Cryptographically Enforced Control Flow Integrity

Ali José Mashtizadeh, Andrea Bittau, David Mazières, Dan Boneh

Stanford University

Abstract

Recent Pwn2Own competitions have demonstrated the continued effectiveness of control hijacking attacks despite deployed countermeasures including stack canaries and ASLR. A powerful defense called Control flow Integrity (CFI) offers a principled approach to preventing such attacks. However, prior CFI implementations use static analysis and must limit protection to remain practical. These limitations have enabled attacks against all known CFI systems, as demonstrated in recent work.

This paper presents a cryptographic approach to control flow integrity (CCFI) that is both fine-grain and practical: using message authentication codes (MAC) to protect control flow elements such as return addresses, function pointers, and vtable pointers. MACs on these elements prevent even powerful attackers with random read/write access to memory from tampering with program control flow. We implemented CCFI in Clang/LLVM, taking advantage of recently available cryptographic CPU instructions. We evaluate our system on several large software packages (including nginx, Apache and memcache) as well as all their dependencies. The cost of protection ranges from a 3–18% decrease in request rate.

1 Introduction

In recent years, sophisticated attacks on software vulnerabilities have emerged, proving that deployed protection mechanisms can be bypassed (e.g., [1–4] and many others). The weaknesses in many deployed defenses is that they focus on patching specific attack techniques rather than addressing the fundamental problem. For example, stack canaries [5] assume a stack overflow; non-executable memory [6] assumes code injection; and address space layout randomization [7] assumes that information cannot be leaked. These defenses can be circumvented, for example, by overflowing the heap, executing a chain of existing code fragments using return-oriented programming, and leaking a pointer. A more principled defense approach is needed.

Exploits often work by hijacking the program’s control flow to execute unintended code, for example, to start a shell. Indeed, all the attacks mentioned above work by hijacking control flow and all the defenses mentioned try to prevent specific approaches to control flow hijacking.

A principled solution, called control flow integrity (CFI) [8], prevents an attacker from arbitrarily modifying the target of indirect jumps (e.g., return addresses, function pointers). Ensuring control flow integrity would prevent all attacks based on control flow hijacking, which includes all the sophisticated attacks listed above.

However, practical implementations of CFI have been shown to be insecure [9, 10] for two main reasons. First, CFI uses static analysis to determine the target of a pointer, which is not always precise and can lead to overly permissive choices. Second, some run-time checks are removed or simplified to reduce performance overhead.

In practice, existing CFI systems are very coarse-grained and group function pointers and return addresses into two different classes, preventing swaps between the two. That is, a function pointer cannot be replaced with a return address, however one can still swap two return addresses (or two function pointers). We are the first system to enforce CFI using cryptography, and our system provides a fine-grain CFI implementation in attempt to avoid arbitrary swaps.

Our contribution. We show that on modern processors fine-grain control flow integrity can be efficiently achieved using cryptography. Our cryptographic control flow integrity (CCFI) system identifies all objects that would affect a program’s control flow (e.g., return addresses, function pointers) and computes a message authentication code (MAC) of such objects each time they are stored in memory. This MAC is stored along with the object and checked every time the value is loaded from memory. The random secret key used for computing these MACs is stored in dedicated registers so that it can never leak by a memory disclosure bug. By checking the MAC of every control-flow element before using it we prevent the attacker from writing an arbitrary memory ad-
and all of their 21 dependencies. Only two packages recompiled SPEC2006, three web servers (Apache, Nginx, Lighttpd), two cache servers (memcached, redis) and all of their 21 dependencies. Only two packages (libapr and Nginx) required code changes for compatibility, where manual MAC computations had to be inserted, a total of three lines changed. The implementation is generalizable to any architecture that supports a fast cryptographic MAC function. The web servers showed a reduced request throughput rate of only 3–18% when serving a static file. When running over SSL, which contends for AES-NI register use, the overhead is 38%. This is a reasonable overhead given the precision of CFI achieved. Our results show that CCFI is practical, and we argue that its level of security can finally put an end to control-flow based attacks.

2 Background

Software vulnerabilities take all shapes and forms. The classic example is a stack buffer overflow, where the lack of bounds checking lets an attacker corrupt a return address on the stack causing execution to jump to an arbitrary location, often leading to execution of arbitrary code. Another example is sending data past the end of a buffer over the network, possibly leaking sensitive information. Yet another example is forgetting to include important authentication steps in the program’s logic. We classify software vulnerabilities and attacks as follows:

1. **Control flow attacks** result in the attacker being able to execute arbitrary code. These are the most common exploits, and they typically yield a remote shell.
2. **Data flow attacks** result in the attacker being able to read or write program memory, not necessarily leading to arbitrary code execution. OpenSSL’s heartbleed bug [12] is an example, where the attacker is able to read the server’s private key from memory.
3. **Logic errors** result in the attacker being able to skip checks. For example, Apple’s goto fail [13] bug did not properly check SSL certificates allowing attackers to mount man-in-the-middle attacks.

Our work focuses on the first class of attacks only. It is, however, the most prevalent class of attack today and the most powerful, because it allows the attacker to achieve everything that other attack classes do. Running arbitrary code lets an attacker disclose memory to leak SSL keys or jump past any checks. Conversely, a data flow bug that merely discloses memory (though still catastrophic) cannot be used to execute a remote shell on the system.

