs). To this regard, we explored another soundness-driven approach [31] and we present the details as follows.}

Given a binary, we first run recursive disassembly on top of FDEs and then collect all the potential function pointers. For each pointer, we validate its legitimacy. Specifically, we run our conservative recursive disassembly from the pointer and check four types of errors: (i) invalid opcodes; (ii) running into the middle of previously disassembled instructions; (iii) control transfers to the middle of previously detected functions; and (iv) invalid calling conventions (to validate calling conventions, we use the rule that all non-argument registers, namely registers other than rdi, rsi, rdx, rcx, r8, r9, must be initialized before use). If no error occurs, we consider the function pointer legitimate and take it as a new function start.

A key challenge in the above approach is the identification of function pointers. To overcome this challenge, we take a conservative approach to collecting a super-set of function pointers. Technically, we scan every consecutive eight-bytes (e.g., [0,...,7], [1,...,8], [2,...,9], etc) in the data segment and the non-disassembled regions, considering each of the eight-bytes as a pointer. We also identify all the constant operands in the disassembled code and consider each constant as a potential pointer. As demonstrated by a recent study [27], this combined strategy can collect all potential function pointers. We further want to note that, once we determine a “legitimate” function pointer, we will update the pointer collection based on the results of recursive disassembly from that pointer.

Applying the above approach to our 1,352 self-built binaries, we detected 154 more function starts without introducing new false positives. We also examined the 414 functions we still missed. These functions belong to two categories. The first category includes 160 unreachable assembly functions (i.e., assembly functions that are not referenced anywhere and their successors). Missing such functions is in principle harmless. The second category contains 254 functions that are only referenced by tail calls in the same function. As we will explain in § V-B, the side effect of missing the 254 functions is equivalent to in-lining them into their parent functions, which

\(\text{\(^3\)Tail call detection is not enabled by default in GHIDRA (neither in ANGR). We tested it because some missing function starts are due to tail calls.}\)
exception handling information under the accuracy of function start detection with average it only reports 0.31 function starts for each binary, is also in general harmless. We finally want to note that while we also want to unlikely to fully avoid such false positives.

Without adapting the design and the standard behind, it is FDE cannot cover multiple non-contiguous code segments. False positives are rooted from the design of FDEs: a single FDEs for the non-beginning parts become false positives. Such false positives are introduced from FDEs in our comparisons for non-contiguous functions. For each non-contiguous function, the binaries. In the case of Mysqld compiled with GCC and Ofast, we compared the function starts extracted from FDEs in our...
The target is not referenced elsewhere other than jumps in the current function. In theory, a tail call does not have to meet this rule. However, our empirical studies with a large-corpus binaries (listed in Table II) show that this rule can perfectly avoid false positives. More importantly, this rule ensures that the target of any missed tail call is not referenced elsewhere. Thus, the side effect of the missed tail call is equivalent to in-lining the target function to the source function, which should be generally harmless.

For a jump that we determine to be not a tail call, we check whether the target has an FDE record and whether the target is not referenced elsewhere. If both conditions hold, we consider the jump part and the target part are from the same function and we merge the two parts to the same function.

To implement Algorithm 1, there are two challenges. First, it needs to know the value of the stack pointer at a jump site. Many tools, such as Dyninst [24] and ANGR [34], include static analysis of stack height. However, as shown in Table IV, these analyses can often provide inaccurate stack height due to side effects of other errors and defects of engineering. To address this challenge, we opt to use the stack height recorded by CFIs in FDEs. For conservativeness, we only pick functions whose CFIs give complete information of stack height, by checking (i) whether the CFA in the CFIs is represented by \texttt{rsp} and the CFA is initialized as \texttt{rsp+8} and (ii) whether a \
\texttt{DW.CFA.def.cfa.offset} instruction exists wherever the stack height is changed. We skip functions with incomplete stack height. Second, the algorithm needs to collect all the references to functions. We overcome this challenge by using the conservative approach in § IV-E.

We also looked at the 3 false positives introduced by the developers. We found that the code blocks pointed to by those FDEs all present invalid calling conventions (using the rules in § IV-C). By checking the calling conventions of each function directly identified from FDEs, we detected the three false positives. After removing the false positives and re-running our pointer-based detection in § IV-E, we also identified the false negatives masked by those three false positives.

C. Algorithm Evaluation

We tested the performance of Algorithm 1 with our 1,352 self-built binaries. On top of FDEs, we first ran our recursive disassembly and our function pointer detection. Then, we ran Algorithm 1 and measured the change of both coverage and accuracy. In total, our algorithm reduced the number of FDE-introduced false positives from 34,772 to 2,659, increasing the number of binaries with full accuracy from 864 to 1,222.

Among the remaining 2,659 false positives, 2,656 are still caused by non-contiguous functions. Our algorithm missed detecting them because CFIs in those functions do not provide complete stack height information, and thus, we skipped processing those functions. With intuition suggests we can re-use static analyses from existing tools (e.g., ANGR and Dyninst) for stack height information in such functions, we opted not to do so. The reason, as aforementioned, is that the static analyses can be incomplete or inaccurate. To validate our choice, we also conducted an empirical evaluation. Specifically, we compared the stack height information from CFIs and the stack height information provided by both ANGR and Dyninst. It is worth noting that we only ran the comparison on functions whose CFIs provide complete stack height information. As shown by the results in Table IV, the stack height analyses by ANGR and Dyninst carries both incompleteness and inaccuracy (even just considering the jump sites), using of which can hurt our tail call detection.

