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Control-Flow Integrity: Precision, Security, and Performance

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Memory corruption errors in C/C++ programs remain the most common source of security vulnerabilities in today's systems. Control-flow hijacking attacks exploit memory corruption vulnerabilities to divert program execution away from the intended control flow. Researchers have spent more than a decade studying and refining defenses based on Control-Flow Integrity (CFI), and this technique is now integrated into several production compilers. However, so far no study has systematically compared the various proposed CFI mechanisms, nor is there any protocol on how to compare such mechanisms.

We compare a broad range of CFI mechanisms using a unified nomenclature based on (i) a qualitative discussion of the conceptual security guarantees, (ii) a quantitative security evaluation, and (iii) an empirical evaluation of their performance in the same test environment. For each mechanism, we evaluate (i) protected types of control-flow transfers, (ii) the precision of the protection for forward and backward edges. For open-source compiler-based implementations, we additionally evaluate (iii) the generated equivalence classes and target sets, and (iv) the runtime performance.

CCS Concepts: •**Security and privacy** → **Systems security; Software and application security;** *Information flow control;* •**General and reference** → *Surveys and overviews;*

Additional Key Words and Phrases: control-flow integrity, control-flow hijacking, return oriented programming, shadow stack

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1. INTRODUCTION

Systems programming languages such as C and C++ give programmers a high degree of freedom to optimize and control how their code uses available resources. While this facilitates the construction of highly efficient programs, requiring the programmer to manually manage memory and observe typing rules leads to security vulnerabilities in practice. Memory corruptions, such as buffer overflows, are routinely exploited by attackers. Despite significant research into exploit mitigations, very few of

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these mitigations have entered practice [Szekeres et al. 2013]. The combination of three such defenses, (i) Address Space Layout Randomization (ASLR) [PaX-Team 2003], (ii) stack canaries [van de Ven and Molnar 2004], and (iii) Data Execution Prevention (DEP) [Microsoft 2006] protects against *code-injection attacks,* but are unable to fully prevent *code-reuse attacks*. Modern exploits use Return-Oriented Programming (ROP) or variants thereof to bypass currently deployed defenses and divert the control flow to a malicious payload. Common objectives of such payloads include arbitrary code execution, privilege escalation, and exfiltration of sensitive information.

The goal of Control-Flow Integrity (CFI) [Abadi et al. 2005a] is to restrict the set of possible control-flow transfers to those that are strictly required for correct program execution. This prevents code-reuse techniques such as ROP from working because they would cause the program to execute control-flow transfers which are illegal under CFI. Conceptually, most CFI mechanisms follow a two-phase process. An *analysis* phase constructs the Control-Flow Graph (CFG) which approximates the set of legitimate control-flow transfers. This CFG is then used at runtime by an *enforcement* component to ensure that all executed branches correspond to edges in the CFG.

During the analysis phase, the CFG is computed by analyzing either the source code or binary of a given program. In either case, the limitations of static program analysis lead to an over-approximation of the control-flow transfers that can actually take place at runtime. This over-approximation limits the security of the enforced CFI policy because some non-essential edges are included in the CFG.

The enforcement phase ensures that control-flow transfers which are potentially controlled by an attacker, i.e., those whose targets are computed at runtime, such as indirect branches and return instructions, correspond to edges in the CFG produced by the analysis phase. These targets are commonly divided into forward edges such as indirect calls, and backward edges like return instructions (so called because they return control back to the calling function). All CFI mechanisms protect forward edges, but some do not handle backward edges. Assuming code is static and immutable [1], CFI can be enforced by instrumenting existing indirect control-flow transfers at compile time through a modified compiler, ahead of time through static binary rewriting, or during execution through dynamic binary translation. The types of indirect transfers that are subject to such validation and the number of valid targets per branch varies greatly between different CFI defenses. These differences have a major impact on the security and performance of the CFI mechanism.

CFI does not seek to prevent memory corruption, which is the root cause of most vulnerabilities in C and C++ code. While mechanisms that enforce spatial [Nagarakatte et al. 2009] and temporal [Nagarakatte et al. 2010] memory safety eliminate memory corruption (and thereby control-flow hijacking attacks), existing mechanisms are considered prohibitively expensive. In contrast, CFI defenses offer reasonably low overheads while making it substantially harder for attackers to gain arbitrary code execution in vulnerable programs. Moreover, CFI requires few changes to existing source code which allows complex software to be protected in a mostly automatic fashion. While the idea of restricting branch instructions based on target sets predates CFI [Kiriansky 2013; Kiriansky et al. 2002; PaX-Team 2003], Abadi et al.'s seminal paper [Abadi et al. 2005a] was the first formal description of CFI with an accompanying implementation. Since this paper was published over a decade ago, the research community has proposed a large number of variations of the original idea. More recently, CFI implementations have been integrated into production-quality compilers, tools, and operating systems.

Current CFI mechanisms can be compared along two major axes: performance and security. In the scientific literature, performance overhead is usually measured through the SPEC CPU2006 benchmarks. Unfortunately, sometimes only a subset of the benchmarks is used for evaluation. To evaluate security, many authors have used the Average Indirect target Reduction (AIR) [Zhang and Sekar 2013] metric that counts the overall reduction of targets for any indirect control-flow transfer.

[1] DEP marks code pages as executable and readable by default. Programs may subsequently change permissions to make code pages writable using platform-specific APIs such as `mprotect`. Mitigations such as PaX MPROTECT, SELinux [McCarty 2004], and the `ProcessDynamicCodePolicy` Windows API restrict how page permissions can be changed to prevent code injection and modification.

Current evaluation techniques do not adequately distinguish among CFI mechanisms along these axes. Performance measurements are all in the same range, between 0% and 20% across different benchmarks with only slight variations for the same benchmark. Since the benchmarks are evaluated on different machines with different compilers and software versions, these numbers are close to the margin of measurement error. On the security axis, AIR is not a desirable metric for two reasons. First, all CFI mechanisms report similar AIR numbers (a $> 99\%$ reduction of branch targets), which makes AIR unfit to compare individual CFI mechanisms against each other. Second, even a large reduction of targets often leaves enough targets for an attacker to achieve the desired goals [Carlini and Wagner 2014; Davi et al. 2014b; Göktas et al. 2014], making AIR unable to evaluate security of CFI mechanisms on an absolute scale.

We systematize the different CFI mechanisms (where "mechanism" captures both the analysis and enforcement aspects of an implementation) and compare them against metrics for security and performance. By introducing metrics for these areas, our analysis allows the objective comparison of different CFI mechanisms both on an absolute level and relatively against other mechanisms. This in turn allows potential users to assess the trade-offs of individual CFI mechanisms and choose the one that is best suited to their use case. Further, our systematization provides a more meaningful way to classify CFI mechanism than the ill-defined and inconsistently used "coarse" and "fine" grained classification.

To evaluate the security of CFI mechanisms we follow a *comprehensive* approach, classifying them according to a *qualitative* and a *quantitative* analysis. In the qualitative security discussion we compare the strengths of individual solutions on a conceptual level by evaluating the CFI policy of each mechanism along several axes: (i) precision in the forward direction, (ii) precision in the backward direction, (iii) supported control-flow transfer types according to the source programming language, and (iv) reported performance. In the quantitative evaluation, we measure the target sets generated by each CFI mechanism for the SPEC CPU2006 benchmarks. The precision and security guarantees of a CFI mechanism depend on the *precision* of target sets used at runtime, i.e., across all control-flow transfers, how many superfluous targets are reachable through an individual control-flow transfer. We compute these target sets for all available CFI mechanisms and compare the ranked sizes of the sets against each other. This methodology lets us compare the actual sets used for the integrity checks of one mechanism against other mechanisms. In addition, we collect all indirect control-flow targets used for the individual SPEC CPU2006 benchmarks and use these sets as a lower bound on the set of required targets. We use this lower bound to compute how close a mechanism is to an *ideal* CFI mechanism. An ideal CFI mechanism is one where the enforced CFG's edges exactly correspond to the executed branches.

As a second metric, we evaluate the performance impact of open-sourced, compiler-based CFI mechanisms. In their corresponding publications, each mechanism was evaluated on different hardware, different libraries, and different operating systems, using either the full or a partial set of SPEC CPU2006 benchmarks. We cannot port all evaluated CFI mechanisms to the same baseline compiler. Therefore, we measure the overhead of each mechanism relative to the compiler it was integrated into. This apples-to-apples comparison highlights which SPEC CPU2006 benchmarks are most useful when evaluating CFI.

The paper is structured as follows. We first give a detailed background of the theory underlying the analysis phase of CFI mechanisms. This allows us to then qualitatively compare the different mechanisms on the precision of their analysis. We then quantify this comparison with a novel metric. This is followed by our performance results for the different implementation. Finally, we highlight best practices and future research directions for the CFI community identified during our evaluation of the different mechanisms, and conclude.

Overall, we present the following contributions:

(1) a systematization of CFI mechanisms with a focus on discussing the major different CFI mechanisms and their respective trade-offs,
(2) a taxonomy for classifying the underlying analysis of a CFI mechanism,

```
void foo(int a){
    return;
}
void bar(int a){
    return;
}
void baz(void){
    int a = input();
    void (*fptr)(int);
    if(a){
      fptr = foo;
      fptr();
    } else {
      fptr = bar;
      fptr();
    }
}
```

Fig. 1: Simplified example of over approximation in static analysis.

(3) presentation of both a qualitative and quantitative security metric and the evaluation of existing CFI mechanisms along these metrics, and
(4) a detailed performance study of existing CFI mechanisms.

2. FOUNDATIONAL CONCEPTS

We first introduce CFI and discuss the two components of most CFI mechanisms: (i) the *analysis* that defines the CFG (which inherently limits the precision that can be achieved) and (ii) the runtime instrumentation that *enforces* the generated CFG. Secondly, we classify and systematize different types of control-flow transfers and how they are used in programming languages. Finally, we briefly discuss the CFG precision achievable with different types of static analysis. For those interested, a more comprehensive overview of static analysis techniques is available in Appendix B.

2.1. Control-Flow Integrity

CFI is a policy that restricts the execution flow of a program at runtime to a predetermined CFG by validating indirect control-flow transfers. On the machine level, indirect control-flow transfers may target any executable address of mapped memory, but in the source language (C, C++, or Objective-C) the targets are restricted to valid language constructs such as functions, methods and switch statement cases. Since the aforementioned languages rely on manual memory management, it is left to the programmer to ensure that non-control data accesses do not interfere with accesses to control data such that programs execute legitimate control flows. Absent any security policy, an attacker can therefore exploit memory corruption to redirect the control-flow to an arbitrary memory location, which is called control-flow hijacking. CFI closes the gap between machine and source code semantics by restricting the allowed control-flow transfers to a smaller set of target locations. This smaller set is determined per indirect control-flow location. Note that languages providing complete memory and type safety generally do not need to be protected by CFI. However, many of these "safe" languages rely on virtual machines and libraries written in C or C++ that will benefit from CFI protection.

Most CFI mechanisms determine the set of valid targets for each indirect control-flow transfer by computing the CFG of the program. The security guarantees of a CFI mechanism depend on the precision of the CFG it constructs. The CFG cannot be perfectly precise for non-trivial programs. Because the CFG is statically determined, there is always some over-approximation due to imprecision of the static analysis. An equivalence class is the set of valid targets for a given indirect control-flow transfer. Throughout the following, we reference Figure 1. Assuming an analysis based on function types or a flow-insensitive analysis, both `foo()` and `bar()` end up in the same equivalence class. Thus, at line 12 and line 15 either function can be called. However, from the source code we can tell that at line 12 only `foo()` should be called, and at line 15 only `bar()` should be called. While this specific problem can be addressed with a flow-sensitive analysis, all known static program analysis techniques are subject to some over-approximation (see Appendix B).