The most widely deployed protections against control flow attacks are stack canaries, non-executable memory (NX), and address space layout randomization (ASLR). Interestingly, none of these solutions protect the return ad-
dress itself, which is what the attacker is after. Instead, they attempt to stop the attack indirectly through other means. In contrast, our CCFI directly protects return addresses and function pointers.

Control flow attacks generalize to exploit any indirect branch (e.g., function pointers) which CCFI also protects. In Section 9 we review related work on protecting function pointers such as PointGuard [14] as well as other stack smashing defenses.

Control flow integrity. CFI [8] is a technique where static analysis determines where an indirect jump can land. Runtime checks are added to enforce that the jump lands only to the valid locations that have been determined ahead of time during static analysis. For example, suppose that the pointer analysis determines that a function pointer can only ever point to read or write. Then the attacker cannot modify the function pointer to call execve as that call is outside the set of valid locations for that particular function pointer. Note, however, that the attacker can still swap a read for a write, which may be enough to conduct an attack.

More fundamentally, however, static analysis has limits; there are cases where it cannot be determined where a function pointer is allowed to point. In this case, the set of valid locations can be any function whose address has been taken. Worse, practical CFI implementations split valid locations into only two sets: function pointers can jump to any function whose address has been taken, and return instructions can return to any return site. These loose implementations are not enough as an attacker can swap return sites to eventually execute arbitrary code and break out of CFI [9, 10].

Our approach is tackling CFI from a cryptographic point of view. We stop the attacker from modifying the return address or function pointer in the first place rather than restricting its values to a particular set (which may be large enough for an attack). This approach does not require static analysis and so does not inherit any of its limitations. The pointer is secured via a MAC at runtime when it is first stored in memory, and validated before use. Function pointer swaps are avoided by preventing replay attacks—i.e., a function pointer is valid in only one location and cannot be reused elsewhere. This lets us provide strong CFI guarantees that are not overly permissive.

3 Threat Model

Many security systems today (e.g., stack canaries, ASLR) assume the attacker cannot read memory. An attacker who can read arbitrary memory can easily defeat these defenses as demonstrated in several recent papers [1, 4]. In this paper we assume a powerful attacker who has the ability to read arbitrary areas of memory. Moreover, the attacker can overwrite all writable control-flow elements in memory (e.g., return addresses and function pointers). However, the attacker is unable to write to executable memory (marked read-only) or read the value of special registers our compiler reserves. These are reasonable assumptions that accurately model modern control hijacking attacks.

4 Design

Our Cryptographic Control Flow Integrity (CCFI) system is a compiler that protects any known object that may affect the program’s control flow. Specifically, it protects:

- Return addresses and frame pointers.
- Function pointers.
- vtable pointers. The vtable is a (read-only) function pointer table used by C++. By swapping vtable pointers, one can cause methods of a different class to be invoked, therefore subverting control flow.
- Exception handlers.

There are other application dependent objects which may eventually influence a program’s control flow. For example, an integer may index a jump table, and if over-written, the attacker may execute a different function. We do not offer any automatic protection against such dataflow attacks. The programmer can, however, use our primitives (defined in Section 4.2) to manually protect such sensitive objects.

CCFI protection is achieved using a MAC. Each time a control-flow object is stored, its MAC is computed, and on each load, its MAC is verified. The MAC is stored alongside the object. Attackers cannot overwrite a control object with an arbitrary value because they do not posses the MAC key needed to produce a valid MAC for the object. The MAC key is randomly generated at program start, and stored in registers the CCFI compiler reserves (In x86-64 we use XMM5–XMM15). The key is never written to memory because the recompiled applications and libraries do not use these registers. Attackers cannot execute (misaligned) code that accesses these registers because they would have to break control flow in the first place.

Care must be taken to prevent replay attacks. For example, an attacker must not be able to swap two function pointers by reading a function pointer and its valid MAC and using these elsewhere (in another function pointer). To combat replay attacks we must first define what is included in the MAC.
4.1 MAC Function

Our MAC is implemented as a single block of AES applied to the input data. More precisely, the MAC function is defined as follows:

$$\text{MAC}(K, \text{pointer}, \text{class}) = \text{AES-128}(K, \{ \text{pointer}, \text{class} \})$$

Where $K$ is the key, and $\text{pointer}$ is the object being secured and $\text{class}$ is the pointer class. In all practical CFI implementations, both runtime and compile time, pointers are grouped into classes. In the original CFI work, there were two classes function pointers and return pointers. In our scheme this can easily be represented by a one or zero. Fine grain CFI may group function pointers based on usage or type signature and create thousands of classes. Any modern CFI system that we know about can use MACs instead of weak runtime checks, which can then benefit from including runtime groupings to offer better security.

Runtime groupings have several benefits. Current CFI systems must determine a fixed set of functions within a class and these are stored as read-only tables, otherwise an attacker could attack the tables used to verify control flow integrity. As an example CCFI can use addresses where pointers are stored to prevent swapping function pointers, this is not possible at compile time. Another benefit is that the size of runtime class can always be smaller or equal to the size of compile time classes. To see why this is imagine a function pointer has one of five valid values, at runtime the attacker may only see three of them because of the program’s state. Thus the attacker can never exploit the remaining two states until the program has generated those pointers.

