SAFE DISPATCH: Securing C++ Virtual Calls from Memory Corruption Attacks

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Abstract—Several defenses have increased the cost of traditional, low-level attacks that corrupt control data, e.g., return addresses saved on the stack, to compromise program execution. In response, creative adversaries have begun circumventing these defenses by exploiting programming errors to manipulate pointers to virtual tables, or vtables, of C++ objects. These attacks can hijack program control flow whenever a virtual method of a corrupted object is called, potentially allowing the attacker to gain complete control of the underlying system. In this paper we present SAFE DISPATCH, a novel defense to prevent such vtable hijacking by statically analyzing C++ programs and inserting sufficient runtime checks to ensure that control flow at virtual method call sites cannot be arbitrarily influenced by an attacker. We implemented SAFE DISPATCH as a Clang++/LLVM extension, used our enhanced compiler to build a vtable-safe version of the Google Chromium browser, and measured the performance overhead of our approach on popular browser benchmark suites. By carefully crafting a handful of optimizations, we were able to reduce average runtime overhead to just 2.1%.

I. INTRODUCTION

Applications like web browsers and office productivity suites are increasingly trusted to store and manipulate highly sensitive data in domains ranging from medical record management to banking. Such systems demand both performance and abstraction, making a low-level, object-oriented language like C++ the tool of choice for their implementation. Unfortunately, this focus on performance has all too often taken precedence over critical security concerns. Malicious attacks frequently exploit the low-level programming errors that plague these systems, allowing an adversary to corrupt control data, pointers to code which the program later jumps to. By compromising control data, attackers are able to hijack program execution, in the worst case leading to arbitrary code execution.

Buffer overflows are one of the most familiar techniques for corrupting control data: by overwriting the return address in a function’s activation record on the stack, the attacker can specify which instruction the CPU will jump to when the function returns, thus hijacking the program’s execution. The security community has responded to such attacks with numerous defenses, including stack canaries [1], data execution prevention [2], and custom allocators to protect the heap [3]. These successful defenses have increased the cost of mounting traditional attacks, forcing adversaries to adopt increasingly sophisticated approaches.

Instead of overwriting return addresses saved on the stack, several recent, high profile attacks have shifted their focus to corrupting another class of control data: heap-based pointers to virtual tables, or vtables. A C++ class’s vtable contains function pointers to the implementations for each of its methods. All major C++ compilers, including GCC, Visual C++, and LLVM, use vtables to implement dynamic dispatch: whenever an object invokes a virtual method, the vtable for that object’s class is consulted to determine which function should be called. This layer of indirection enables polymorphism in C++ by allowing a subclass to invoke its own version of a method, overriding its parent class.

For performance, the first word of a C++ object with virtual methods is a pointer to its class’s vtable. Unfortunately, this efficiency comes at a price: memory safety violations can nullify an important invariant: the vtable pointer stored in an object of type \( \tau \) always points to the vtable of \( \tau \) or one of its subclasses. If an attacker can corrupt an object’s vtable pointer to instead point to a counterfeit vtable, then they can hijack program control flow whenever that object calls one of its virtual methods, potentially executing malicious shellcode [4]. In this paper, we call such attacks vtable hijacking and describe an efficient technique to prevent them.

Security researchers previously demonstrated one of the many ways an attacker can hijack vtables: by exploiting use-after-free errors. In this particular attack method, an adversary first identifies a dangling pointer, a reference to an object that has been freed. The attacker then tricks the program into allocating both: (1) a counterfeit vtable and (2) a pointer to this counterfeit vtable at the start of the memory where the freed object was stored. Finally, the attacker manipulates the program to invoke a virtual method via the dangling pointer. Because the attacker has overwritten the vtable pointer in the freed object, this method call will jump to an address of the attacker’s choosing, as specified by their counterfeit vtable.

Exploiting such use-after-free errors is just one way to launch vtable hijacking attacks, others include traditional buffer overflows on the stack or the heap [4] and type confusion [5]. [6] attacks. Unfortunately, such vtable hijacking attacks are no longer merely a hypothetical threat [7], [8].

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NDSS ’14, 23–26 February 2014, San Diego, CA, USA
http://dx.doi.org/doi-info-to-be-provided-later
We increasingly observe robust vtable hijacking attacks in the wild, often leading to the execution of malicious shellcode. Such attacks have recently been shown practical in complex applications, including major web browsers: in recent Pwn2Own competitions, vtable hijacking enabled multiple arbitrary code execution attacks in Google Chrome [9], Internet Explorer [10], and Mozilla Firefox [11]. In fact, abusing dynamic dispatch in C++ was the major security weakness in all these browsers. In a recent Google Chrome exploit, Pinkie Pie employed a vtable hijacking attack to construct a Zero-day vulnerability to escape the tab sandbox and execute arbitrary code [12]. As a result of such attacks, researchers have recently singled out vtable hijacking as one of the most straightforward attack vectors exploiting heap vulnerabilities, as an attacker can often construct inputs to influence when a program allocates and frees objects.