Once the CFI mechanism has computed an approximate CFG, it has to enforce its security policy. We first note that CFI does not have to enforce constraints for control-flows due to direct branches because their targets are immune to memory corruption thanks to DEP. Instead, it focuses on attacker-corruptible branches such as indirect calls, jumps, and returns. In particular, it must protect control-flow transfers that allow runtime-dependent, targets such as `void (*fptr)(int)` in Figure 1. These targets are stored in either a register or a memory location depending on the compiler and the exact source code. The indirection such targets provide allows flexibility as, e.g., the target of a function may depend on a call-back that is passed from another module. Another example of indirect control-flow transfers is return instructions that read the return address from the stack. Without such an indirection, a function would have to explicitly enumerate all possible callers and check to which location to return to based on an explicit comparison.

For indirect call sites, the CFI enforcement component validates target addresses before they are used in an indirect control-flow transfer. This approach detects code pointers (including return addresses) that were modified by an attacker – if the attacker's chosen target is not a member of the statically determined set.

2.2. Classification of Control-Flow Transfers

Control-flow transfers can broadly be separated into two categories: (i) *forward* and (ii) *backward*. Forward control-flow transfers are those that move control to a new location inside a program. When a program returns control to a prior location, we call this a backward control-flow[2].

A CPU's instruction-set architecture (ISA) usually offers two forward control-flow transfer instructions: call and jump. Both of these are either direct or indirect, resulting in four different types of forward control-flow:

— *direct jump*: is a jump to a constant, statically determined target address. Most local control-flow, such as loops or if-then-else cascaded statements, use direct jumps to manage control.
— *direct call*: is a call to a constant, statically determined target address. Static function calls, for example, use direct call instructions.
— *indirect jump*: is a jump to a computed, i.e., dynamically determined target address. Examples for indirect jumps are switch-case statements using a dispatch table, Procedure Linkage Tables (PLT), as well as the threaded code interpreter dispatch optimization [Bell 1973; Debaere and van Campenhout 1990; Kogge 1982].
— *indirect call*: is a call to a computed, i.e., dynamically determined target address. The following three examples are relevant in practice:
Function pointers are often used to emulate object-oriented method dispatch in classical record data structures, such as C `structs`, or for passing callbacks to other functions.
vtable dispatch is the preferred way to implement dynamic dispatch to C++ methods. A C++ object keeps a pointer to its *vtable*, a table containing pointers to all virtual methods of its dynamic type. A method call, therefore, requires (i) dereferencing the vtable pointer, (ii) computing table index using the method offset determined by the object's static type, and (iii) an indirect call instruction to the table entry referenced in the previous step. In the presence of multiple inheritance, or multiple dispatch, dynamic dispatch is slightly more complicated.

[2]Note the ambiguity of a backward edge in machine code (i.e., a backward jump to an earlier memory location) which is different from a backward control-flow transfer as used in CFI.

Smalltalk-style `send`-method dispatch that requires a dynamic type look-up. Such a dynamic dispatch using a `send`-method in Smalltak, Objective-C, or JavaScript requires walking the class hierarchy (or the prototype chain in JavaScript) and selecting the first method with a matching identifier. This procedure is required for all method calls and therefore impacts performance negatively. Note that, e.g., Objective-C uses a lookup cache to reduce the overhead.

We note that jump instructions can also be either conditional or unconditional. For the purposes of this paper this distinction is irrelevant.

All common ISAs support backward and forward indirect control-flow transfers. For example, the x86 ISA supports backward control-flow transfers using just one instruction: return, or just `ret`. A return instruction is the symmetric counterpart of a call instruction, and a compiler emits function prologues and epilogues to form such pairs. A call instruction pushes the address of the immediately following instruction onto the native machine stack. A return instruction pops the address off the native machine stack and updates the CPU's instruction pointer to point to this address. Notice that a return instruction is conceptually similar to an indirect jump instruction, since the return address is unknown a priori. Furthermore, compilers are emitting call-return pairs by *convention* that hardware usually does not enforce. By modifying return addresses on the stack, an attacker can "return" to all addresses in a program, the foundation of return-oriented programming [Checkoway et al. 2010; Roemer et al. 2012; Shacham 2007].

Control-flow transfers can become more complicated in the presence of exceptions. Exception handling complicates control-flows locally, i.e., within a function, for example by moving control from a try-block into a catch-block. Global exception-triggered control-flow manipulation, i.e., interprocedural control-flows, require unwinding stack frames on the current stack until a matching exception handler is found.

Other control-flow related issues that CFI mechanisms should (but not always do) address are: (i) separate compilation, (ii) dynamic linking, and (iii) compiling libraries. These present challenges because the entire CFG may not be known at compile time. This problem can be solved by relying on LTO, or dynamically constructing the combined CFG. Finally, keep in mind that, in general, not all control-flow transfers can be recovered from a binary.

Summing up, our classification scheme of control-flow transfers is as follows:

— **CF.1**: backward control-flow,
— **CF.2**: forward control-flow using direct jumps,
— **CF.3**: forward control-flow using direct calls,
— **CF.4**: forward control-flow using indirect jumps,
— **CF.5**: forward control-flow using indirect calls supporting function pointers,
— **CF.6**: forward control-flow using indirect calls supporting vtables,
— **CF.7**: forward control-flow using indirect calls supporting Smalltalk-style method dispatch,
— **CF.8**: complex control-flow to support exception handling,
— **CF.9**: control-flow supporting language features such as dynamic linking, separate compilation, etc.

According to this classification, the C programming language uses control-flow transfers 1–5, 8 (for setjmp/longjmp) and 9, whereas the C++ programming language allows all control-flow transfers except no. 7.

2.3. Classification of Static Analysis Precision

As we saw in Section 2.1, the security guarantees of a CFI mechanism ultimately depend on the precision of the CFG that it computes. This precision is in turn determined by the type of static analysis used. For the purposes of this paper, the following classification summarizes prior work to determine forward control-flow transfer analysis precision (see Appendix B for full details). In order of increasing static analysis precision (SAP), our classifications are:

— **SAP.F.0**: No forward branch validation

— **SAP.F.1a**: ad-hoc algorithms and heuristics
— **SAP.F.1b**: context- and flow-insensitive analysis
— **SAP.F.1c**: labeling equivalence classes
— **SAP.F.2**: class-hierarchy analysis
— **SAP.F.3**: rapid-type analysis
— **SAP.F.4a**: flow-sensitive analysis
— **SAP.F.4b**: context-sensitive analysis
— **SAP.F.5**: context- and flow-sensitive analysis
— **SAP.F.6**: dynamic analysis (optimistic)

The following classification summarizes prior work to determine backward control-flow transfer analysis precision:

— **SAP.B.0**: No backward branch validation
— **SAP.B.1**: Labeling equivalence classes
— **SAP.B.2**: Shadow stack

Note that there is well established and vast prior work in static analysis that goes well beyond the scope of this paper [Nielson et al. 2009]. The goal of our systematization is merely to summarize the most relevant aspects and use them to shed more light on the precision aspects of CFI.

2.4. Nomenclature and Taxonomy

Prior work on CFI usually classifies mechanisms into fine-grained and coarse-grained. Over time, however, these terms have been used to describe different systems with varying granularity and have, therefore, become overloaded and imprecise. In addition, prior work only uses a rough separation into forward and backward control-flow transfers without considering sub types or precision. We hope that the classifications here will allow a more precise and consistent definition of the precision of CFI mechanisms underlying analysis, and will encourage the CFI community to use the most precise techniques available from the static analysis literature.

3. SECURITY

In this section we present a security analysis of existing CFI implementations. Drawing on the foundational knowledge in Section 2, we present a qualitative analysis of the theoretical security of different CFI mechanisms based on the policies that they implement. We then give a quantitative evaluation of a selection of CFI implementations. Finally, we survey previous security evaluations and known attacks against CFI.

3.1. Qualitative Security Guarantees

Our qualitative analysis of prior work and proposed CFI implementations relies on the classifications of the previous section (cf. Section 2) to provide a higher resolution view of precision and security. Figure 2 summarizes our findings among four dimensions based on the author's reported results and analysis techniques. Figure 3 presents our verified results for open source LLVM-based implementations that we have selected. Further, it adds a quantitative argument based on our work in Section 3.2.

In Figure 2 the axes and values were calculated as follows. Note that (i) the scale of each axis varies based on the number of data points required and (ii) weaker/slower always scores lower and stronger/faster higher. Therefore, the area of the spider plot roughly estimates the security/precision of a given mechanism:

— CF: supported control-flow transfers, assigned based on our classification scheme in Section 2.2;
— RP: reported performance numbers. Performance is quantified on a scale of 1-10 by taking the arctangent of reported runtime overhead and normalizing for high granularity near the median overhead. An implementation with no overhead receives a full score of 10, and one with about 35% or greater overhead receives a minimum score of 1.

— SAP.F: static-analysis precision of forward control-flows, assigned based on our classification in Section 2.3; and
— SAP.B: static-analysis precision of backward control-flows, assigned based on our classification in Section 2.3.

The shown CFI implementations are ordered chronologically by publication year, and the colors indicate whether a CFI implementation works on the binary-level (blue), relies on source-code (green), or uses other mechanisms (red), such as hardware implementations.

Our classification and categorization efforts for reported performance were hindered by methodological variances in benchmarking. Experiments were conducted on different machines, different operating systems, and also different or incomplete benchmark suites. Classifying and categorizing static analysis precision was impeded by the high level, imprecise descriptions of the implemented static analysis by various authors. Both of these impediments, naturally, are sources of imprecision in our evaluation.