Our implementation defines the class as follows:

$$\text{class} := \begin{cases} \{0, \text{old frameaddress}\} & \text{For return addresses} \\ \{1, \text{address}\} & \text{For function pointers} \end{cases}$$

Our system uses the address of the $\text{pointer}$ as the class for function pointers with the highest bit set. On the x86-64 architecture only 48 bits of virtual address space are used, thus leaving us with the 16-bits that we can modify safely. For return pointers we use the old frame pointer as our class. Setting the most significant bit for function pointers gives us domain separation that ensures an attacker cannot use a function pointer as a return address and vice versa.

The 64-bit $\text{pointer}$ is concatenated with its 64-bit $\text{class}$ to form a 128-bit AES block, which is then encrypted using AES with a 128 bit key. Our implementation crucially leverages the AES-NI instructions available on the Intel x86-64 architecture [15] to minimize the performance impact of these computations.

Including the pointer address in the MAC data ensures that an attacker cannot swap a pointer stored in one memory address with a pointer stored in a different memory address. However, the attacker can still replace a pointer stored at location $x$ at time $t$ with a pointer stored at the same location $x$ at time $t' < t$. We refer to this as a replay attack and discuss defenses against it in Section 4.7.

Our approach generalizes to any hardware supporting fast MACs. Hardware support for AES, SHA-1, and SHA-256 are available or will be available on many modern architectures. This enables efficient implementation of CCFI on many modern platforms: ARM 64-bit architecture includes support for these instructions and implementations will be widely available for server deployments later this year [16]. The latest SPARC and the PowerPC architecture include AES instructions [17].

HMAC-SHA-256 is a good alternative to our AES-based MAC. HMAC may offer performance benefits because it requires fewer registers for the key schedule and MAC computation. At the time of writing the SHA-1/256 instructions are not yet available on x86 to offer a point of comparison.

4.2 Protection Primitives

CCFI protection is built on two main primitives that we provide as compiler intrinsics. This enables our system and an application programmer to use these intrinsics to protect any values they deem vulnerable. Listing 1 shows the two intrinsics as exposed to the C programming language on x86.

Listing 1: Compiler intrinsics for protecting and checking a pointer’s integrity.

```c
__m128d __builtin_ccfi_macptr(uint64_t ptr, uint64_t class);
uint64_t __builtin_ccfi_checkptr(uint64_t ptr, uint64_t class);
```

The first intrinsic __builtin_ccfi_macptr it used to protect a pointer. It computes the MAC of the function pointer and the class. The MAC is then stored in a region of memory indexed by the address argument.

The second intrinsic __builtin_ccfi_checkptr recomputes the MAC and compares it against the previously saved MAC. If they are not identical it will return a zero value.
These two primitives can be used by a programmer to protect application specific objects that may affect control flow, like, for example, an index to a jump table.

4.3 Stack Protection

To protect stack-based control flow objects, on each function prologue, we MAC both the saved return address and frame pointer (instead of address). A slot on the stack is reserved to store the MAC. In the epilogue, we verify the MAC before returning to the caller. MACing the frame pointer prevents exploits that, for example, reposition the upper stack frame to pop and return to unexpected return addresses [6].

We further optimize leaf functions (functions that do not call out any other functions) by storing the return address in a register rather than memory thereby eliminating the need to MAC their return address.

4.4 Pointer Protection

Function pointers and vtable pointers are protected in the same way. They both point to read-only memory so only the pointer itself needs protection. On a store, the MAC is computed, and on a load, the MAC is checked. Logically, the MAC should be stored side-by-side with the pointer. We use a different, simpler, implementation that does not require resizing function pointers, structures and classes. It stores the MAC in an external table, indexed by the location of the pointer. A simple hash function can be used to translate a pointer's address to a slot in the hash table.

C++ adds some complexity in protecting pointers. Pointers to member functions of classes are represented by a pair of 64-bit values. If the first value is not odd, then it is the address of a non-virtual function. Otherwise, a virtual function is being pointed to, and the second 64-bit value indicates the index in the vtable.

Constructors need to be extended to MAC the vtable pointer as the object is being instantiated. Care must be taken to support vtable tables (VTTs), a condition that arises from multiple inheritance when derived classes share a common base (C++’s diamond problem).

4.5 Other Control Flow Protections

We must also protect other sensitive pointers, specifically the global offset table (GOT) and global destructors (.dtors). The GOT is used for dynamic linking and filled by the loader with the addresses of external library functions. Global destructors (like global constructors) are function pointers registered at program load time and executed at program termination.

To protect these we use an existing mechanism, RELRO [18], which computes relocations at program load time and marks the GOT and .dtors read-only. This prevents the attacker from tampering with these sensitive pointers.

4.6 Compatibility

Because our MAC protects the location of a control pointer, each time a control pointer is copied, the MAC must be recomputed. This is not a problem for return addresses and vtable pointers because they are not exposed to programmers so our system can take care that they are properly handled. Function pointers, however, can be copied by the programmer. When type information is preserved, the CCFI compiler can detect that a function pointer is being copied and automatically recompute the MAC for the copy. If, however, a function pointer is cast to another type and then copied, the compiler cannot detect that a function pointer is being copied so the MAC is not recomputed. The result is that if the function pointer is later used, a MAC failure will occur. MAC check will always be present because a function pointer must be cast to a function pointer type before being used so the system will err in the favor of safety.

In practice, we observed two programs that copy pointers around after casting them to void, using memcpy. Apache and nginx both have a dynamic array implementation which stores its elements in a void* memory region, and copies them using memcpy if the array is resized. This array is used for storing function pointers. These cases were easy to detect in practice because the programs would crash at initialization (due to MAC failures).