Unfortunately, existing defenses that could prevent vtable hijacking are either incomplete or do not specifically take advantage of the C++ type system to provide the best possible performance. Techniques like reference counting can help mitigate vtable hijacking attacks that exploit dangling pointers, e.g. by preventing dangling pointers from being used for invoking methods. Unfortunately, there are many other ways to mount vtable hijacking attacks that do not require a dangling pointer. Other techniques like control flow integrity [13], [14], [15], [16], [17] can secure all indirect jumps to prevent many kinds of control flow hijacking attacks, including vtable hijacking. However, these techniques do not take advantage of the C++ type system for the specific task of securing virtual method calls, and therefore none of these techniques treat C++ virtual method calls both precisely and efficiently.

In this paper, we address the growing threat of vtable hijacking with SAFEDISPATCH, an enhanced C++ compiler that prevents such attacks. SAFEDISPATCH first performs a static class hierarchy analysis (CHA) to determine, for each class c in the program, the set of valid method implementations that may be invoked by an object of static type c. SAFEDISPATCH uses this information to instrument the program with dynamic checks, ensuring that, at runtime, all method calls invoke a valid method implementation according to C++ dynamic dispatch rules. By carefully optimizing these checks, we were able to reduce runtime overhead to just 2.1% and memory overhead to just 7.5% in the first vtable-safe version of the Google Chromium browser which we built with the SAFEDISPATCH compiler.

To summarize, this paper makes the following contributions:

- We develop SAFEDISPATCH, a comprehensive defense against vtable hijacking attacks. We detail the static analysis and compilation techniques to efficiently ensure control flow integrity through virtual method calls.
- We detail the implementation of SAFEDISPATCH as an enhanced C++ compiler and discuss several security and performance tradeoffs that influenced our design.
- We applied SAFEDISPATCH to the entire Google Chromium web browser code base to evaluate the effectiveness and efficiency of our approach. By developing a handful of carefully crafted optimizations, we were able to reduce runtime overhead to just 2.1% and memory overhead to just 7.5%.

The next section provides additional background on C++ dynamic dispatch and vtable hijacking and then overview how SAFEDISPATCH prevents such attacks. Section III follows, where we detail the SAFEDISPATCH compiler, key optimizations we developed to minimize overhead, and some of the different security and performance tradeoffs we considered. Next, in Section VI we evaluate our SAFEDISPATCH implementation along several dimensions, including performance overhead, while in Section VII we discuss the security implications of our approach. In Section VIII we survey existing defenses, discussing their effectiveness at mitigating vtable hijacking in complex, high performance systems and comparing them with SAFEDISPATCH. Finally, in Section IX we consider future directions and conclude.

II. SAFEDISPATCH Overview

In this section we provide additional background on dynamic dispatch in C++, illustrate vtable hijacking with a detailed example, and provide a high level description of how SAFEDISPATCH prevents such attacks.

A. Dynamic Dispatch in C++

Before detailing an example vtable hijacking attack, we briefly review how dynamic dispatch invokes object methods in C++. Consider the code in the upper part of Figure 1, which declares two classes: a Window class with one virtual method named display for displaying a string on the screen and a MobileWin subclass of Window which overrides display to provide an implementation specialized for smaller screens.

C++ dynamic dispatch rules dictate that when an object calls a virtual method, the actual implementation invoked

Fig. 1. C++ Dynamic Dispatch. Consider the simple Window class above for displaying a string on the screen. C++ compilers translate each virtual method call into lower level code that performs three steps: (1) dereference the first word of the calling object to retrieve its class’s vtable, (2) index into the vtable by the method’s position in the class to retrieve the appropriate function pointer, and (3) call the retrieved function pointer, passing the calling object as the first argument, followed by any additional arguments. If an attacker corrupts an object’s vtable pointer to point to a counterfeit vtable, possibly by exploiting a dangling pointer, then they can cause steps (1) and (2) to lookup malicious code and step (3) to execute it.

We detail the implementation of SAFEDISPATCH to the entire Google Chromium web browser code base to evaluate the effectiveness and efficiency of our approach. By developing a handful of carefully crafted optimizations,
depends on the runtime type of the calling object. This layer of indirection allows subclasses to override their parent class’s implementation of methods and is one of the key mechanisms for polymorphism in C++. For example, in the code snippet from Figure 1 the call \( w \rightarrow \text{display} \) \("Hello" \) will either invoke \texttt{Window::display} or \texttt{MobileWin::display}, depending on what \( w \) refers to at run-time, which in turn is determined by the flag variable.

Of the many implementation strategies for dynamic dispatch, Virtual Method Tables, or vtables are the most common. Prevalent C++ compilers, including GCC, Visual C++, and Clang++, all use vtables due to their efficiency. To implement vtables, the compiler assigns each virtual method in a class an identifier, which for simplicity we assume is done by numbering virtual methods sequentially. A vtable for class \( C \) is then an array \( t \) such that \( t[i] \) is the implementation of method \( i \) for class \( C \). At compile time, the compiler constructs a vtable for each class, and inserts code in the constructor of each class to initialize the first word of the constructed object with a pointer to the vtable for that class.