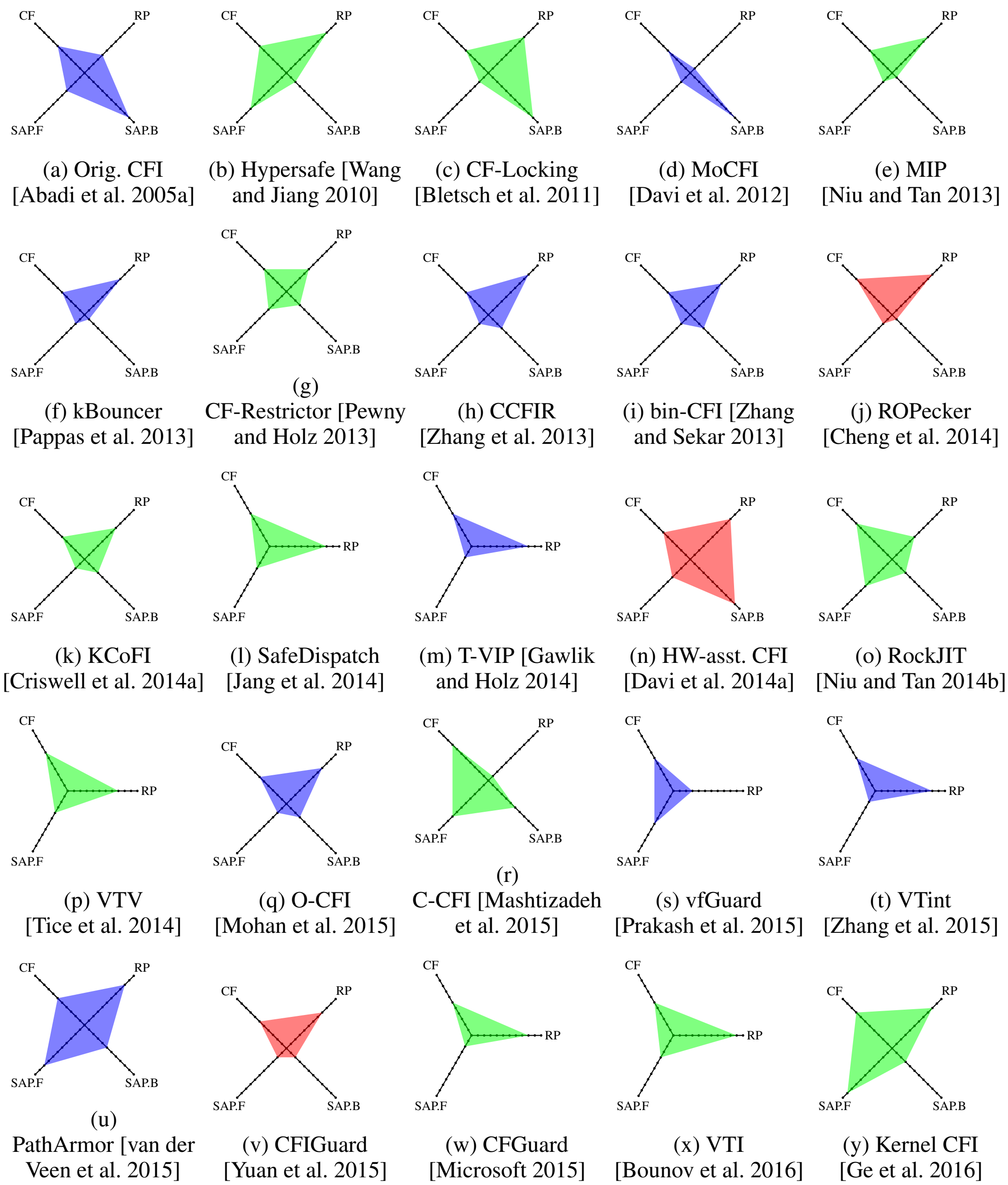
Comprehensive protection through CFI requires the validation of both forward and backward branches. This requirement means that the reported performance impact for forward-only approaches (i.e., SafeDispatch, T-VIP, VTV, IFCC, vfGuard, and VTint) is restricted to partial protection. The performance impact for backward control-flows must be considered as well, when comparing these mechanisms to others with full protection.

CFI mechanisms satisfying SAP.B.2, i.e., using a shadow stack to obtain high precision for backward control-flows are: original CFI [Abadi et al. 2005a], MoCFI [Davi et al. 2012], HAFIX [Arias et al. 2015; Davi et al. 2014a], and Lockdown [Payer et al. 2015]. PathArmor emulates a shadow stack through validating the last-branch register (LBR).

Increasing the precision of static analysis techniques that validate whether any given control-flow transfer corresponds to an edge in the CFG decreases the performance of the CFI mechanism. Most implementations choose to combine precise results of static analysis into an equivalence class. Each such equivalence class receives a unique identifier, often referred to as a label, which the CFI enforcement component validates at runtime. By not using a shadow stack, or any other comparable high-precision backward control-flow transfer validation mechanism, even high precision forward control-flow transfer static analysis becomes imprecise due to labeling. The explanation for this loss in precision is straightforward: to validate a control-flow transfer, all callers of a function need to carry the same label. Labeling, consequently, is a substantial source of imprecision (see Section 3.2 for more details). The notable exception in this case is πCFI, which uses dynamic information, to activate pre-determined edges, dynamically enabling high-resolution, precise control-flow graph (somewhat analogous to dynamic points-to sets [Mock et al. 2001]. Borrowing a term from information-flow control [Sabelfeld and Myers 2003], πCFI can, however, suffer from *label creep* by accumulating too many labels from the static CFG.

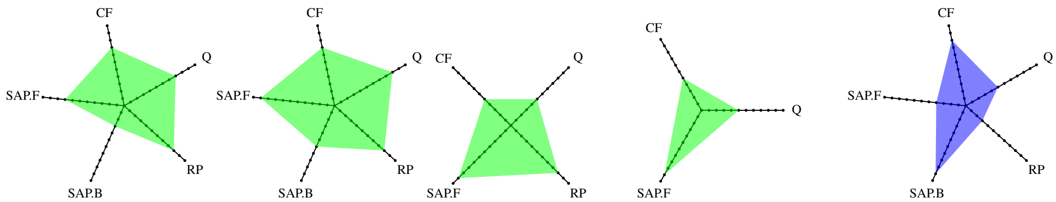
CFI implementations introducing imprecision via labeling are: the original CFI paper [Abadi et al. 2005a], control-flow locking [Bletsch et al. 2011], CF-restrictor [Pewny and Holz 2013], CCFIR [Zhang et al. 2013], MCFI [Niu and Tan 2014a], KCoFI [Criswell et al. 2014b], and RockJIT [Niu and Tan 2014b].

According to the criteria established in analyzing points-to precision, we find that at the time of this writing, πCFI [Niu and Tan 2015b] offers the highest precision due to leveraging dynamic points-to information. πCFI's predecessors, RockJIT [Niu and Tan 2014b] and MCFI [Niu and Tan 2014a], already offered a high precision due to the use of context-sensitivity in the form of types. Ideal PathArmor also scores well when subject to our evaluation: high-precision in both directions, forward and backward, but is hampered by limited hardware resources (LBR size) and restricting protection to the main executable (i.e., trusting libraries). Lockdown [Payer et al. 2015] offers high precision on the backward edges but derives its equivalence classes from the number of libraries used in an application and is therefore inherently limited in the precision of the forward edges. IFCC [Tice et al. 2014] offers variable static analysis granularity. On the one hand, IFCC describes a Full mode that uses type information, similar to πCFI and its predecessors. On the other hand, IFCC mentions



(a) Orig. CFI [Abadi et al. 2005a]
(b) Hypersafe [Wang and Jiang 2010]
(c) CF-Locking [Bletsch et al. 2011]
(d) MoCFI [Davi et al. 2012]
(e) MIP [Niu and Tan 2013]
(f) kBouncer [Pappas et al. 2013]
(g) CF-Restrictor [Pewny and Holz 2013]
(h) CCFIR [Zhang et al. 2013]
(i) bin-CFI [Zhang and Sekar 2013]
(j) ROPecker [Cheng et al. 2014]
(k) KCoFI [Criswell et al. 2014a]
(l) SafeDispatch [Jang et al. 2014]
(m) T-VIP [Gawlik and Holz 2014]
(n) HW-asst. CFI [Davi et al. 2014a]
(o) RockJIT [Niu and Tan 2014b]
(p) VTV [Tice et al. 2014]
(q) O-CFI [Mohan et al. 2015]
(r) C-CFI [Mashtizadeh et al. 2015]
(s) vfGuard [Prakash et al. 2015]
(t) VTint [Zhang et al. 2015]
(u) PathArmor [van der Veen et al. 2015]
(v) CFIGuard [Yuan et al. 2015]
(w) CFGuard [Microsoft 2015]
(x) VTI [Bounov et al. 2016]
(y) Kernel CFI [Ge et al. 2016]

Fig. 2: CFI implementation comparison: supported control-flows (CF), reported performance (RP), static analysis precision: forward (SAP.F) and backward (SAP.B). Backward (SAP.B) is omitted for mechanisms that do not support back edges. Color coding of CFI implementations: binary are blue, source-based are green, others red.



(a) MCFI [Niu and Tan 2014a] (b) πCFI [Niu and Tan 2015b] (c) IFCC [Tice et al. 2014] (d) LLVM-CFI-3.7 (2015) (e) Lockdown [Payer et al. 2015]

Fig. 3: Quantitative comparison: control-flows (CF), quantitative security (Q), reported performance (RP), static analysis precision: forward (SAP.F) and backward (SAP.B).

less precise modes, such as using a single set for all destinations, and separating by function arity. With the exception of Hypersafe [Wang and Jiang 2010], all other evaluated CFI implementations with supporting academic publications offer lower precision of varying degrees, at most as precise as SAP.F.3.

3.2. Quantitative Security Guarantees

Quantitatively assessing how much security a CFI mechanism provides is challenging as attacks are often program dependent and different implementations might allow different attacks to succeed. So far, the only existing quantitative measure of the security of a CFI implementation is Average Indirect Target Reduction (AIR). Unfortunately, AIR is known to be a weak proxy for security [Tice et al. 2014]. A more meaningful metric must focus on the number of targets (i.e., number of equivalence classes) available to an attacker. Furthermore, it should recognize that smaller classes are more secure, because they provide less attack surface. Thus, an implementation with a small number of large equivalence classes is more vulnerable than an implementation with a large number of small equivalence classes.

One possible metric is the product of the number of equivalence classes (EC) and the inverse of the size of the largest class (LC), see Equation 1. Larger products indicate a more secure mechanism as the product increases with the number of equivalence classes and decreases with the size of the largest class. More equivalence classes means that each class is smaller, and thus provides less attack surface to an adversary. Controlling for the size of the largest class attempts to control for outliers, e.g., one very large and thus vulnerable class and many smaller ones. A more sophisticated version would also consider the usability and functionality of the sets. Usability considers whether or not they are located on an attacker accessible "hot" path, and if so how many times they are used. Functionality evaluates the quality of the sets, whether or not they include "dangerous" functions like mprotect. A large equivalence class that is pointed to by many indirect calls on the hot path poses a higher risk because it is more accessible to the attacker.

$$EC * \frac{1}{LC} = QuantitativeSecurity \tag{1}$$

This metric is not perfect, but it allows a meaningful direct comparison of the security and precision of different CFI mechanisms, which AIR does not. The gold standard would be adversarial analysis. However, this currently requires a human to perform the analysis on a per-program basis. This leads to a large number of methodological issues: how many analysts, which programs and inputs, how to combine the results, etc. Such a study is beyond the scope of this work, which instead uses our proposed metric which can be measured programatically.

This section measures the number and sizes of sets to allow a meaningful, direct comparison of the security provided by different implementations. Moreover, we report the dynamically observed number of sets and their sizes. This quantifies the maximum achievable precision from the implementations' CFG analysis, and shows how over-approximate they were for a given execution of the program.

3.2.1. Implementations. We evaluate four compiler-based, open-source CFI mechanisms IFCC, LLVM-CFI, MCFI, and πCFI. For IFCC and MCFI we also evaluated the different analysis techniques available in the implementation. Note that we evaluate two different versions of LLVM-CFI, the first release in LLVM 3.7 and the second, highly modified version in LLVM 3.9. In addition to the compiler-based solutions, we also evaluate Lockdown, which is a binary-based CFI implementation.

MCFI and πCFI already have a built-in reporting mechanism. For the other mechanisms we extend the instrumentation pass and report the number and size of the produced target sets. We then used the implementations to compile, and for πCFI run, the SPEC CPU2006 benchmarks to produce the data we report here. πCFI must be run because it does dynamic target activation. This does tie our results to the ref data set for SPEC CPU2006, because as with any dynamic analysis the results will depend on the input.

IFCC[3] comes with four different CFG analysis techniques: *single*, *arity*, *simplified*, and *full*. *Single* creates only one equivalence class for the entire program, resulting in the weakest possible CFI policy. *Arity* groups functions into equivalence classes based on their number of arguments. *Simplified* improves on this by recognizing three types of arguments: composite, integer, or function pointer. *Full* considers the precise return type and types of each argument. We expect full to yield the largest number of equivalence classes with the smallest sizes, as it performs the most exact distribution of targets.

Both MCFI and πCFI rely on the same underlying static analysis. The authors claim that disabling tail calls is the single most important precision enhancement for their CFG analysis [Niu and Tan 2015a]. We measure the impact of this option on our metric. MCFI and πCFI are also unique in that their policy and enforcement mechanisms consider backward edges as well as forward edges. When comparing to other implementations, we only consider forward edges. This ensures direct comparability for the number and size of sets. The results for backward edges are presented as separate entries in the figures.