We wrote a simpler static analyzer to help programmers find cases where type information is lost for function pointers and manual MAC checks may be necessary. The Nginx compatibility issue was in fact found by our tool.

4.7 Replay Attacks

Replay attacks in cryptography exist because an attacker can record a properly signed message and send it again (without modification) at a later time. Protection against replay attacks in cryptography is done by including a counter or nonce in every message so that the verifier can detect replayed messages.

In the context of CCFI, we compute the MAC on a pointer and its address. The address functions as a (naive) nonce. However, it is still possible to replace the current pointer at location \(x\) with an old pointer previously stored at location \(x\) and potentially disrupt control flow.
We stress that this is the only attack possible with our basic MAC method. This problem does not exist with globals, because they can exist in only one place, and their address effectively acts as a unique nonce. The problem with the heap and stack is that the nonce (i.e., the address) can be reused.

One approach to fixing potential replays is to add randomness to every memory allocation (including stack frames) to prevent addresses from aligning. This reduces the likelihood that two function pointers share the same memory address (and hence same nonce), which prevents replay attacks. Our final CCFI design MACs the object’s data and address and furthermore randomizes allocations as described in Section 5.2. An alternative that does not rely on randomization is discussed in Section 8.

Our stack and heap randomization, used to mitigate replay attacks, is quite different from randomization used in ASLR. ASLR is applied once at program startup to prevent an attacker from predicting the address of memory objects. Our randomization is applied on every allocation to prevent two function pointers from always being allocated to the same address. Some systems like OpenBSD already randomize this way: every call to malloc returns a random memory chunk. We similarly randomly pad stack frames to prevent two return addresses from always being placed in the same stack address. This way even if the same call graph is executed multiple times, the location of any return address and local function pointer will vary.

5 Implementation

Our system is built on the Clang/LLVM compiler framework and supports x86_64, tested on FreeBSD. The implementation consists of the following major components:

- **Memory randomization:** A change in libc’s malloc to return random memory chunks, and an LLVM function pass that randomly offsets the stack pointer on each call. This further prevents replay attacks.

- **LLVM Target:** ABI changes to reserve registers to ensure the compiler never leaks the key. Implement stack protection into the target specific code.

- **Compiler Intrinsics:** macptr and checkptr compiler intrinsics are implemented as machine specific code and made available to the C language.

- **Pointer Protection:** This is a high-level LLVM pass that identifies critical function pointers and vtable pointers that must be protected. A small runtime library provides error reporting and handling of globals in a central place to reduce the increase in code size.

- **Static analysis tool:** This finds any possible code that may break our automatic MAC protection because function pointers are being copied without type information and hence the MAC is not being automatically recomputed by the CCFI compiler.

Any application wishing to be hardened with CCFI must be recompiled along with all of its dependencies. We provide a command-line compatible wrapper to clang and clang++.

5.1 ABI Changes

We implemented our MAC using the AES-NI instructions on x86. These instructions take their arguments in XMM registers. A 128-bit AES key expands to 11 128-bit values, requiring 11 XMM registers (each 128-bits wide) to hold the key.

XMM registers are normally used for floating point and vector operations in the AMD64 ABI specification. They are also used for argument passing. We must therefore reserve 11 of these registers to hold our expanded key. An additional scratch XMM register is needed while computing the AES rounds. This register must not be used for argument passing or it would be clobbered during our AES computation during the function’s prologue. It can, however, be used in the function’s body as a temporary. Table 1 shows how we change the ABI we made to manage our AES encryption.

The ABI change reduces the available registers for floating point and vector computation to only five. This limits the compiler’s ability to keep more variables in the registers and thus can have a substantial impact on per-

| Registers     | SysV ABI       | CCFI ABI       |
|---------------|----------------|----------------|
| xmm0-xmm3    | Arguments      | Arguments      |
| xmm4          | Arguments      | Temporary*     |
| xmm5-xmm7    | Arguments      | Expanded Key   |
| xmm8-xmm15   | Temporary      | Expanded Key   |

Table 1: Shows how the XMM register usage in the AMD64 SysV ABI differs from that of our ABI. The general purpose registers, float point stack and MMX registers remain unchanged in the new ABI. The changes only affect the XMM registers, which are used for floating point and vector operations. *When optimizing protection for leaf functions stack protection uses XMM4 to store the return instruction pointer and frame pointer.
formance. Code that does not use floating point or vector math operations should not notice a performance impact from this change. Some programs use the XMMs also for copying memory, zeroing memory, and similar operations. These tasks typically require only one or two XMM registers.

5.2 Memory Randomization

To prevent replay attacks where control pointers align, each memory and stack frame allocation is randomized. The basic idea is to add a random offset to each malloc and stack frame. There is a trade-off between how much virtual memory to waste and how much entropy to add. OpenBSD already implements this for malloc and we use their same entropy parameter of four bits.

We implemented randomized allocations in FreeBSD’s libc malloc by adding a random offset to each allocated chunk. Unlike OpenBSD, we are not allowed to store a randomness source in memory because the attacker can modify this as per our threat model. Instead, we are required to use registers. Ideally we would use Intel’s random instruction [19]. This was not available on our processor so in the interim we chose to use the CPU’s cycle counter. The attacker would have to both align memory layout and time (at a cycle granularity) to conduct an attack.