To implement a virtual method call the compiler generates code that performs three steps: (1) load the vtable pointer, located at position 0 in the calling object, (2) lookup index \( i \) in the vtable, where \( i \) is the index of the method being called (3) call the method implementation found at index \( i \) in the vtable. The lower part of Figure 1 uses C++ notation to illustrate the behavior of code generated for \( w \rightarrow \text{display} \) \("Hi" \), assuming that \texttt{display} is given index 0 by the compiler. Note that if \( w \) points to a \texttt{Window} object, then the vtable will contain \texttt{Window::display} at location 0, whereas if \( w \) points to a \texttt{MobileWin} object, then the vtable will contain \texttt{MobileWin::display} at location 0.

Because vtables are used in determining control flow, if an attacker can illegally manipulate an object’s vtable pointer, they can hijack program execution whenever that object invokes a virtual method. Since objects are ubiquitous in C++ programs, such control data is abundant, making virtual hijacking an attractive target for adversaries seeking to exploit low-level programming errors. We next illustrate how an attacker may mount such attacks.

B. vtable Hijacking

Having reviewed C++ dynamic dispatch, we now illustrate an example of vtable hijacking using the code in Figure 2. This code mimics the structure of a browser kernel in the style of OP [18] or Google Chrome [19], [20]. In these browsers, tabs run as separate, strictly sandboxed, processes whose only capability is communicating with the browser kernel process. To perform privileged operations, e.g. rendering to the screen or initiating a network connection, a tab process must send requests to the browser kernel process which enforces access control for privileged operations. This architecture provides strong security properties: even fully compromising a tab does not immediately grant an attacker the ability to run arbitrary code since the tab sandbox prevents an exploited tab from performing any privileged operations. Of course, if the browser kernel contains an exploitable bug, the attacker may take full control of the underlying system.

class Shell {  
  public: virtual string run(string cmd) { ... } 
};  
// for displaying content on screen  
class Window {  
  public: virtual void display(string s) { ... } 
};  
// specialized for small screens on mobile devices  
class MobileWin: public Window {  
  public: virtual void display(string s) { ... } 
};  
void tab_request_handler_loop(void) {  
  Shell* sh = NULL;  
  Window* win = SMALL_SCREEN ? new MobileWin() : new Window();  
  while (TRUE) {  
    TabRequest r = recv_tab_request();  
    switch (r.kind) {  
      case GET_DATE:  
        win->display(r.msg);  
        break;  
      case DISPLAY_ALERT:  
        win->display(r.msg);  
        break;  
      default:  
        if (sh == NULL)  
          sh = new Shell();  
        // shell with safe, const string  
        string d = sh->run("date");  
        send_tab_response(r.originating_tab, d);  
        break;  
      }  
  }  
  delete win;  
  // BUG: accidental delete, win ptr now dangling  
  delete win;  
}  

// attack request sequence to run arbitrary shell command  
GET_HTML, GET_DATE, DISPLAY_ALERT

Fig. 2. Example vtable Hijacking. The above code sketches the core of a browser kernel in the style of Google Chrome: tabs run as separate, strictly sandboxed processes and send requests to the kernel to perform privileged operations like running shell commands or accessing the network. The main loop above illustrates how such a browser kernel responds to unprivileged tab requests. Due to a use-after-free error, an attacker can craft a sequence of requests causing the above code to run arbitrary shell commands.

The attack we demonstrate here assumes an adversary has already compromised a tab process which they now use to mount an attack against the highly privileged browser kernel. Although the code in this example is greatly simplified, a similar attack was central to Pinkie Pie’s 2012 Zero-day exploit against Google Chrome [12]. Furthermore, while this example shows how vtable hijacking can be used to compromise a browser kernel, the approach generalizes to mounting attacks against many kinds of software, allowing an adversary to hijack program control flow, and thus potentially execute malicious shellcode.

The core of Figure 2 depicts a loop inside the browser kernel to handle requests from unprivileged tab processes.
For this simplified example, we consider three handlers which together enable a vtable hijacking attack that will allow an adversary to execute an arbitrary shell command.

The handler for GET_DATE uses a Shell object to execute a shell command which retrieves the system’s date information, and then sends the result back to the requesting tab. Note that the parameter passed to Shell::run is a safe, constant string.

The handler for DISPLAY_ALERT renders a tab-provided string to the screen using a Window object. According to the C++ type system, at runtime this object will be an instance of Window or any of its subclass. In this case, there are two possibilities, either the Window class or the MobileWin class, which is specialized to render on smaller screens, and is used depending on the setting in the SMALL_SCREEN variable flag.

These two handlers alone do not contain an exploitable bug. However, we now introduce a third handler for GET_HTML requests which, somewhere in the process of fetching HTML for a tab-provided URL, inadvertently deletes the Window object pointed to by win, leaving the win pointer dangling.