We finally examined whether Algorithm 1 brought false negatives and false positives. It turns out that the algorithm did not bring extra false positives, but it introduced 161 new false negatives, slightly reducing the number of binaries with full coverage from 1,346 to 1,334 (see Figure 5c). All the 161 false negatives are because we merged targets of true tail calls to the call sites. Despite missing the 161 functions slightly affects coverage, the 161 functions are only referenced by tail calls in a single function (otherwise they will be detected by our algorithm). In this sense, the side effect of missing those functions is equivalent to in-lining them to their parent functions, which in general produces no harm. This is also the reason why the 254 false negatives we discussed in § IV-E are harmless.

VI. COMPARING WITH OTHER APPROACHES

We finally conducted an extra comparison, where we compared the optimal strategies of using FDEs and 8 existing tools (using the 1,352 self-built binaries shown in Table II). For simplicity of presentation, we will use FETCH (Function dETection with exCeption Handling) to represent our optimal strategies of using FDEs.

Setup: FETCH works by first extracting FDEs and then running our safe recursive disassembly (§ IV-B), our function pointer detection (§ IV-E), and our tail call detection (§ V-B). The 6 other tools that do not use FDEs are from two categories: (i) open-source tools that are designated for function detection or have a component of function detection (Dyninst [24], BAP [7], Radeare2 [32], and Nucleus [4]), and (ii) commercial tools that can detect functions (IDA Pro [14] and Binary Ninja [26]). Their configure are same as [27]. The results of Ghidra and ANGR are also included for convenience of comparison.

Coverage and Accuracy: As shown in Table III, FETCH presents extremely high coverage and accuracy. It only brings hundreds (or dozens) false positives and false negatives from the total 1,352 binaries, regardless of the optimization level. FETCH outperforms all the 8 other tools. It produces the best coverage in all the settings and the best accuracy except under optimization level Ofast. These results demonstrate the benefits of the FDE-assisted solutions.

Efficiency: We also measured the average time required by each tool to run a binary, and we show the results in Table V. Overall, FETCH can finish analyzing a binary in around 3.3 seconds, which represents a high efficiency.
In this section, we discuss the limitations and future directions of our research.

A. Threats to Validity

In this research, we focus on exploring the best strategies to (i) achieve optimal coverage and accuracy of using FDEs for function start detection and (ii) minimize the risks to the reliability. There exists potential threats to the fidelity of our findings. First, we concluded that running safe recursive disassembly on top of FDEs can achieve extremely high coverage with guaranteed reliability. However, recursive disassembly in practice may not ensure safety due to complex constructs like indirect jumps and non-returning functions. To reduce this threat, we have adopted the most conservative strategies to handle them (§ IV-C). Second, the reliability of our approach to fixing FDE-introduced errors is threatened by the completeness of the algorithm of tail call detection. To mitigate this threat, we adopted three restrictive criteria to detect tail calls, which have empirically proven completeness (§ V-B). Finally, as we unveiled in § V-A, developers may manually insert or modify the contents of eh_frame (intentionally or unintentionally) in a way that introduces errors. This is a threat to the accuracy and we currently cannot avoid the threat. However, such errors rarely happen in practice and therefore, we envision it would not raise major concerns.

B. Generality of Study

Our study focuses on x64 System-V binaries because such binaries are guaranteed by the ABI to have call frames. In fact, the methods used in our study are architecture independent and can work with any types of binaries that have call-frame-similar data structures. We have already conducted preliminary studies on other types of binaries and confirmed the availability of a structure similar to call frames. In particular, we found that x86 System-V binaries also widely carry FDEs, covering nearly all the functions. We also discovered that x64 PE binaries adopt an FDE-similar data structure to support exception handling [13], which contains the starts and boundaries of functions. Our preliminary results show that at least 70% of the functions are covered by this structure. In addition, the ABI of Arm architecture also has the similar structure to support exception handling [12]. As a future work, we plan to extend our study to cover other types of binaries.

VIII. Conclusion

In this paper, we focus on studying the use of call frames to detect function starts. We found that the use of call frames by existing tools has two common problems. First, beyond using call frames and safe approaches, existing tools also run additional unsafe approaches to detect function starts, seeking to improve the coverage. However, the unsafe approaches can often introduce errors and their capacity of improving coverage is unclear. Second, the existing tools fully trust the information from call frames, without recognizing that call frames can also introduce errors. To gain a deeper understanding of the two problems and hence, bring insights towards optimal strategies of using call frames for function start detection, we conducted two studies. In the first study, we measured the coverage and accuracy of function starts detected by different approaches that existing tools run on top of call frames. Our key finding is that combing safe recursive disassembly and call frames can already achieve the maximal coverage, and additionally including other unsafe approaches cannot benefit the coverage but can hurt the accuracy and reliability of the results. In the second study, we systematically unveiled and quantified the errors that call frames can introduce. We further presented the first approach that can effectively fix nearly all the errors without introducing side effects.

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