As of LLVM 3.7, LLVM-CFI could not be directly compared to the other CFI implementations because its policy was strictly more limited. Instead of considering all forward, or all forward and backward edges, LLVM-CFI 3.7 focused on virtual calls and ensures that virtual, and non-virtual calls are performed on objects of the correct dynamic type. As of LLVM 3.9, LLVM-CFI has added support for all indirect calls. Despite these differences, we show the full results for both LLVM-CFI implementations in all tables and graphs.

Lockdown is a CFI implementation that operates on compiled binaries and supports the instrumentation of dynamically loaded code. To protect backward edges, Lockdown enforces a shadow stack. For the forward edge, it instruments libraries at runtime, creating one equivalence class per library. Consequently, the set size numbers are of the greatest interest for Lockdown. Lockdown's precision depends on symbol information, allowing indirect calls anywhere in a particular library if it is stripped. Therefore, we only report the set sizes for non-stripped libraries where Lockdown is more precise.

To collect the data for our lower bound, we wrote an LLVM pass. This pass instruments the program to collect and report the source line for each indirect call, the number of different targets for each indirect call, and the number of times each of those targets was used. This data is collected at runtime. Consequently, it represents only a subset of all possible indirect calls and targets that are required for the sample input to run. As such, we use it to present a lower bound on the number of equivalence sets (i.e. unique indirect call sites) and size of those sets (i.e. the number of different locations called by that site).

3.2.2. Results. We conducted three different quantitative evaluations in line with our proposed metric for evaluating the overall security of a CFI mechanism and our lower bound. For IFCC,

[3]Note that the IFCC patch was pulled by the authors and will be replaced by LLVM-CFI.

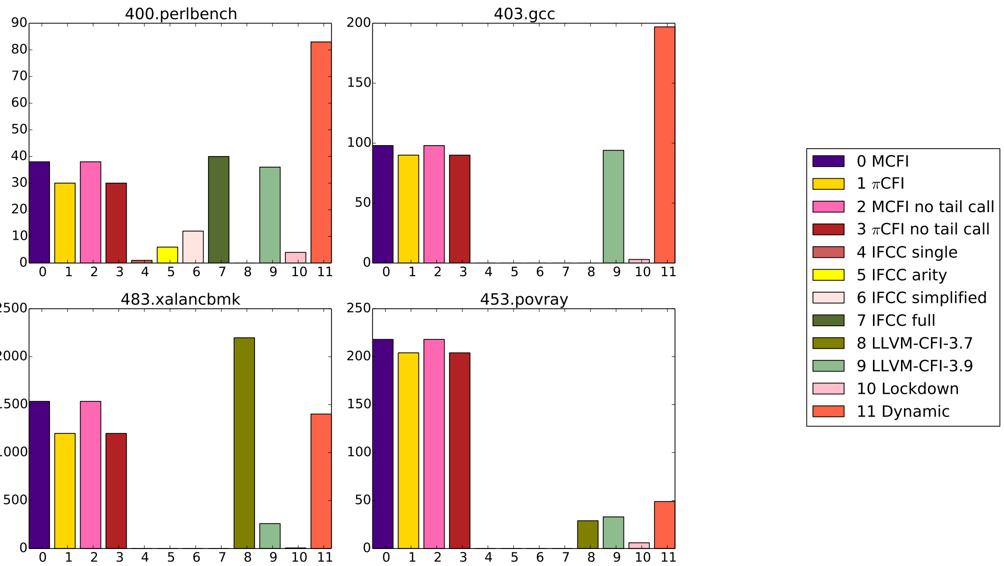


Fig. 4: Total number of forward-edge equivalence classes when running SPEC CPU2006 (higher is better).

LLVM-CFI (3.7 and 3.9), and MCFI it is sufficient to compile the SPEC CPU2006 benchmarks as they do not dynamically change their equivalence classes. πCFI uses dynamic information, so we had to run the SPEC CPU2006 benchmarks. Similarly, Lockdown is a binary CFI implementation that only operates at run time. We highlight the most interesting results in Figure 3, see Table III in Appendix C for the full data set.

Figure 4 shows the number of equivalence classes for the five CFI implementations that we evaluated, as well as their sub-configurations. As advertised, IFCC *Single* only creates one equivalence class. This IFCC mode offers the least precision of any implementation measured. The other IFCC analysis modes only had a noticeable impact for perlbench and soplex. Indeed, on the sjeng benchmark all four analysis modes produced only one equivalence class.

On forward edges, MCFI and πCFI are more precise than IFCC in all cases except for perlbench where they are equivalent. LLVM-CFI 3.9 is more precise than IFCC while being less precise than MCFI. MCFI and πCFI are the only implementations to consider backward edges, so no comparison with other mechanisms is possible on backward edge precision. Relative to each other, πCFI's dynamic information decreases the number of equivalence classes available to the attacker by 21.6%. The authors of MCFI and πCFI recommend disabling tail calls to improve CFG precision. This only impacts the number of sets that they create for backward edges, not forward edges, see Appendix C. As such this compiler flag does not impact most CFI implementations, which rely on a shadow stack for backward edge security.

LLVM-CFI 3.7 creates a number of equivalence classes equal to the number of classes used in the C++ benchmarks. Recall that it only provides support for a subset of indirect control-flow transfer types. However, we present the results in Figure 4 and Figure 5 to show the relative cost of protecting vtables in C++ relative to protecting all indirect call sites.

We quantify the set sizes for each of the four implementations in Figure 5. We show box and whisker graphs of the set sizes for each implementation. The red line is the median set size and a smaller median set size indicates more secure mechanisms. The blue box extends from the 25th percentile to the 75th, smaller boxes indicate a tight grouping around the median. An implementation might have a low median, but large boxes indicate that there are still some large equivalence classes

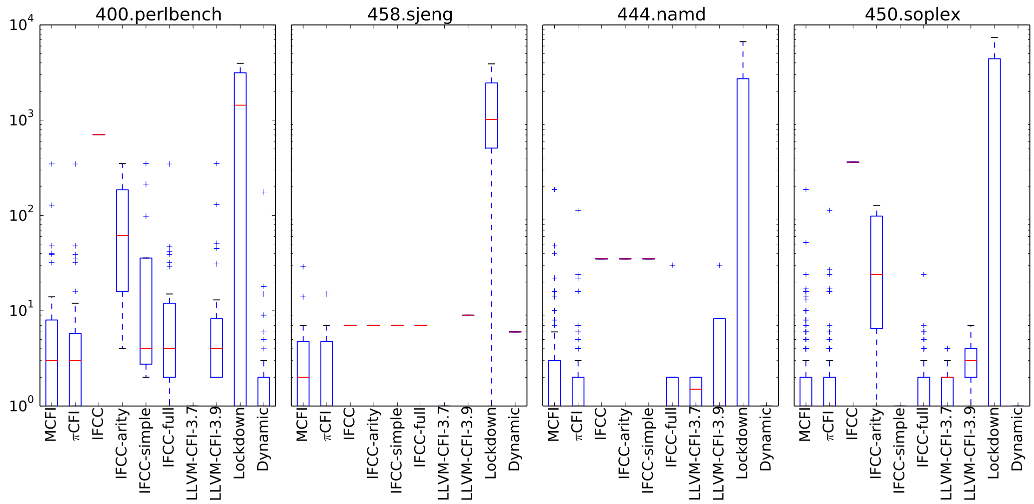


Fig. 5: Whisker plot of equivalence class sizes for different mechanisms when running SPEC CPU2006. (Smaller is Better)

for an attacker to target. The top whisker extends from the top of the box for 150% of the size of the box. Data points beyond the whiskers are considered outliers and indicate large sets. This plot format allows an intuitive understanding of the security of the distribution of equivalence class sizes. Lower medians and smaller boxes are better. Any data points above the top of the whisker show very large, outlier equivalence classes that provide a large attack surface for an adversary.

Note that IFCC only creates a single equivalence class for xalancbmk and namd (except for the Full configuration on namd which is more precise). Entries with just a single equivalence class are reported as only a median. IFCC data points allow us to rank the different analysis methods, based on the results for benchmarks where they actually impacted set size: perlbench and soplex. In increasing order of precision (least precise to most precise) they are: *single*, *arity*, *simplified*, and *full*. This does not necessarily mean that the more precise analysis methods are more secure, however. For perlbench the more precise methods have outliers at the same level as the median for the least precise (i.e., *single*) analysis. For soplex the outliers are not as bad, but the *full* outlier is the same size as the median for *arity*. While increasing the precision of the underlying CFG analysis increases the overall security, edge cases can cause the incremental gains to be much smaller than anticipated.

The MCFI forward-edge data points highlight this. The MCFI median is always smaller than the IFCC median. However, for all the benchmarks where both ran, the MCFI outliers are greater than or equal to the largest IFCC set. From a quantitative perspective, we can only confirm that MCFI is at least as secure as IFCC. The effect of the outlying large sets on relative security remains an open question, though it seems likely that they provide opportunities for an attacker.

LLVM-CFI 3.9 presents an interesting compromise. As the full set of whisker plots in Appendix C shows, it has fewer outliers. However, it also has, on average, a greater median set size. Given the open question of the importance of the outliers, LLVM-CFI 3.9 could well be more secure in practice.

LLVM-CFI 3.7 - which only protects virtual tables - sets do not have extreme outliers. Additionally, Figure 5 shows that the equivalence classes that are created have a low variance, as seen by the more compact whisker plots that lack the large number of outliers present for other techniques. As such, LLVM-CFI 3.7 does not suffer from the edge cases that effect more general analyzes.

Lockdown consistently has the largest set sizes, as expected because it only creates one equivalence class per library and the SPEC CPU2006 benchmarks are optimized to reduce the amount of external library calls. These sets are up to an order of magnitude larger than compiler techniques. However, Lockdown isolates faults into libraries as each library has its independent set of targets compared to a single set of targets for other binary-only approaches like CCFIR and bin-CFI.

The lower bound numbers were measured dynamically, and as such encapsulate a subset of the actual equivalence sets in the static program. Further, each such set is at most the size of the static set. Our lower bound thus provides a proxy for an ideal CFI implementation in that it is perfectly precise for each run. However, all of the IFCC variations report fewer equivalence classes than our dynamic bound.

The whisker plots for our dynamic lower bound in Figure 5 show that some of the SPEC CPU2006 benchmarks inherently have outliers in their set sizes. For perlbench, gcc, gobmk, h264ref, omnetpp, and xalancbmk our dynamic lower bound and the static set sizes from the compiler-based implementations all have a significant number of outliers. This provides quantitative backing to the intuition that some code is more amenable to protection by CFI. Evaluating what coding styles and practices make code more or less amenable to CFI is out of scope here, but would make for interesting future work.

Note that for namd and soplex in Figure 5 there is no visible data for our dynamic lower bound because all the sets had a single element. This means the median size is one which is too low to be visible. For all other mechanisms no visible data means the mechanism was incompatible with the benchmark.

3.3. Previous Security Evaluations and Attacks

Evaluating the security of a CFI implementation is challenging because exploits are program dependent and simple metrics do not cover the security of a mechanism. The Average Indirect target Reduction (AIR) metric [Zhang and Sekar 2013] captures the average reduction of allowed targets, following the idea that an attack is less likely if fewer targets are available. This metric and variants were then used to measure new CFI implementations, generally reporting high numbers of more than 99%. Such high numbers give the illusion of relatively high security but, e.g., if a binary has 1.8 MB of executable code (the size of the glibc on Ubuntu 14.04), then an AIR value of 99.9% still allows 1,841 targets, likely enough for an arbitrary attack. A similar alternative metric to evaluate CFI effectiveness is the gadget reduction metric [Niu and Tan 2014a]. Unfortunately, these simple relative metrics give, at best, an intuition for security and we argue that a more rigorous metric is needed.