The attack now consists of the adversary controlled tab sending three requests: GET_HTML, GET_DATE, and DISPLAY_ALERT. First, when kernel processes the GET_HTML request, the win object is accidently deleted. Second, when the kernel processes the GET_DATE request, a new Shell object is allocated. The memory allocator may place this object at the same memory location just freed by the previous handler, leaving the dangling win pointer to refer to this newly allocated Shell object. Third, when the kernel processes the DISPLAY_ALERT request, the method call win->display(r.msg) dereferences the first word of win to get a vtable and calls the first function contained in that vtable. However, since win now points to a Shell object, its vtable pointer refers to Shell’s vtable whose first element is the run method. Therefore, win->display(r.msg) actually calls Shell::run with r.msg as a parameter, a value provided by the attacker controlled tab. Thus, by sending these three requests in order, the compromised tab has tricked the kernel into running an arbitrary shell command, completely violating the kernel’s security guarantee: the browser kernel’s prime directive is to prevent the previously described attack, but also adds only minimal overhead compared to the existing dynamic dispatch code.

To prevent such attacks, SAFE_DISPATCH inserts code to check the integrity of control-flow transfers for virtual method calls. In particular, at each virtual method call site, SAFE_DISPATCH inserts checks to ensure that the code being invoked is a valid implementation of the method according to the C++ type system. In this case, there are two valid methods in this case, Window::display and MobileWin::display. This check ensures that control flow through method calls satisfies the C++ type system, effectively preventing the attacker from executing arbitrary code. We detail our general approach in Section III.

III. THE SAFE_DISPATCH COMPILER

At their core, vtable hijacking attacks cause a virtual method call to jump into code which is not a valid implementation of that method. SAFE_DISPATCH defends against all such attacks by instrumenting programs to ensure that, at every virtual method call site, the function pointer retrieved from the object’s vtable at runtime is a valid implementation of the method being called (according to C++ dynamic dispatch rules), even if an attacker has managed to corrupt memory by exploiting a bug in the program.

In this section we describe our implementation of SAFE_DISPATCH as an enhanced C++ compiler, built on top of the Clang++/LLVM compiler infrastructure [21]. SAFE_DISPATCH extends this infrastructure with three major passes to insert checks which protect an application from vtable hijacking: (1) a variant of static Class Hierarchy Analysis (CHA) which allows us to determine, at compile time, all the valid method implementations that may be invoked by an object of a particular static type at a given method call site, (2) a pass which uses the results from CHA to insert runtime checks that will ensure all method calls jump to valid implementations during program execution, and (3) various optimizations to reduce the SAFE_DISPATCH runtime and code overhead on complex, industrial scale applications is relatively low.

C. SAFE_DISPATCH Vtable Protection

The attack illustrated in Figure 2 compromises control flow through the win->display(r.msg) method call to trick the program into invoking Shell::run(r.msg) instead.

```cpp
// SAFE_DISPATCH protection for win->display(r.msg)
vtble t = vtable + i; // load vtable
method m = t[0]; // lookup method
if(m == Window::display ||
   m == MobileWin::display) // check ensures m valid
   m(win, r.msg); // otherwise, signal error
else
   error("bogus method implementation!");
```

Fig. 3. SAFE_DISPATCH Protection. The SAFE_DISPATCH compiler inserts checks at each method call site, analogous to those shown in bold above, to ensure that a method looked up from an object’s vtable is valid given the object’s static type, i.e. that it is a method of the object’s class or one of its subclasses. Since our Window class has one subclass which overrides display, there are two valid methods in this case, Window::display and MobileWin::display. This check ensures that control flow through method calls satisfies the C++ type system, effectively preventing the attacker from executing arbitrary code. We detail our general approach in Section III.
size overhead. We describe each of these three passes in more detail below.

A. Class Hierarchy Analysis

SAFE DISPATCH instruments a program to ensure all runtime virtual method calls are valid, but before inserting these dynamic checks we must first determine, at compile time, which implementations are valid for each virtual method call site. Class Hierarchy Analysis (CHA) is a static analysis that gathers this information by constructing the program’s class hierarchy, i.e., immediate subtyping relation, and then traverses this class hierarchy to compute the set of valid implementations for each virtual method of every class. The end result produced by CHA will be a map \( \text{ValidM} \) which gives us, for each class \( c \) and each virtual method \( n \), the set \( \text{ValidM}[c][n] \) of method implementations that could be invoked at runtime if an object with static type \( c \) were used to call \( n \).

Consider the example CHA results in Figure 4. In this case, the program being analyzed only contains five classes forming a three-layer hierarchy: \( D \) and \( E \) are subclasses of \( C \) while \( B \) and \( C \) are subclasses of \( A \). Conceptually, this hierarchy is computed by creating a graph containing a node for each class in the program and then adding an edge from class \( c \) to \( c' \) whenever \( c \) extends \( c' \). Each node also stores information about its class’s methods, in particular indicating which implementations are inherited from parents (which we depict using \( \ast \)) and which the class overrides with its own implementation (which we depict using the method’s name).