Stack randomization is implemented similarly. On each function prologue, we alloca a random size which has the effect of padding the stack frame by a random value.

5.3 Stack Protection

Our stack protection mechanism allocates a local variable to store the MAC of return address and frame pointer. The prologue of a function generates the MAC and stores it. The epilogue must recompute the MAC, and compare it, and crash the program if the MAC does not match. In the event of a bad MAC, it crashes the program by storing zeros in the return address and (if there is one) frame pointer, which saves a few instructions and avoids a branch.

The leaf optimization for stack protection stores the return instruction pointer and frame pointer in XMM4. Rather than encrypting it we just verify that it has not been modified. Since leaf functions do not make any calls we can safely rely on a register to store the value.

5.4 Compiler Intrinsics

The two portable intrinsics checkptr and macptr are exposed to the programmer and to our protection pass. Their implementation is machine specific depending on the availability of cryptographic instructions. We implemented ours using the AES-NI x86 instructions. These primitives depend on our ABI changes and never leak any part of the expanded key on to the stack.

Both primitives are implemented using a large in-memory hash table that stores the generated MACs. The hash table approach allows us to avoid the complexity associated with wide pointers. Ideally, we would eventually support wide pointers, but this makes incremental deployment more difficult as one cannot mix libraries compiled with and without CCFI as types now have different sizes. Using a hash table causes additional performance overhead due to the computation of the hash function and potential cache misses associated with accessing a separate hash table. We intend to support wide pointers in the future to eliminate these issues.

5.5 Pointer Protection

The pointer protection is a module pass which does two things. First, it goes through each basic block to find loads and stores of function pointers, adding calls to checkptr and macptr respectively. Care must be taken to recursively walk every structure, array and vector so that nested function pointers are found. When a structure is copied, the code results in an LLVM memcpy intrinsic. These structures may contain function pointers so we must verify and recompute the MAC of the function pointer when this occurs.

The second action of the module pass is to go through all globals and identify any function pointers (even within structures) that are defined. These must be MACed before starting the program. We create constructor functions that add MACs to those. This is not necessary for globally defined C++ objects because actual constructor code, where the MAC is set, will be called.

Some systems calls take or return function pointers. No special handling is needed when these pointers reside in registers, as the compiler already checks function pointers when they are loaded into registers. However, some system calls, such as sigaction, exchange structures containing function pointers. Instead of modifying the kernel, we modified libc to check pointers in argument structures and MAC those in return structures.

5.5.1 Runtime

The runtime mostly provides common functions to limit binary size bloat. We have a constructor function that is executed on program launch to allocate a memory region for MAC storage (our hash table). A global MAC helper
function helps reduce the instantiations of the `macptr` intrinsics inside constructors. Lastly, we provide a function to call on failure to help with debugging and identifying whether it might be a program issue (e.g., missing MAC on untyped function pointer copy) or attack.

5.6 Static Analysis Tool
We wrote a static analysis tool using Clang’s static analyzer to find any code which may circumvent the automatic MACing of function pointers and therefore cause bogus MAC failures. It can be invoked as a wrapper to `make` to analyze an entire application. It detects and flags the following cases:

- A `memcpy` where both supplied arguments (before casting) are of type `void*`. These could be pointers to data structures containing function pointers cast to `void*` in another object file. In our test applications, so far we found this to be the only case where we miss function pointer copies.
- Any place where a function pointer is cast to a non-function pointer type e.g., unsigned long, or `void*`.
- Any place where a non-function pointer type is cast back to a function pointer.

We also provide users with a utility function, `ccfi_memcpy`, that can be useful for debugging MAC failures due to `memcpy`ing untyped function pointers around. Our `ccfi_memcpy` analyzes the region being copied and checks if a MAC is associated with any of the elements in the memory region. If so, the MAC is recomputed in the new region. We used this in Nginx and libapr for example, where function pointers were being `memcpy`ied without type information and the MAC had to be recomputed.

6 Security Analysis

6.1 Address Aliasing
Our weakest design point is that two different pointers may be stored at the same address, and an attacker could swap those pointers if he happens to have observed both of them and their corresponding MACs. Programs themselves may write two different pointers to the same variable, but swapping these two is valid from the perspective of the control flow graph. We only need to prevent unrelated variables aliasing to the same address. The randomization of stack and heap layout helps to mitigate this by reducing the probability that pointers alias to the same address. Also return addresses and function pointers use different MAC schemes making them fundamentally incompatible.

One way future work could strengthen this is to use a slab allocator to store objects of the same type in the same virtual address space without any possible overlap with other objects. As pointed out in our ideal model this can over be difficult and some types hide the full type information to be able to implement this. Randomization could be used for the remaining types we cannot reason about. Lastly, types that do not contain sensitive pointers may be a shared heap.

The return stack may be addressed using a slab allocator in combination with segmented stacks. The goal again is to prevent address space reuse for the stack. Local sensitive pointers, and return pointers will be protected. One caveat though, similar to all fine-grain CFI approaches we know about, this technique would still allow an attacker to return to any function that is a valid return target for the current function.

Another avenue for improving the defense is to add a hash of the type signature of functions into `macptr` and `checkptr`. This would prevent two pointers of different types from being swapped as the type signature hash would be statically defined in the code using and creating pointers. This doesn’t prevent pointers with the same type signature and very different meanings from being swapped. C programs often cast function pointer types, e.g., when arguments are unused, which we can address by verifying and recomputing the MAC with the new type signature.