A first set of attacks against CFI implementations targeted *coarse-grained* CFI that only had 1-3 equivalence classes [Carlini and Wagner 2014; Davi et al. 2014b; Göktas et al. 2014]. These attacks show that equivalence classes with a large number of targets allow an attacker to execute code and system calls, especially if return instructions are allowed to return to any call site.

Counterfeit Object Oriented Programming (COOP) [Schuster et al. 2015] introduced the idea that whole C++ methods can be used as gadgets to implement Turing-complete computation. Virtual calls in C++ are a specific type of indirect function calls that are dispatched via vtables, which are arrays of function pointers. COOP shows that an attacker can construct counterfeit objects and, by reusing existing vtables, perform arbitrary computations. This attack shows that indirect calls requiring another level-of-indirection (e.g., through a vtable) must have additional checks that consider the types at the language level for the security check as well.

Control Jujutsu [Evans et al. 2015b] extends the existing attacks to so-called fine-grained CFI by leveraging the imprecision of points-to analysis. This work shows that common software engineering practices like modularity (e.g., supporting plugins and refactoring) force points-to analysis to merge several equivalence classes. This imprecision results in target sets that are large enough for arbitrary computation.

Control-Flow Bending [Carlini et al. 2015] goes one step further and shows that attacks against ideal CFI are possible. Ideal CFI assumes that a precise CFG is available that is not achievable in practice, i.e., if any edge would be removed then the program would fail. Even in this configuration attacks are likely possible if no shadow stack is used, and sometimes possible even if a shadow stack is used.

Several attacks target data structures used by CFI mechanisms. StackDefiler [Conti et al. 2015] leverages the fact that many CFI mechanisms implement the enforcement as a compiler transformation. Due to this high-level implementation and the fact that the optimization infrastructure of the compiler is unaware of the security aspects, an optimization might choose to spill registers that hold sensitive CFI data to the stack where it can be modified by an attack [Abadi et al. 2005b]. Any CFI mechanism will rely on some runtime data structures that are sometimes writeable (e.g., when MCFI loads new libraries and merges existing sets). Missing the Point [Evans et al. 2015a] shows that ASLR might not be enough to hide this secret data from an adversary.

4. PERFORMANCE

While the security properties of CFI (or the lack thereof for some mechanisms) have received most scrutiny in the academic literature, performance characteristics play a large part in determining which CFI mechanisms are likely to see adoption and which are not. Szekeres et al. [Szekeres et al. 2013] surveyed mitigations against memory corruption and found that mitigations with more than 10% overhead do not tend to see widespread adoption in production environments and that overheads below 5% are desired by industry practitioners.

Comparing the performance characteristics of CFI mechanisms is a non-trivial undertaking. Differences in the underlying hardware, operating system, as well as implementation and benchmarking choices prevents apples-to-apples comparison between the performance overheads reported in the literature. For this reason, we take a two-pronged approach in our performance survey: for a number of publicly available CFI mechanisms, we measure performance directly on the same hardware platform and, whenever possible, on the same operating system, and benchmark suite. Additionally, we tabulate and compare the performance results reported in the literature.

We focus on the aggregate cost of CFI enforcement. For a detailed survey of the performance cost of protecting backward edges from callees to callers we refer to the recent, comprehensive survey by Dang et al. [2015].

4.1. Measured CFI Performance

Selection Criteria. It is infeasible to replicate the reported performance overheads for all major CFI mechanisms. Many implementations are not publicly available or require substantial modification to run on modern versions of Linux or Windows. We therefore focus on recent, publicly available, compiler-based CFI mechanisms.

Several compiler-based CFI mechanisms share a common lineage. LLVM-CFI, for instance, improves upon IFCC, πCFI improves upon MCFI, and VTI is an improved version of SafeDispatch. In those cases, we opted to measure the latest available version and rely on reported performance numbers for older versions.

Method. Most authors use the SPEC CPU2006 benchmarks to report the overhead of their CFI mechanism. We follow this trend in our own replication study. All benchmarks were compiled using the `-O2` optimization level. The benchmarking system was a Dell PowerEdge T620 dual processor server having 64GiB of main memory and two Intel Xeon E5-2660 CPUs running at 2.20 GHz. To reduce benchmarking noise, we ran the tests on an otherwise idle system and disabled all dynamic frequency and voltage scaling features. Whenever possible, we benchmark the implementations under 64-bit Ubuntu Linux 14.04.2 LTS. The CFI mechanisms were baselined against the compiler they were implemented on top of: VTV on GCC 4.9, LLVM-CFI on LLVM 3.7 and 3.9, VTI on LLVM 3.7, MCFI on LLVM 3.5, πCFI on LLVM 3.5. Since CFGuard is part of Microsoft Visual C++ Compiler, MSVC, we used MSVC 19 to compile and run SPEC CPU2006 on a pristine 64-bit Windows 10 installation. We report the geometric mean overhead averaged over three benchmark runs using the reference inputs in Table I.

Some of the CFI mechanisms we benchmark required link-time optimization, LTO, which allows the compiler to analyze and optimize across compilation units. LLVM-CFI and VTI both require LTO, so for these mechanisms, we report overheads relative to a baseline SPEC CPU2006 run that also had

LTO enabled. The increased optimization scope enabled by LTO can allow the compiler to perform additional optimizations such as de-virtualization to lower the cost of CFI enforcement. On the other hand, LLVM's LTO is less practical than traditional, separate compilation, e.g., when compiling large, complex code bases. To measure the πCFI mechanism, we applied the author's patches[4] for 7 of the SPEC CPU2006 benchmarks to remove coding constructs that are not handled by πCFI's control-flow graph analysis [Niu and Tan 2014a]. Likewise, the authors of VTI provided a patch for the xalancbmk benchmark. It updates code that casts an object instance to its sibling class, which can cause a CFI violation. We found these patches for hmmer, povray, and xalancbmk to also be necessary for LLVM-CFI 3.9, which otherwise reports a CFI violation on these benchmarks. VTI was run in interleaved vtable mode which provides the best performance according to its authors [Bounov et al. 2016].

Results. Our performance experiments show that recent, compiler-based CFI mechanisms have mean overheads in the low single digit range. Such low overhead is well within the threshold for adoption specified by [Szekeres et al. 2013] of 5%. This dispenses with the concern that CFI enforcement is too costly in practice compared to alternative mitigations including those based on randomization [Larsen et al. 2014]. Indeed, mechanisms such as CFGuard, LLVM-CFI, and VTV are implemented in widely-used compilers, offering some level of CFI enforcement to practitioners.

We expect CFI mechanisms that are limited to virtual method calls—VTV, VTI, LLVM-CFI 3.7— to have lower mean overheads than those that also protect indirect function calls such as IFCC. The return protection mechanism used by MCFI should introduce additional overhead, and πCFI's runtime policy ought to result in a further marginal increase in overhead. In practice, our results show that LLVM-CFI 3.7 and VTI are the fastest, followed by CFGuard, πCFI, and VTV. The reported numbers for IFCC when run in *single* mode show that it achieves -0.3%, likely due to cache effects. Although our measured overheads are not directly comparable with those reported by the authors of the seminal CFI paper, we find that researchers have managed to improve the precision while lowering the cost[5] of enforcement as the result of a decade worth of research into CFI enforcement.

The geometric mean overheads do not tell the whole story, however. It is important to look closer at the performance impact on benchmarks that execute a high number of indirect branches. Protecting the xalancbmk, omnetpp, and povray C++ benchmarks with CFI generally incurs substantial overheads. All benchmarked CFI mechanisms had above-average overheads on xalancbmk. LLVM-CFI and VTV, which take virtual call semantics into account, were particularly affected. On the other hand, xalancbmk highlights the merits of the recent virtual table interleaving mechanism of VTI which has a relatively low 3.7% overhead (vs. 1.4% reported) on this challenging benchmark.

Although povray is written in C++, it makes few virtual method calls [Zhang et al. 2015]. However, it performs a large number of indirect calls. The CFI mechanisms which protect indirect calls—πCFI, and CFGuard—all incur high performance overheads on povray. Sjeng and h264ref also include a high number of indirect calls which again result in non-negligible overheads particularly when using πCFI with tail calls disabled to improve CFG precision. The hmmer, namd, and bzip2 benchmarks on the other hand show very little overhead as they do not execute a high number of forward indirect branches of any kind. Therefore these benchmarks are of little value when comparing the performance of various CFI mechanisms.

Overall, our measurements generally match those reported in the literature. The authors of VTV [Tice et al. 2014] only report overheads for the three SPEC CPU2006 benchmarks that were impacted the most. Our measurements confirm the authors' claim that the runtimes of the other C++ benchmarks are virtually unaffected. The leftmost πCFI column should be compared to the reported column for πCFI. We measured overheads higher than those reported by Niu and Tan. Both gobmk and xalancbmk show markedly higher performance overheads in our experiments; we believe this is

[4]The patches are available at: https://github.com/mcfi/MCFI/tree/master/spec2006.

[5]Non-CFI related hardware improvements, such as better branch prediction [Rohou et al. 2015], also help to reduce performance overhead.

Table I: Measured and reported CFI performance overhead (%) on the SPEC CPU2006 benchmarks. The programming language of each benchmark is indicated in parenthesis: C(C), C++(+), Fortran(F). CF in a cell indicates we were unable to build and run the benchmark with CFI enabled. Blank cells mean that no results were reported by the original authors or that we did not attempt to run the benchmark. Cells with bold fonts indicate 10% or more overhead, ntc stands for no tail calls.