Our version of CHA analyzes, for each method \( n \) of each class \( c \), which of \( c \)’s subclasses override \( n \) with their own implementation. Along with \( c \)’s (possibly inherited) implementation, the set of all such method implementations are the only valid callees that may be invoked by an object of static type \( c \) when it calls \( n \) at runtime. This is made precise by the code shown in Figure 5 which computes this information and stores the result in a table called \( \text{ValidM} \).

In practice, implementing CHA for large, complex applications like browsers poses a serious challenge, primarily due to subtle interactions between the many C++ inheritance mechanisms, e.g. access modifiers, templates, virtual vs. non-virtual method properties, overloading, and multiple inheritance. To manage this complexity, we build on top of the Clang++ module responsible for constructing C++ vtables at compile time. Clang++ is an industrial strength compiler, capable of handling the tremendous complexity that arises in real-world C++ applications.

Precision and Scalability. SAFE DISPATCH uses CHA to determine, at compile time, which program locations a runtime method call may legitimately jump to. As a type-based analysis, CHA is relatively lightweight and scales up to large, complex applications. However, type-based analyses scale because they are generally coarse-grained and therefore less precise. It is possible that an object \( x \) stored in a variable of static type \( c \) only ever has runtime type \( c' \) where \( c' \) is a subclass of \( c \). In such instances, CHA will overestimate the set of valid implementations \( x \) may invoke, including the implementation for \( c \) and all implementations in subclasses of \( c \), while in reality only the implementation in \( c' \) should be called at runtime.

Such sources of imprecision could be remedied by using a more powerful static analysis. The additional precision would
provide stronger security guarantees by further restricting an
attacker’s ability to invoke method implementations that should
never arise during legitimate program execution. However,
accurately tracking which classes flow to a particular variable
\( x \) at compile time would require a precise whole program
dataflow analysis. While such analyses exist, they often don’t
scale to the kinds of programs we aim to protect, leading to
unacceptable increases in compile time. Those analyses that
can scale in fact do so by giving up on precision, which
would bring us back to square one. As a result, we feel that
our type-based approach in CHA presents the best tradeoff
by being precise enough to prevent real world attacks without
dramatically increasing compile times.

We do note that CHA is fundamentally a whole program
analysis, and thus requires all an application’s code to be
available at compile time. Unfortunately, this currently pre-
cludes the use of separate compilation in our prototype im-
plementation. However, our SAFE\textsc{Dispatch} implementation
is a research prototype and we feel that future work can
address this limitation by annotating compiled object files with
partial analysis results and composing those results to complete
SAFE\textsc{Dispatch}’s program instrumentation at linktime.

B. SAFE\textsc{Dispatch} Method Checking Instrumentation

After SAFE\textsc{Dispatch} computes the CHA results, it can
instrument the program with checks to ensure that whenever
an object calls a virtual method, control jumps to one of
the method implementations statically determined to be
valid. Figure 6 shows how SAFE\textsc{Dispatch} instruments each
source level method call. For now, consider the basic strategy
illustrated in part (A) of Figure 6. In the generated code
for \( o \rightarrow x(\text{args}) \), after the implementation \( m \) for method
name "x" has been looked up in the vtable dereferenced
from \( o \)'s vtable pointer, SAFE\textsc{Dispatch} inserts a call to
\texttt{check} (static typeof(\( o \)), "x", m) before invoking \( m \). This
call to \texttt{check} consults the CHA results in \texttt{ValidM} to ensure
that \( m \) is one of the valid implementations for "x" when called
by an object which has \( o \)'s static type. Note that expressions
in italics are evaluated at compile time as they require source-
level information available only to the compiler. As shown
in part (B) of Figure 6, SAFE\textsc{Dispatch} also reduces runtime
overhead by partially inlining calls to the \texttt{check} function,
which we discuss in greater detail below.

Data Structures for Checking. The operation for checking
method validity, \texttt{ValidM}[c][n].contains(m), is critical
for performance since it is inserted at every virtual method
call site. Broadly speaking, SAFE\textsc{Dispatch} uses an array
of sets of valid method implementations to perform this validity
checking. More specifically, for each pair (c, n) where c is a
class and n is a method name, SAFE\textsc{Dispatch} generates at
compile time a unique natural number \( i_{(c,n)} \) which is used to
index into a large array of sets. The set at position \( i_{(c,n)} \),
which contains the possible implementations for method \( n \) of
class c, is represented as an unordered array of pointers to
method addresses. Therefore \texttt{ValidM}[c][n].contains(m) in-
volves an array lookup to retrieve \texttt{ValidM}[c][n], followed
by a linear scan through the resulting set. In our experiments
we found that the average set size was very small (1.44 for
method checking) and as result we do not expect that using a
more elaborate data structure for representing these sets (e.g. a
hash-set) would reduce the overhead significantly. Instead,
we focus on other aggressive optimizations, for example the
inlining of common checks, as explained in Section III.C