6.2 Pointer Table Indices
Program data that can modify control flow is vulnerable, and we do not defend against this in any way. Developers should use our `macptr` and `checkptr` intrinsics to protect indices into function tables and critical conditional values (i.e., whether a connection is authenticated or not).

7 Evaluation
We evaluate two aspects:

1. Do applications break? When copying function pointers, they must be reMACed. This will not occur automatically if a function pointer is cast to a non-function pointer type.
2. What is the overhead of the MAC computations and checks?

All performance benchmarks were conducted on a computer running FreeBSD 10.0 powered by dual Intel
Xeon E5620 processors running at 2.4 GHz with four cores each. The machine had 48 GBs of RAM and an Intel SSD. A second identical machine running Ubuntu Linux was directly connected via gigabit Ethernet to launch the network benchmarks.

### 7.1 Application Compatibility

We compiled 21 libraries, 5 servers, and SPEC CINT2006 using CCFI. Out of these, we only had to modify two lines in libapr and a single line in nginx, all of which copied function pointers over with `memcpy`, breaking our MAC. In both cases, the programs (nginx and Apache using libapr) crashed upon initialization due to a null MAC.

We ran our static analysis on nginx and it pointed out three dangerous calls to `memcpy`. Two were in a variable sized array implementation which would `memcpy` its elements to a new buffer when resizing. The third was in a resolver code. Sixteen calls to function pointers being cast to void types were spotted. All of these were calls to push function pointers into the array implementation containing the `memcpy`. This information directly pointed us to the problematic `memcpy`. Interestingly, libapr had the same exact problem. A custom array implementation was used to store function pointers in non-function pointer typed memory.

OpenSSL is a heavy user of function pointers and we were able to run it unmodified. We had to disable some of the assembly optimizations that used our reserved XMM registers. We could have modified the assembly code to save and restore our key in YMM registers. In fact, we are looking to implement this directly in LLVM to automatically support hand written assembly code that uses our reserved XMMs.

### 7.2 Microbenchmarks

Our system proposes to compute AES on every call, return and indirect branch. This seems like a high price to pay but the key to making this practical is the low latency offered by the AES-NI instructions.

Table 2 shows the latency in cycles for each of our intrinsic functions which essentially run AES on a single block. We see that the MAC computation and verification is approximately 40 cycles.

Table 3 examines how the MAC computation time effects function call and return times in cycles. This is our worst case performance because the function does not do any work. Stack protection adds approximately 63 cycles to the function (70-7). This value is less than twice the average MAC computation time because it is the operation latency. The function prologue’s latency can be hidden partly by the function’s body and epilogue computation. The epilogue latency could also be hidden if we schedule useful (but safe) work to occur after the MAC verification. Any function performing significant amount of computation will mask our fixed overhead of 70 cycles.

The function pointer call latency is listed in the second row. We see that function pointer protection costs an additional 43 cycles. When enable both this numbers increases to 153 cycles.

Finally, two C++ call benchmarks: a non-virtual method pointer call and a virtual method pointer call are shown. Calls made through method pointers are more expensive because C++ on x86 lowers them into an if-statement that either calls the vtable entry if it is virtual otherwise calls the pointer directly. Virtual calls are the most expensive because of the extra vtable access.

Overall, CCFI adds a fixed overhead ranging from 70–164 cycles to function calls. Any function doing significant work will amortize this fixed latency. As a reference point, a single cache miss is 300 cycles on modern machines. Larger functions enable the processor to take advantage of instruction reordering and speculative execution to hide some of this latency. These processor optimizations explain the non-linearity visible in this table. We evaluate application benchmarks next to measure the overall effect.

| Operation   | Baseline | Ptr Prot. | CCFI |
|-------------|----------|-----------|------|
| Func. call  | 7        | -         | 70   |
| Fptr. call  | 7        | 50        | 153  |
| Mthd. call  | 8        | 53        | 156  |
| Vptr. call  | 17       | 60        | 164  |

Table 2: Shows the cycles for computing or checking a function pointer. This is only the intrinsic and excludes the conditional statements that are inserted when `checkptr` fails.

| Operation   | Baseline | CCFI |
|-------------|----------|------|
| macptr intrinsic | 40      |      |
| checkptr intrinsic | 39   |      |

Table 3: Shows the round-trip function call and return for an empty function in cycles. The baseline numbers include no protection using an unmodified compiler. CCFI without stack protection shows the overhead when only function pointer protection is enabled. The CCFI column shows the results with stack and function pointer protection enabled.
7.3 SPEC2006 Benchmarks

Figure 1 shows the results from the SPEC CPU2006 integer benchmarks. We omitted the GCC and Perl benchmarks as they crashed when compiled with the modern vanilla GCC or Clang compilers that we tested. All other benchmarks worked both with Clang and CCFI, with no changes to the benchmark source code.

The Figure uses an unmodified Clang 3.3 compiler as the baseline and the other results are normalized to this measurement. We also measured the overhead of the ABI changes alone which put register pressure, but the result was negligible so we did not plot it. All the overhead comes from stack and function pointer protection.

We show the results of SPEC for full protection with and without the leaf optimization for stack frames. The stack protection overhead appears as the lower half of the bar in each of the two cases. We measured an average of 45% overhead for all benchmarks, and 23% overhead for the C benchmark.