Benchmark	Measured Performance							Reported Performance									
	VTV	LLVM-CFI		VTI	CFGuard	πCFI	πCFI	VTV	VTI	πCFI	IFCC	MCFI	PathArmor	Lockdown	C-CFI	ROPecker	bin-CFI
Version		3.7	3.9														
Options		LTO	LTO	LTO			ntc		LTO		LTO						
400.perlbench(C)			2.4			8.2	5.3			5.0	1.9	5.0	**15.0**	**150.0**		5.0	**12.0**
401.bzip2(C)			-0.7		-0.3	1.2	0.8			1.0		1.0	0.0	8.0	5.0	0.0	-9.0
403.gcc(C)			CF			6.1	**10.5**			4.5		4.5	9.0	**50.0**		3.0	4.5
429.mcf(C)			3.6		0.5	4.0	1.8			4.0		4.0	1.0	2.0	**10.0**	1.0	0.0
445.gobmk(C)			0.2		-0.2	**11.4**	**11.8**			7.5		7.0	0.0	**43.0**	**50.0**	1.0	**15.0**
456.hmmer(C)			0.1		0.7	0.1	-0.1			0.0		0.0	1.0	3.0	**10.0**	0.0	-0.5
458.sjeng(C)			1.6		3.4	8.4	**11.9**			5.0		5.0	0.0	**80.0**	**40.0**	0.0	-2.5
464.h264ref(C)			5.3		5.4	7.9	8.3			6.0		6.0	1.0	**43.0**	**45.0**	1.0	**28.0**
462.libquantum(C)			-6.9			-3.0	-1.0			-0.3		0.0	3.0	5.0	**10.0**	0.0	-0.5
471.omnetpp(+)	5.8	-1.9	CF	CF	3.8	6.7	**18.8**	8.0	1.2	5.0	-1.2	5.0				2.0	**45.0**
473.astar(+)	3.6	-0.3	0.9	1.6	0.1	2.0	2.9	2.4	0.1	4.0	-0.2	3.5		**17.0**	**75.0**	0.0	**14.0**
483.xalancbmk(+)	**24.0**	7.1	7.2	3.7	5.5	**10.3**	**17.6**	**19.2**	1.4	7.0	3.1	7.0		**118.0**	**170.0**	**15.0**	
410.bwaves(F)														1.0			
416.gamess(F)														**11.0**			
433.milc(C)			0.2		2.0	-1.7	1.4			2.0		2.0	4.0	8.0			2.5
434.zeusmp(F)														0.0			
435.gromacs(C,F)														1.0			
436.cactusADM(C,F)														0.0			
437.leslie3d(F)														1.0			
444.namd(+)	-0.1	-0.2	0.1	-0.3	0.1	-0.3	-0.5			-0.5	-0.2	-0.5		3.0			-2.0
447.dealII(+)	0.7	CF	7.9	CF	-0.1	5.3	4.4			4.5	-2.2	4.5					
450.soplex(+)	0.5	0.5	-0.3	-0.6	2.3	-0.7	0.9		-0.7	-4.0	-1.7	-4.0		**12.0**			3.5
453.povray(+)	-0.6	1.5	8.9	2.0	**10.8**	**11.3**	**17.4**			**10.5**	0.2	**10.0**		**90.0**			**37.0**
454.calculix(C,F)														3.0			
459.gemsFDTD(F)														7.0			
465.tonto(F)														**19.0**			
470.lbm(C)			-0.2		4.2	-0.2	-0.5			1.0		1.0	0.0	2.0			-2.5
482.sphinx3(C)			-0.8		-0.1	0.7	2.4			1.5		1.5	3.0	8.0			0.5
Geo Mean	4.6	1.1	4.4	1.3	2.3	4.0	5.8	9.6	0.5	3.2	-0.3	2.9	3.0	**20.0**	**45.0**	2.6	8.5

in part explained by the fact that Niu and Tan used a newer Intel Xeon processor having an improved branch predictor [Rohou et al. 2015] and higher clock speeds (3.4 vs 2.2 GHz).

We ran πCFI in both normal mode and with tail calls disabled. The geometric mean overhead increased by 1.9% with tail calls disabled. Disabling tail calls in turn increases the number of equivalence classes on each benchmark Figure 4. This is a classic example of the performance/security precision trade-off when designing CFI mechanisms. Implementers can choose the most precise policy within their performance target. CFGuard offers the most efficient protection of forward indirect branches whereas πCFI offers higher security at slightly higher cost.

4.2. Reported CFI Performance

The right-hand side of Table I lists reported overheads on SPEC CPU2006 for CFI mechanisms that we do not measure. IFCC is the first CFI mechanism implemented in LLVM which was later replaced by LLVM-CFI. MCFI is the precursor to πCFI. PathArmor is a recent CFI mechanism that uses dynamic binary rewriting and a hardware feature, the Last Branch Record (LBR) [Intel Inc. 2013] register, that traces the 16 most recently executed indirect control-flow transfers. Lockdown is a pure dynamic binary translation approach to CFI that includes precise enforcement of returns using a shadow stack. C-CFI is a compiler-based approach which stores a cryptographically-secure hash-based message authentication code, HMAC, next to each pointer. Checking the HMAC of a pointer before indirect branches avoids a static points-to analysis to generate a CFG. ROPecker is a CFI mechanism that uses a combination of offline analysis, traces recorded by the LBR register, and emulation in an attempt to detect ROP attacks. Finally, the bin-CFI approach uses static binary rewriting like the original CFI mechanism; bin-CFI is notable for its ability to protect stripped, position-independent ELF binaries that do not contain relocation information.

The reported overheads match our measurements: xalancbmk and povray impose the highest overheads—up to 15% for ROPecker, which otherwise exhibits low overheads, and 1.7x for C-CFI. The interpreter benchmark, perlbench, executes a high number of indirect branches, which leads to high overheads, particularly for Lockdown, PathArmor, and bin-CFI.

Looking at CFI mechanisms that do not require re-compilation—PathArmor, Lockdown, ROPecker, and bin-CFI we see that the mechanisms that only check the contents of the LBR before system calls (PathArmor and ROPecker) report lower mean overheads than approaches that comprehensively instrument indirect branches (Lockdown and bin-CFI) in existing binaries. More broadly, comparing compiler-based mechanisms with binary-level mechanisms, we see that compiler-based approaches are typically as efficient as the binary-level mechanisms that trace control flows using the LBR although compiler-based mechanisms do not limit protection to a short window of recently executed branches. More comprehensive binary-level mechanisms, Lockdown and bin-CFI generally have higher overheads than compiler-based equivalents. On the other hand, Lockdown shows the advantage of binary translation: almost any program can be analyzed and protected, independent from the compiler and source code. Also note that Lockdown incurs additional overhead for its shadow stack, while none of the other mechanisms in Table I have a shadow stack.

Although we cannot directly compare the reported overheads of bin-CFI with our measured overheads for CFGuard, the mechanisms enforce CFI policies of roughly similar precision (compare Figure 2i and Figure 2w). CFGuard, however, has a substantially lower performance overhead. This is not surprising given that compilers operate on a high-level program representation that is more amenable to static program analysis and optimization of the CFI instrumentation. On the other hand, compiler-based CFI mechanisms are not strictly faster than binary-level mechanisms, C-CFI has the highest reported overheads by far although it is implemented in the LLVM compiler.

Table II surveys CFI approaches that do not report overheads using the SPEC CPU2006 benchmarks like the majority of recent CFI mechanisms do. Some authors, use an older version of the SPEC benchmarks [Abadi et al. 2005a; Mohan et al. 2015] whereas others evaluate performance using, e.g., web browsers [Jang et al. 2014; Zhang et al. 2013], or web servers [Payer et al. 2015; Xia et al. 2012]. Although it is valuable to quantify overheads of CFI enforcement on more modern and realistic programs, it remains helpful to include the overheads for SPEC CPU2006 benchmarks.

Table II: CFI performance overhead (%) reported from previous publications. A label of ^{C} indicates we computed the geometric mean overhead over the listed benchmarks, otherwise it is the published average.

	Benchmarks	Overhead
ROPGuard [Fratric 2012]	PCMark Vantage, NovaBench, 3DMark06, Peacekeeper, Sunspider, SuperPI 16M	0.5%
SafeDispatch [Jang et al. 2014]	Octane, Kraken, Sunspider, Balls, linelayout, HTML5	2.0%
CCFIR [Zhang et al. 2013]	SPEC2kINT, SPEC2kFP, SPEC2k6INT	^{C} 2.1%
kBouncer [Pappas et al. 2013]	wmplayer, Internet Explorer, Adobe Reader	^{C} 4.0%
OCFI [Mohan et al. 2015]	SPEC2k	4.7%
CFIMon [Xia et al. 2012]	httpd, Exim, Wu-ftpd, Memcached	6.1%
Original CFI [Abadi et al. 2005a]	SPEC2k	16.0%

4.3. Discussion

As Table I shows, authors working in the area of CFI seem to agree to evaluate their mechanisms using the SPEC CPU2006 benchmarks. There is, however, less agreement on whether to include both the integer and floating point subsets. The authors of Lockdown report the most complete set of benchmark results covering both integer and floating point benchmarks and the authors of bin-CFI, πCFI, and MCFI include most of the integer benchmarks and a subset of the floating point ones. The authors of VTV and IFCC only report subsets of integer and floating point benchmarks where their solutions introduce non-negligible overheads. Except for CFI mechanisms focused on a particular type of control flows such as virtual method calls, authors should strive to report overheads on the full suite of SPEC CPU2006 benchmarks. In case there is insufficient time to evaluate a CFI mechanism on all benchmarks, we strongly encourage authors to focus on the ones that are challenging to protect with low overheads. These include perlbench, gcc, gobmk, sjeng, omnetpp, povray, and xalancbmk. Additionally, it is desirable to supplement SPEC CPU2006 measurements with measurements for large, frequently targeted applications such as web browsers and web servers.

Although "traditional" CFI mechanisms (e.g., those that check indirect branch targets using a pre-computed CFG) can be implemented most efficiently in a compiler, this does not automatically make such solutions superior to binary-level CFI mechanisms. The advantages of the latter type of approaches include, most prominently, the ability to work directly on stripped binaries when the corresponding source is unavailable. This allows CFI enforcement to be applied independently of the code producer and therefore puts the performance/security trade off in the hands of the end-users or system administrators. Moreover, binary-level solutions naturally operate on the level of entire program modules irrespective of the source language, compiler, and compilation mode that was used to generate the code. Implementers of compiler-based CFI solutions on the other hand must spend additional effort to support separate compilation or require LTO operation which, in some instances, lowers the usability of the CFI mechanism [Szekeres et al. 2013].

5. CROSS-CUTTING CONCERNS

This section discusses CFI enforcement mechanisms, presents calls to action identified by our study for the CFI community, and identifies current frontiers in CFI research.

5.1. Enforcement Mechanisms

The CFI precursor Program Shepherding [Kiriansky et al. 2002] was built on top of a dynamic optimization engine, RIO. For CFI like security policies, Program Shepherding effects the way RIO links basic blocks together on indirect calls. They improve the performance overhead of this approach by maintaining traces, or sequences of basic blocks, in which they only have to check that the indirect branch target is the same.

Many CFI papers follow the ID-based scheme presented by Abadi et. al [Abadi et al. 2005a]. This scheme assigns a label to each indirect control flow transfer, and to each potential target in the program. Before the transfer, they insert instrumentation to insure that the label of the control flow transfer matches the label of the destination.

Recent work from Google [Collingbourne 2015; Tice et al. 2014] and Microsoft [Microsoft 2015] has moved beyond the ID-based schemes to optimized set checks. These rely on aligning metadata such that pointer transformations can be performed quickly before indirect jumps. These transformations guarantee that the indirect jump target is valid.

Hardware-Supported Enforcement Modern processors offer several hardware security-oriented features. Data Execution Prevention is a classical example of how a simple hardware feature can eliminate an entire class of attacks. Many processors also support AES encryption, random number generation, secure enclaves, and array bounds checking via instruction set extensions.

Researchers have explored architectural support for CFI enforcement [Arias et al. 2015; Christoulakis et al. 2016; Davi et al. 2014a; Sullivan et al. 2016] with the goal of lowering performance overheads. A particular advantage of these solutions is that backward edges can be protected by a fully-isolated shadow stack with an average overhead of just 2% for protection of forward and backward edges. This stands in contrast to the average overheads for software-based shadow stacks which range from 3 to 14% according to Dang et al. [2015].

There have also been efforts to repurpose existing hardware mechanisms to implement CFI [Cheng et al. 2014; Pappas et al. 2013; van der Veen et al. 2015; Yuan et al. 2015]. Pappas et al. [2013] were first to demonstrate a CFI mechanism using the 16-entry LBR branch trace facility of Intel x86 processors. The key idea in their kBouncer solution is to check the control flow path that led up to a potentially dangerous system call by inspecting the LBR; a heuristic was used to distinguish execution traces induced by ROP chains from legitimate execution traces. ROPecker by Cheng et al. [2014] subsequently extended LBR-based CFI enforcement to also emulate what code would execute past the system call. While these approaches offer negligible overheads and do not require recompilation of existing code, subsequent research showed that carefully crafted ROP attacks can bypass both of these mechanisms [Carlini and Wagner 2014; Davi et al. 2014b; Göktas et al. 2014]. The CFIGuard mechanism [Yuan et al. 2015] uses the LBR feature in conjunction with hardware performance counters to heuristically detect ROP attacks. [Xia et al. 2012] used the branch trace store, which records control-flow transfers to a buffer in memory, rather than the LBR for CFI enforcement. Mashtizadeh et al. [2015]'s C-CFI uses the Intel AES-NI instruction set to compute cryptographically-enforced hash-based message authentication codes, HMACs, for pointers stored in attacker-observable memory. By verifying HMACs before pointers are used, C-CFI prevents control-flow hijacking. Mohan et al. [2015] leverage Intel's MPX instruction set extension by re-casting the problem of CFI enforcement as a bounds checking problem over a randomized CFG.