Externalizing Linktime Symbols. One subtlety of the
method checking instrumentation is that the compiler does not
statically know the concrete address where method imple-
mementations will be placed at linktime. It may seem that
SAFE\textsc{Dispatch} compiler can handle this issue by simply
referring to the linktime symbols for each method imple-
mentation. However, many modern C++ compilers restrict
the linktime symbols for method implementations to only internal
symbols, meaning that they cannot be referred to outside of
code for their class. This poses a problem for SAFE\textsc{Dispatch}
as we need to check method implementation addresses where-
ever they may be called, not just in the class where they're
defined. To address this issue, we externalize all linktime
symbols for method implementations, allowing us to refer to
them outside of their defining class. It would be straightforward
to add an additional pass to check that these externalized
symbols are only used in (1) internally by the defining class
or (2) in SAFE\textsc{Dispatch} instrumentation, together providing
a guarantee equivalent to that of the unmodified C++ compiler.

Fig. 6. SAFE\textsc{Dispatch} Instrumentation. At each method call site,
SAFE\textsc{Dispatch} inserts a check in the generated code to ensure that objects
only invoke methods allowed by the static C++ type system. As shown
in (A), the basic SAFE\textsc{Dispatch} instrumentation simply adds a call to the
\texttt{check}() function immediately before the jump to a method implementa-
tion. \texttt{check}(c, n, m) consults the \texttt{ValidM} table to ensure that function pointer m
is a valid implementation of the method named n for objects with static type c.
To avoid an extra function call at every method invocation, SAFE\textsc{Dispatch}
actually uses profiling information to partially inline \texttt{check}(). As shown
in (B), SAFE\textsc{Dispatch} inserts a branch to test if the function pointer
looked up from the calling object’s vtable is one of the most common valid
implementations of the method used at this call site. If it is, SAFE\textsc{Dispatch}
safely skips the call to \texttt{check}(), thus avoiding the overhead of an additional
function call in the common case. Note that all expressions in italics in
the code above are evaluated at compile time as they require source-level
information available only to the compiler.

// source level method call
\( o \rightarrow x(\text{args}) \);

// (A) generated code without check inlining
vtable t = *(vtable *)o;
method m = t[\text{static position}(x)];
check (static typeof(o), "x", m);
m(o, args);

// (B) generated code with check partially inlined
if (m != m1 && m != m2 && m != m3)
check (static typeof(o), "x", m);
void check(type c, string n, method m) {
  if (!ValidM[c][n].contains(m)) {
    error("bogus method implementation!");
  }
}
C. SafeDispatch Optimizations

To minimize SafeDispatch’s runtime overhead, we developed a handful of optimizations to reduce the cost of each check. Most importantly, we profile applications and partially inline the checks performed by the check function as shown in part (B) of Figure 6. This partial inlining compares the function pointer retrieved from an object’s vtable against the concrete addresses of the N most common implementations of the method being called in profiling. In Figure 6 we limit N to just the three most common implementations, but in practice we can choose a value that balances the performance improvement of inlining against the increase in code size, which, in the worst case, could negatively impact instruction cache performance. In our actual experiments, discussed in Section VI we inline all checks observed during profiling, which increases codesize, but did not present significant performance overhead for our benchmarks.

SafeDispatch also performs devirtualization: in the case that CHA is able to statically determine there is a single valid method implementation at a given method call site, we rewrite the call to forgo vtable lookup and directly call the unique valid implementation. This avoids unnecessary memory operations to load the vtable and other computations to set up a virtual method call. Now that we have inlined frequently executed checks, the high-level code in part (B) of Figure 6 still needs to be translated into low-level code. A direct naïve translation leaves room for two important optimizations, which we now describe. Consider again the code in part (B) of Figure 6, and let’s look at a direct unoptimized translation to low-level code, as shown in part (A) of Figure 7. One source of overhead in this low-level code is that there are two opportunities for branch mis-prediction: one is to mis-predict which of the if (…) goto L1 statements will fire; the second is to mis-predict where the indirect call through m will go (note that m is a function pointer). Our first low-level optimization is that we can remove the second mis-prediction opportunity by placing a direct call once we know which of the three conditional has fired. This is shown in part (B) of Figure 7, where we now have direct calls for all checks that have been inlined. However, this code now has a lot of code duplication – namely all the setup for parameters. While this doesn’t affect the number of instructions executed at run-time, it creates code bloat, which can have adverse effects on instruction-cache performance. Our second low-level optimization is that we hoist the duplicate code from inside the conditionals and use a single copy right before the conditionals, as shown in part (C) of Figure 7.

With all of the above optimizations, namely profile-based inlined checks and low-level optimizations, we were able to reduce the runtime overhead of SafeDispatch to 2.1% and the codesize overhead to 7.5%. Section VI will provide a more detailed empirical evaluation of the overheads of SafeDispatch.  