Function pointer protection overhead becomes more apparent in the C++ benchmarks that we have measured. This is because inheritance depends on vtable pointers that must be protected. The C code has very few hot paths containing function pointers thus why we do not see a significant performance difference between stack protection alone and full protection.

7.4 Stack leaf optimization gains

Our stack protection cost dominates in small functions. The effect worsens when such functions are called frequently. To better understand this behavior, we study our worst and best cases from SPEC (omnetpp and bzip). Figures 2 and 3 show the approximate total cost per function (instruction_count × number_of_calls) for omnetpp and bzip2, when using different compilers. Each curve is sorted by function cost. The gap between the top curve (stack protection) and the bottom curve (vanilla compiler) shows the overhead of stack protection. The middle curve approximates the cost graph with the leaf optimization. In the omnetpp case, there are many frequent calls to smaller functions (typical in C++) and hence the higher overhead. This is indicated by the middle curve that hugs the unoptimized curve on the left side of the graph (costly functions). On the remainder of the graph however the optimization pays back as it sits between the baseline and unoptimized curve. Our leaf optimization reduces a 5x overhead to 3.5x.

C code represented by bzip2 has many calls to larger functions that is indicated by the lines overlapping for most of the graph. The optimization has a smaller impact on overall performance as stack protection contributes to a smaller percentage of a functions execution time.

More aggressive function inlining with link time optimization (LTO) should bring down the cost of C++ for real world uses. Pointer protection could be eliminated for many small accessor functions that are executed very frequently by inlining.

7.5 Applications

We compiled a number of high performance servers and all their dependencies with CCFI. Table 4 shows the request rate when comparing a vanilla build of the system compared to CCFI. We used default settings for all servers and the ApacheBench benchmarking tool. In the HTTP case, there is a 3–18% overhead depending on the server used.

In the HTTPS case, performance drops by 38% for two reasons. First, we disabled some of the assembly code in OpenSSL which used XMM registers 5–15. Second, all the intensive math C code felt the XMM register pressure. Although we disabled OpenSSL’s AES-NI implementation, we used FreeBSD’s cryptodev kernel AES-NI implementation for high speed AES. This comes at the cost of a system call but is amortized for large messages (anything over 128 bytes will break even). Further performance improvements would require changes to OpenSSL’s code. Specifically, all assembly optimizations would have to be enabled, and for those using many XMM registers, CCFI’s XMMs registers would have to be saved and restored in YMMs.

We also measured the performance of memcached and redis, shown in Table 5. We used the mutilate tool to benchmark memcached, and redis’ own benchmark tool for redis. The performance degradation is between 3–18%.

These results are promising for securing network
Figure 1: Shows the SPEC2006 results. The left bar is unoptimized CCFI and the right bar is optimized. Results are normalized to baseline execution (of 1x). The bars are stacked to show the overhead of stack protection and function pointer protection.

Figure 2: Shows the approximate performance cost of the top 220 functions for omnetpp, a C++ benchmark, with vanilla Clang, and stack protection with and without the leaf optimization. We have many very high frequency smaller sized functions that appear in the graph as the large gap between the vanilla and unoptimized lines. Our optimization reduces almost half the cost as shown by optimized line which is bounded by the other two.

Figure 3: Shows the approximate performance cost of the top 60 functions for bzip2, a C benchmark, with vanilla Clang, and stack protection with and without the leaf optimization. The lines almost completely overlap except for the lowest cost functions (far right). The low cost functions are executed few times and are not very long thus showing more dramatically the cost of stack protection.
servers where most of the overhead comes from IO or complex application code.

8 Discussion

8.1 Hardware Mechanisms

Our CCFI work preserves the immutability of objects through cryptography. Other implementation approaches include using other hardware mechanisms like paging. For example, a shadow memory can be used for storing function pointers. This memory is made available only prior to indirect call or jump instructions. Switching page tables using a tagged TLB (or invlpg instruction) could be one implementation. More promising is Supervisor Mode Access Protection (SMAP), an upcoming feature that prevents kernels from accessing user space memory. An efficient instruction is available to toggle when a kernel is able to read user memory. This feature could be used in a system like Dune [20] by running a process in privileged mode, but storing function pointers in user space memory. Before a call, the SMAP bit can be flipped to access user space memory, and the bit can then be toggled back in a function prologue.

Another way to defend the return stack is to use hardware performance counters to verify the integrity of the return stack. This by itself has been done in previous work [21] to have the operating system kernel check the last few stack frames. The technique could be applied to user level, but at an increased cost to the function epilogue. Another approach would be to store a few return addresses in registers. When the registers reserved are all full we would batch MAC and store these values on the stack. This optimization allows us to exploit parallelism in the AES-NI implementation. We could see as much as a four time reduction in stack protection costs. This technique could help us defend against more sophisticated stack smashing attacks without the need for randomization. Potentially by doing a more expensive MAC computation.

Most existing CFI systems operate on binaries by disassembling them and instrumenting them. Our approach was to modify the compiler and so we require sources or a recompilation of binaries. We could implement CCFI for unmodified binaries using a system like Pin [22].

8.2 Avoiding Address Space Reuse

Eliminating the use per-frame stack and per-object heap randomization can offer stronger security guarantees. A simple fix to this is to never reallocate address space to different types of objects or stack frames. This will guarantee that two different sensitive pointers will never overlap in the same address space. For the heap we will take any object that contains a sensitive pointer and give it a unique pool based on its type to allocate from. The stack on the other hand would require segmented stacks that is supported by LLVM to ensure that stack segments belonging to different functions never reuse address space. With no address space reuse our MACs would always be unique and give us a stronger guarantee than any CFI system alone.