Most recently, Intel announced hardware support for CFI in future x86 processors [Patel 2016]. Intel Control-flow Enforcement Technology (CET) adds two new instructions, ENDBR32 and ENDBR64, for forward edge protection. Under CET, the target of any indirect jump or indirect call must be a ENDBR instruction. This provides coarse-grained protection where any of the possible indirect targets are allowed at every indirect control-flow transfer. There is only one equivalence class which contains every ENDBR instruction in the program. For backward edges, CET provides a new Shadow Stack Pointer (SSP) register which is exclusively manipulated by new shadow stack instructions. Memory used by the shadow stack resides in virtual memory and is protected with page permissions. In summary, CET provides precise backward edge protection using a shadow stack, but forward edge protection is imprecise because there is only one possible label for destinations.

5.2. Open Problems

As seen in Section 3.1 most existing CFI implementations use ad hoc, imprecise analysis techniques when constructing their CFG. This unnecessarily weakens these mechanisms, as seen in Section 3.2.

All future work in CFI should use flow-sensitive and context-sensitive analysis for forward edges, SAP.F.5 from Section 2.3. On backward edges, we recommend shadow stacks as they have negligible overhead and are more precise than any possible static analysis. In this same vein, a study of real world applications that identifies coding practices that lead to large equivalence classes would be immensely helpful. This could lead to coding best practices that dramatically increase the security provided by CFI.

Quantifying the incremental security provided by CFI, or any other security mechanism, is an open problem. However, a large adversarial analysis study would provide additional insight into the security provided by CFI. Further, it is likely that CFI could be adapted as a result of such a study to make attacks more difficult.

5.3. Research Frontiers

Recent trends in CFI research target improving CFI in directions beyond new analysis or enforcement algorithms. Some approaches have sought to increase CFI protection coverage to include just-in-time code and operating system kernels. Others leverage advances in hardware to improve performance or enable new enforcement strategies. We discuss these research directions in the CFI landscape which cross-cut the traditional categories of performance and security.

Protecting Operating System Kernels. In monolithic kernels, all kernel software is running at the same privilege levels and any memory corruption can be fatal for security. A kernel is vastly different from a user-space application as it is directly exposed to the underlying hardware and an attacker in that space has access to privileged instructions that may change interrupts, page table structures, page table permissions, or privileged data structures. KCoFI [Criswell et al. 2014a] introduces a first CFI policy for commodity operating systems and considers these specific problems. The CFI mechanism is fairly coarse-grained: any indirect function call may target any valid functions and returns may target any call site (instead of executable bytes). Xinyang Ge et al. [Ge et al. 2016] introduce a precise CFI policy inference mechanism by leveraging common function pointer usage patterns in kernel code (SAP.F.4b on the forward edge and SAP.B.1 on the backward edge).

Protecting Just-in-time Compiled Code. Like other defenses, it is important that CFI is deployed comprehensively since adversaries only have to find a single unprotected indirect branch to compromise the entire process. Some applications contain just-in-time, JIT, compilers that dynamically emit machine code for managed languages such as Java and JavaScript. Niu and Tan [2014b] presented RockJIT, a CFI mechanism that specifically targets the additional attack surface exposed by JIT compilers. RockJIT faces two challenges unique to dynamically-generated code: (i) the code heap used by JIT compilers is usually simultaneously writable and executable to allow important optimizations such as inline caching [Hölzle and Ungar 1994] and on-stack replacement, (ii) computing the control-flow graphs for dynamic languages during execution without imposing substantial performance overheads. RockJIT solves the first challenge by replacing the original heap with a shadow code heap which is readable and writable but not executable and by introducing a sandboxed code heap which is readable and executable, but not writable. To avoid increased memory consumption, RockJIT maps the sandboxed code heap and the shadow heap to the same physical memory pages with different permissions. RockJIT addresses the second challenge by both (i) modifying the JIT compiler to emit meta-data about indirect branches in the generated code and (ii) enforcing a coarse-grained CFI policy on JITed code which avoids the need for static analysis. The authors argue that a less precise CFI policy for JITed code is acceptable as long as both (i) the host application is protected by a more precise policy and (ii) JIT-compiled code prevents adversaries from making system calls. In the Edge browser, Microsoft has updated the JIT compilers for JavaScript and Flash to instrument generated calls and to inform CFGuard of new control-flow targets through calls to `SetProcessValidCallTargets` [Falcon 2015; Miscosoft 2015; Weston and Miller 2016].

Protecting Interpreters. Control-flow integrity for interpreters faces similar challenges as just-in-time compilers. Interpreters are widely deployed, e.g., two major web browsers, Internet Explorer and Safari, rely on mixed-mode execution models that interpret code until it becomes “hot” enough for just-in-time compilation [Aycock 2003], and some Desktop software, too, is interpreted, e.g., Dropbox's client is implemented in Python. We have already described the "worst-case" interpreters pose to CFI from a security perspective: even if the interpreter's code is protected by CFI, its actual functionality is determined by a program in data memory. This separation has two important implications: (i) static analysis for an interpreter dispatch routine will result in an over-approximation, and (ii) it enables non-control data attacks through manipulating program source code in writeable data memory prior to JIT compilation.

Interpreters are inherently dynamic, which on the one hand means, CFI for interpreters could rely on precise dynamic points-to information, but on the other hand also indicates problems to build a complete control-flow graph for such programs. Dynamically executing strings as code (`eval`) further complicates this. Any CFI mechanism for interpreters needs to address this challenge.

Protecting Method Dispatch in Object-Oriented Languages. In C/C++ method calls use vtables, which contain addresses to methods, to dynamically bind methods according to the dynamic type of an object. This mechanism is, however, not the only possible way to implement dynamic binding. Predating C++, for example, is Smalltalk-style method dispatch, which influenced the method dispatch mechanisms in other languages, such as Objective-C and JavaScript. In Smalltalk, all method calls are resolved using a dedicated function called `send`. This `send` function takes two parameters: (i) the object (also called the receiver of the method call), and (ii) the method name. Using these parameters, the `send` method determines, at call-time, which method to actually invoke. In general, the determination of which methods are eligible call targets, and which methods cannot be invoked for certain objects and classes cannot be computed statically. Moreover, since objects and classes are both data, manipulation of data to hijack control-flow suffices to influence the method dispatch for malicious intent. While Pewny and Holz [Pewny and Holz 2013] propose a mechanism for Objective-C send-like dispatch, the generalisation to Smalltalk-style dispatch remains unsolved.

6. CONCLUSIONS

Control-flow integrity substantially raises the bar against attacks that exploit memory corruption vulnerabilities to execute arbitrary code. In the decade since its inception, researchers have made major advances and explored a great number of materially different mechanisms and implementation choices. Comparing and evaluating these mechanisms is non-trivial and most authors only provide ad-hoc security and performance evaluations. A prerequisite to any systematic evaluation is a set of well-defined metrics. In this paper, we have proposed metrics to qualitatively (based on the underlying analysis) and quantitatively (based on a practical evaluation) assess the security benefits of a representative sample of CFI mechanisms. Additionally, we have evaluated the performance trade-offs and have surveyed cross-cutting concerns and their impacts on the applicability of CFI.

Our systematization serves as an entry point and guide to the now voluminous and diverse literature on control-flow integrity. Most importantly, we capture the current state of the art in terms of precision and performance. We report large variations in the forward and backward edge precision for the evaluated mechanisms with corresponding performance overhead: higher precision results in (slightly) higher performance overhead.

We hope that our unified nomenclature will gradually displace the ill-defined qualitative distinction between "fine-grained" and "coarse-grained" labels that authors apply inconsistently across publications. Our metrics provide the necessary guidance and data to compare CFI implementations in a more nuanced way. This helps software developers and compiler writers gain appreciation for the performance/security trade-off between different CFI mechanisms. For the security community, this work provides a map of what has been done, and highlights fertile grounds for future research. Beyond metrics, our unified nomenclature allows clear distinctions of mechanisms. These metrics, if adopted, are useful to evaluate and describe future improvements to CFI.

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B. PRIOR WORK ON STATIC ANALYSIS

Static analysis research has attracted significant interest from the research community. Following our classification of control-flows in Section 2.2, we are particularly interested in static analysis that identifies indirect calls/jump targets. Researchers refer to this kind of static analysis as *points-to analysis*. The wealth of information and results in points-to analysis goes well beyond the scope of this paper. We refer the interested reader to Smaragdakis and Balatsouras [Smaragdakis and Balatsouras 2015] and focus our attention on how points-to analysis affects CFI precision.

B.1. A Theoretical Perspective

Many compiler optimizations benefit from points-to analysis. As a result, points-to analysis must be sound at all times and therefore conservatively over-approximates results. The program analysis literature (e.g., [Hind 2001; Hind and Pioli 2000; Nielson et al. 1999; Smaragdakis and Balatsouras 2015]) expresses this conservative aspect as a *may*-analysis: A specific object "may" point to any members of a computed points-to set.

For the purposes of this paper, the following orthogonal dimensions in points-to analysis affect precision:

— *flow-sensitive* vs. *flow-insensitive*: this dimension states whether an analysis considers control-flow (sensitive) or not (insensitive).
— *context-sensitive* vs. *context-insensitive*: this dimension states whether an analysis considers various forms of context (sensitive) or not (insensitive). The literature further separates the following context information sub-categories: (i) call-site sensitive: the context includes a function's call-site (e.g., call-strings [Sharir and Pnueli 1981]), (ii) object sensitive: the context includes the specific receiver object present at a call-site [Milanova et al. 2002], (iii) type sensitive: the context includes type information of functions or objects at a call-site [Smaragdakis et al. 2011].

Both dimensions, context and flow sensitivity, are orthogonal and a points-to analysis combining both yields higher precision.

Flow-Sensitivity. Figures 6a – 6c show the effect of flow sensitivity on points-to analysis. A flow-sensitive analysis considers the state of the program per line. We see, for instance, in Figure 6b how a flow-sensitive analysis computes the proper object type per allocation site. A flow-insensitive

```
Object o;
o= new A();
...

o= new B();
```

$o \rightarrow$ A
...

$o \rightarrow$ B

$o \rightarrow \{$A, B$\}$

(a) Flow-sensitivity example. (b) Flow-sensitive result. (c) Flow-insensitive result.

```
// identity function
Object id(Object o) { return o; }

x= new A();
y= new B();
a= id(x);
b= id(y);
```

$x \rightarrow$ A
$y \rightarrow$ B
$a \rightarrow$ A; $id_1 \rightarrow$ A
$b \rightarrow$ B; $id_2 \rightarrow$ B

$x \rightarrow$ A
$y \rightarrow$ B
$a \rightarrow$ id; $id \rightarrow$ A
$b \rightarrow$ id; $id \rightarrow \{$A, B$\}$

(d) Context-sensitivity example. (e) Context-sensitive result. (f) Context-insensitive result.

Fig. 6: Effects of flow/context sensitivity on precision.

analysis, on the other hand, computes sets that are valid for the whole program. Or, simply put, it lumps all statements of the analyzed block (intra- or interprocedural) into one set and computes a single points-to set that satisfies all of these statements. From a CFI perspective, a flow-sensitive points-to analysis offers higher precision.