IV. An Alternate Approach: Vtable Checking

The previous section showed how SafeDispatch checks the control flow transfer at virtual method call sites. In this section, we present an alternate technique which establishes the same control-flow guarantee, but provides additional data integrity guarantees in the face of multiple inheritance, at the expense of additional runtime overhead. Later, in Section VI we evaluate and compare the overhead of both approaches.

A. Pointer Offsets for Multiple Inheritance

To better explain this alternate approach, we first review vtables in more detail. In practice, vtables store more than just function pointers; they also contain offset values that are used to adjust the this pointer appropriately in the face of multiple inheritance.

For example, consider a class C that inherits from both A and B. The data layout of C objects will first include the fields from A, followed by the fields from B. Inherited methods from
A will work unmodified on objects of type C because the offset of A’s data fields are the same in A as in C. However, methods inherited from B will not work, because B’s methods assume that B’s fields start at the beginning of the object, whereas in C these fields are located after A’s fields.

To address this problem, the compiler creates wrappers in C for methods inherited from B. Before calling B’s original implementation of the method, the wrapper adjusts the calling object’s this pointer by an appropriate offset so that it points to the B part of the C object. The situation is further complicated if C is subclassed again using additional multiple inheritance, in which case the layout for the fields inherited from A and B could change in the subclass of C. To address this problem, pointer offsets for this are stored in the vtable, so that the correct offset can be used at run-time depending on what class is being used to make the method call.

While our approach from Section III always protects against malicious control flow at virtual method call sites, it does not defend against an attacker counterfeiting a vtable with incorrect this pointer offsets. If an attacker successfully mounts such an attack, our previously described approach would still protect the control flow at virtual method calls, but the attacker could corrupt the this offset on entry to a method, potentially leading to further data corruption.

B. vtable Checking

To additionally protect this pointer offsets at method calls, we implemented an alternate vtable hijacking defense called vtable checking. Instead of checking the validity of the function pointer looked up from an object’s vtable, we check the vtable pointer itself to ensure that it is valid given the static type of the calling object. In this way, we not only guarantee valid control flow at method calls, but also ensure that the offset value of this is computed appropriately.

Figure 8 shows how each source level method call is instrumented in the vtable checking approach. As in Figure 6, expressions in italics are evaluated at compile time as they require source-level information available only to the compiler. We insert a check similar to the method checking instrumentation shown in Figure 6, but move the instrumentation earlier to check the vtable itself instead of the function pointer retrieved from it. In general, for code generated for method call o->x(args), we insert a call to the vt_check(static_typeof(o), t) after vtable t has been loaded from o’s vtable pointer. This call to vt_check consults the results of a modified CHA analysis to ensure that t is one of the valid vtables for an object of o’s static type. The computation for ValidVT is a modified, simpler version of the computation for ValidM described in the previous section, since the compiler already computes vtables. In particular, for each class c we collect the vtables for c and all of its subclasses, and store this entire set in ValidVT[c]. Similarly to method checking, the operation ValidVT[c].contains(t) is performed in two steps: ValidVT[c] is implemented as an array lookup and contains(t) is implemented using linear search. Here again, the average size of ValidVT[c] in our experiments was very small (2.58) and we reduce runtime overhead by selectively inlining calls to the vt_check function, taking advantage of profiling information as discussed in the previous section.

C. Performance Implications

The vtable checking approach described above provides a stronger security guarantee than the method checking approach described in the previous section, as it also ensures the integrity of this pointer offsets. Unfortunately, this stronger guarantee also incurs higher runtime overhead: since subclasses frequently inherit method implementations from their parent classes, at any virtual method call site, the number of valid vtables is always greater than or equal to the number of valid method implementations that can be invoked.

To better understand why this is the case, consider an example in which a class A declares method foo, and suppose there are many subclasses of A, none of which override foo. Now for any method call x->foo() where the static type of x is A, method checking just needs to compare against A::foo, since it is the only valid implementation of foo. On the other hand, vtable checking must compare against each vtable of the many subclasses of A, since each subclass has its own vtable. In practice, we’ve measured the difference between the number of valid vtables and the number of valid method implementations at a given call site to be roughly a factor of two. We explore the performance implications of this difference further in Section VI.

V. A Hybrid Approach for Method Pointers

In previous sections we described two vtable hijacking defenses, method checking and vtable checking, each presenting
method pointers: if an attacker could arbitrarily set the method
ification is essential for preventing hijacking attacks through
implementations retrieved by indexing into valid vtables with
that vtable indices from method pointers are within the valid
validity of vtables at runtime, S
Fortunately, vtable checking correctly handles method pointers
First, consider our vtable checking technique from Section IV.
checking and vtable checking, in the face of method pointers.
A. Revisiting Previous Approaches
A pointer's value is used to index into the calling object's vtable
f
f
void (A::*f)(int); // declare f as ptr to some method of A
f = &A::foo; // f now points to the foo method
A* a = new A();
(a->*f)(5); // method call via f ptr, invokes A::foo
a = new B();
(a->*f)(5); // method call via f ptr, invokes B::foo

Fig. 9. Method Pointer Example. Because C++ method pointers are invoked
dynamic dispatch, even though f is only assigned once, the first call above
jumps to A::foo while the second jumps to B::foo.

different tradeoffs. To best choose between these tradeoffs, we
must consider additional subtleties arising from yet another
C++ feature: method pointers. Conceptually, C++ method
pointers are similar to traditional function pointers, except that
pointers to virtual methods are invoked by dynamic dispatch,
which means they could be exploited by vtable hijacking
attacks and thus SAFE DISPATCH must also protect virtual calls
through method pointers.