The heap change may even gain us performance from better cache utilization, which is one goal of slab and pool allocators [23]. The stack change will cost performance as an allocation is required per-frame, but we can benefit from existing work on stack segmentation as it is used in many languages today.

8.3 Just-in-Time Compilers

Our threat model lets an attacker write to any memory, but assumes that executable pages are read-only. Modern JITs often require that pages are marked writable and executable at the same time. One approach is to implement the JIT as an external process. The JIT agent will share a region of memory with the main process as read-only and executable. The agent can then emit code and generate valid MACs to pointers to be used by the JIT runtime.

This design hopes to prevent attackers from using the JIT to jump to arbitrary code fragments or write into executable memory. Only allowing the JIT to create pointers with valid MACs allows us to omit any oracle functions inside the main process. The JIT may never reuse an entry point as it cannot revoke the MAC once generated, but we can reuse memory with the exception the entry point byte that would be replaced with an invalid instruction.

9 Related Work

Modern operating systems in conjunction with compilers implement several security features. Address Space Layout randomization [24] attempts to randomize a program and libraries location in memory to make stack smashing attacks against known binaries difficult. In addition most popular compilers including support for stack cookies that attempt to detect stack smashing attacks [5]. These systems both require recompilation of software and have been circumvented by attackers for years in 32-bit systems. The BROP attack showed that a generalized attack was practical even on 64-bit systems without knowledge
of the binary. While these solutions raise the attack’s complexity it offers no principled security.

After the initial CFI implementation [8] was introduced by Abadi et al. there are now many CFI systems built on static analysis techniques to achieve security. All these systems classify pointers into several categories such as call-sites and function pointers. Arguably the most secure of these is CCFIR [25] that only classifies pointers into four categories. This along with the difficulty of achieving compatibility within the limits of static analysis has lead to practical attacks on all known CFI systems [9,10]. Cryptographic CFI offers the first new approach to CFI since the original paper. Unlike existing CFI systems we require binaries and libraries to be recompiled, as existing libraries may leak our key or destroy it.

Forward edge CFI is a new system that enforces fine-grain classification for function pointer only [26]. Like CCFI, forward edge CFI offers fine grain classification of function pointers, but does nothing for return addresses. Return addresses are left unprotected falling back to existing mechanisms that are known to be weak. As with previous CFI systems, forward edge CFI does not have the runtime benefits that CCFI does.

Another very related work is PointGuard [14]. The PointGuard system exclusive-or’s all function pointers with a random value chosen at startup. In a way this can be thought of like pointer encryption except it assumes that attackers will only read or modify a single pointer. Once an attacker has read several pointers the secret exclusive-or value can be computed. Cryptographically secure encryption (or MAC’ing) by itself provides little as functions can be swapped. CCFI improvement over PointGuard is realizing the connection between inputs to a MAC and CFI. Another problem is that modifying pointers in-place meant that a lot more program/library changes are required. Pointers had to be manually decrypted/encrypted when issuing system calls.

Several systems use memory protection hardware to protect the return stack such as shadow stack. The StackGhost system relied on register windows and OS support on the SPARC architecture to provide stack smashing protection [27]. StackShield implemented a shadow stack using the data segment so that it would not be susceptible to stack smashing attacks [28]. These systems do not protect local function pointers stored on the stack. Some shadow stack implementations on x86 use segmentation to isolate the shadow stack, such that an attacker could not overwrite it without the use of a special instruction prefix. This CPU feature is not supported by any popular architecture today including x86-64 and thus an attacker with a stronger threat model could attack the shadow stack.

Another hardware based approach kBouncer [21] used performance counters on x86 to record the last few stack entries, and have the operating system verify it during the execution of a system call. This technique only protects the top few levels (2–16 depending on the processor support) of the stack.

10 Conclusion

We showed that cryptographic control flow integrity is a viable approach to protecting program control flow on modern processors. Our system ensures that an attacker who has random read access to memory cannot tamper with control flow data, such as return addresses and function pointers, without being detected. While attackers can cause the program to crash, they cannot alter control flow to execute code of their choice.

Our implementation of CCFI classifies pointers by the address at which they are stored and a single bit to differentiate return pointers from function functions. Classifying pointers by a runtime attribute (addresses) was not previously possible. With no static analysis our modified Clang/LLVM compiler can build protected binaries with fine grain control flow integrity.

Our implementation is general enough to integrate with fine grain CFI, when a practical CFI analysis is made available in Clang. This can work in conjunction with our address based classification to restrict control flow further than any compile-time solution can.

We experimented with our CCFI system on a number of large software packages. In all cases the packages compiled with no problems after changing at most one line of code in each package.

Clearly a cryptographic system that provides strong control flow protection must incur some performance cost. By optimizing the system and leveraging hardware support for AES available in modern processors we were able to achieve between 3–18% slowdown over the unprotected system. In many environments this is a worthwhile trade off given the strong protection it provides.

This work shows how to protect control flow structures, but does not protect other data in memory. It would be interesting to explore extending the cryptographic protection described in this work to protect other memory structures, including structures holding application data. This will potentially prevent attacks that exploit data flow vulnerabilities such as Heartbleed [12]. We leave this as an interesting direction for future work.
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