Context-Sensitivity. Figures 6d – 6f show the effects of context sensitivity on points-to analysis. In Figure 6d we see that the function `id` is called twice, with parameters of different dynamic types. Context-insensitive analysis (cf. Figure 6f), does not distinguish between the two different calling contexts and therefore computes an over-approximation by lumping all invocations into one points-to set (e.g., the result of calling `id` is a set with two members). A context-insensitive analysis, put differently, considers a function independent from its callers, and is therefore the forward control-flow transfer symmetric case of a backward control-flow transfers returning to many callers [Nielson et al. 1999]. Context-sensitive analysis (cf. Figure 6e), on the other hand, uses additional context information to compute higher precision results. The last two lines in Figure 6e illustrate the higher precision by inferring the proper dynamic types `A` and `B`. From a CFI perspective, a context-sensitive points-to analysis offers higher precision.

Object-Oriented Programming Languages. A C-like language requires call-string or type context-sensitivity to compute precise results for function pointers. Due to dynamic dispatch, however, a C++-like language should consider more context provided by object sensitivity [Lhoták and Hendren 2006; Milanova et al. 2002]. Alternatively, prior work describes several algorithms to "devirtualize" call-sites. If a static analysis identifies that only one receiver is possible for a given call-site (i.e., if the points-to set is a singleton) a compiler can sidestep expensive dynamic dispatch via the vtable and generate a direct call to the referenced method. Class-hierarchy analysis (CHA) [Dean et al. 1995] and rapid-type analysis (RTA) [Bacon and Sweeney 1996] are prominent examples that use domain-specific information about the class hierarchy to optimize virtual method calls. RTA differs from CHA by pruning entries from the class hierarchy from objects that have not been instantiated. As a result, the RTA precision is higher than CHA precision [Grove and Chambers 2001]. Grove and Chambers [Grove and Chambers 2001] study the topic of call-graph construction and present a partial order of various approaches' precision (Figure 19, pg. 735). With regards to CFI, higher precision in the call-graph of virtual method invocations translates to either (i) more de-virtualized call-sites, which replace an indirect call by a direct call, or (ii) shrinking the points-to sets, which reduce an

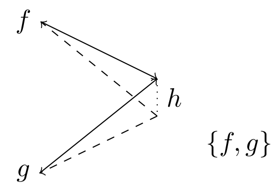

Fig. 7: Backward control-flow precision. Solid lines correspond to function calls and dashed lines to returns from functions to their call sites. Call-sites are singletons whereas h's return can return to two callers.

adversary's attack surface. Note that the former, de-virtualization of a call-site also has the added benefit of removing the call-site from a points-to set and transforming an indirect control-flow transfer to a direct control-flow transfer that need not be validated by the CFI enforcement component.

B.2. A Practical Perspective

Points-to analysis over-approximation reduces precision and therefore restricts the optimization potential of programs. The reduced precision also lowers precision for CFI, opening the door for attackers. If, for instance, the over-approximated set of computed targets contains many more "reachable" targets, then an attacker can use those control-flow transfers without violating the CFI policy. Consequently, prior results from studying the precision of static points-to analysis are of key importance to understanding CFI policies' security properties.

Mock et al. have studied dynamic points-to sets and compared them to statically determined points-to sets [Mock et al. 2001]. More precisely, the study used an instrumentation framework to compute dynamic points-to sets and compared them with three flow- and context-insensitive points-to algorithms. The authors report that static analyses identified 14% of all points-to sets as singletons, whereas dynamic points-to sets were singletons in 97% of all cases. In addition, the study reports that one out of two statically computed singleton points-to sets were optimal in the sense that the dynamic points-to sets were also singletons. The authors describe some caveats and state that flow and context sensitive points-to analyses were not practical in evaluation since they did not scale to practical programs. Subsequent work has, however, established the scalability of such points-to analyses [Hackett and Aiken 2006; Hardekopf and Lin 2007, 2011], and a similar experiment evaluating the precision of computed results is warranted.

Concerning the analysis of devirtualized method calls, prior work reports the following results. By way of manual inspection, Rountev et al. [Rountev et al. 2004] report that 26% of call chains computed by RTA were actually infeasible. Lhotak and Hendren [Lhoták and Hendren 2006] studied the effect of context-sensitivity to improve precision on object-oriented programs. They find that context sensitivity has only a modest effect on call-graph precision, but also report substantial benefits of context sensitivity to resolve virtual calls. In particular, Lhotak and Hendren highlight the utility of object-sensitive analyses for this task. Tip and Palsberg [Tip and Palsberg 2000] present advanced algorithms, XTA among others, and report that it improves precision over RTA, on average, by 88%.

B.3. Backward Control Flows

Figure 7 shows two functions, f and g, which call another function h. The return instruction in function h can, therefore, return to either function f or g, depending on which function actually called h at run-time. To select the proper caller, the compiler maintains and uses a stack of activation records, also known as stack frames. Each stack frame contains information about the CPU instruction pointer of the caller as well as bookkeeping information for local variables.

Since there is only one return instruction at the end of a function, even the most precise static analysis can only infer the set of callers for all calls. Computing this set, inevitably, leads to imprecision and all call-sites of a given function must therefore share the same label/ID such that the CFI check succeeds. Presently, the only known alternative to this loss of precision is to maintain a shadow stack and check whether the current return address equals the return address of the most recent call instruction.

C. FULL QUANTITATIVE SECURITY RESULTS

This appendix presents the full quantitative security results. An abbreviated version of these results was presented in Section 3.2. The full results are presented here for completeness. Table III contains the number of equivalence sets for each benchmark and every CFI mechanism that we evaluated. Figure 8 contains the full set of box and whisker plots. As this data is fundamentally three dimensional, these plots are the best way to display it. As a final note, the holes in this data reflect the fact that the CFI mechanisms that we evaluated cannot run the full set of SPEC CPU2006 benchmarks. This greatly complicates the task of comparatively evaluating them, as there is only a narrow base of programs that all the CFI mechanisms run.

Benchmark	CFI Implementation															
	MCFI	πCFI	MCFI	πCFI	MCFI	πCFI	MCFI	πCFI	IFCC				LLVM-CFI		Lock-	Dynamic
	back edge				forward edge				single	arity	simpl.	full	3.7	3.9	down	
			no tail call				no tail call									
400.perlbench	978	310	1192	429	38	30	38	30	1	6	12	40	0	36	4	83
401.bzip2	484	82	489	86	14	10	14	10	1	2	2	2	0	2	3	12
403.gcc	2219	1260	3282	1836	98	90	98	90	0	0	0	0	0	94	3	197
429.mcf	475	96	475	96	12	8	12	8	0	0	0	0	0	0	3	0
445.gobmk	922	283	1075	230	21	17	21	17	0	0	0	0	0	11	4	0
456.hmmer	663	134	720	147	14	9	14	9	0	0	0	0	0	3	4	9
458.sjeng	540	119	557	125	13	9	13	9	1	1	1	1	0	1	3	1
462.libquantum	495	88	519	102	12	8	12	8	1	1	1	1	0	0	4	0
464.h264ref	773	285	847	327	21	15	21	15	0	0	0	0	0	9	4	59
471.omnetpp	1693	581	1784	624	357	321	357	321	0	0	0	0	114	35	0	224
473.astar	1096	226	1108	237	166	150	166	150	0	0	0	0	1	1	6	1
483.xalancbmk	6161	2381	7162	2869	1534	1200	1534	1200	0	0	0	0	2197	260	6	1402
433.milc	602	169	628	180	13	9	13	9	0	0	0	0	0	1	4	3
444.namd	1080	217	1087	224	166	150	166	150	1	1	1	5	4	4	6	12
447.dealII	2952	817	3468	896	293	258	293	258	0	0	0	0	43	15	0	95
450.soplex	1444	432	1569	479	321	291	321	291	1	7	0	186	41	9	6	157
453.povray	1748	650	1934	743	218	204	218	204	0	0	0	0	29	33	6	49
470.lbm	465	70	470	74	12	8	12	8	0	0	0	0	0	0	4	0
482.sphinx3	633	239	677	257	13	9	13	9	0	0	0	0	0	1	4	2

Table III: Full quantitative security results for number of equivalence classes.

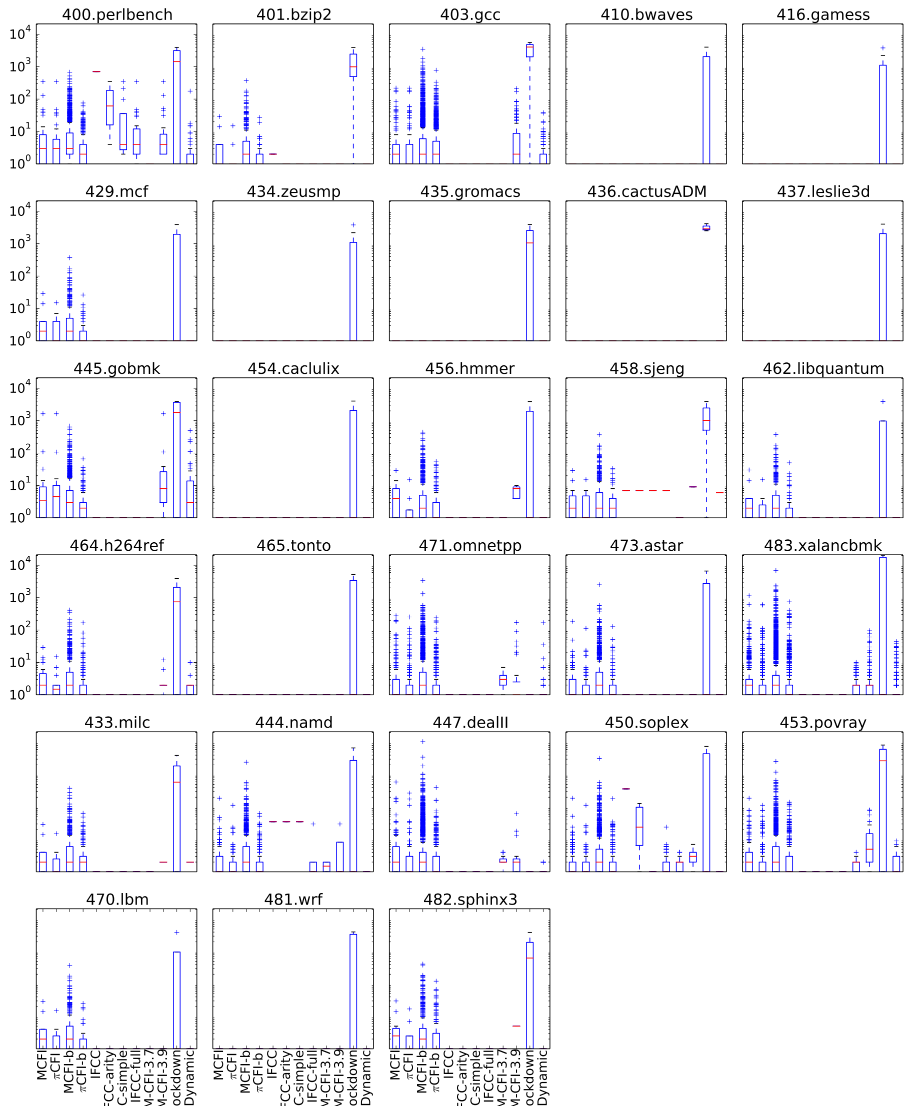

Fig. 8: Whisker plot of equivalence classes size for all SPEC CPU2006 benchmarks across all implementations (smaller is better).