Figure 9 illustrates the behavior of C++ method pointers
with two simple classes, A and B, where A contains a single
method foo and B extends A and overrides foo. The method
pointer f is declared to point to a method of an object of
type A or one of A's subclasses, and then f is assigned to
point to A::foo. Next an A object is allocated and A::foo
is called through the method pointer f. Afterward a B object
is allocated and the same method pointer, f, is used to call
one of the object's methods. However, in this case, control
jumps to B::foo instead of A::foo since method pointers
are invoked by dynamic dispatch.

To implement method pointer semantics, C++ compilers
generate code which stores a vtable index in method pointers
instead of the concrete address of a method's implementation.
For example, if foo is placed at index 0 in the vtables of A and
B, then the statement f = &A::foo will store the value 0 in
f. When a call is made through a method pointer, the method
pointer's value is used to index into the calling object's vtable
to retrieve the appropriate method implementation to invoke.

A. Revisiting Previous Approaches
We now evaluate our previous two approaches, method
checking and vtable checking, in the face of method pointers.
First, consider our vtable checking technique from Section IV.
Fortunately, vtable checking correctly handles method pointers
with only a slight modification: since a method pointer is
simply a vtable index and vtable checking guarantees the
validity of vtables at runtime, SAFE DISPATCH simply checks
that vtable indices from method pointers are within the valid
range of methods for the given class, thus ensuring that method
implementations retrieved by indexing into valid vtables with
a method pointer will also be valid. While simple, this mod-
ification is essential for preventing hijacking attacks through
method pointers: if an attacker could arbitrarily set the method
index to be out of range for the given class's vtable, they could
cause a virtual method pointer call to jump to malicious code.

Second, consider our method checking technique from
Section III. In particular, consider a call through a method
pointer of the form (x->*f) ( . . . ), where the class used in
the declaration of method pointer f is C. We must modify
our method checking approach so that for such calls, the
instrumentation checks, at runtime, that the function pointer
extracted from the calling object's vtable is one of the im-
plementations for any method of C or its subclasses. This
conservative approach can lead to a blow up in the number of
required checks for large class hierarchies with many methods,
like those found in modern web browsers. This effect is seen in
Section VI where we evaluate and further compare our
different defenses. Unfortunately, improving on this approach
would require a precise whole program dataflow analysis to
compute which method implementations a pointer may point
to. Despite decades of research, such analyses are very difficult
to scale to the large, complex applications most frequently
targeted by vtable hijacking attacks.

B. Hybrid Approach
Comparing method checking and vtable checking in the
face of method pointers leads to a key observation: at
method pointer call sites, vtable checking typically requires
many fewer comparisons than method pointer checking, since
method pointer checking must compare against all method
implementations from several classes. This situation is exactly
the opposite from traditional method calls where vtable check-
ing always demands at least as many comparisons as method
checking, as discussed at the end of Section IV.

This observation suggests a hybrid approach: perform
vtable checking (enhanced with vtable index range checks)
at method pointer call sites and method checking at traditional
method call sites. We implemented this hybrid approach in
SAFE DISPATCH and found that it incurs less runtime overhead
than all other techniques, while providing the same strong
security guarantees against vtable hijacking. We further dis-
cuss the performance implications of our hybrid approach in
Section VI. At a member function call site, the numbers of
method/vtable checks are compared, and vtable checks are
used only when the number of the vtable checks is strictly
less than the number of the method checks.

VI. Evaluation
In this section we evaluate SAFE DISPATCH along three
primary dimensions: (A) runtime and code size overhead, (B)
effort to develop our prototype, and (C) compatibility with
existing applications and programming practice.

A. SAFE DISPATCH Overhead
To evaluate the overhead of our SAFE DISPATCH defense,
we used our enhanced C++ compiler to build a vtable-safe
version of Google Chromium [20], a full-featured, open source
web browser which forms the core of the popular Google
Chrome browser [19]. Google Chromium is extremely large
and complex, far larger than any SPEC benchmark for ex-
ample. It contains millions of lines of production code, in di-
verse components (HTML renderer, JPEG decoder, Javascript

JIT, IPC library, etc.) developed across multiple organizations (Google and various open source groups). Chromium serves as an ideal test case for SAFE_DISPATCH: not only is it a complex, high performance C++ application with millions of users, but has also been targeted by several viable hijacking attacks [12], [9].

**Benchmarks.** We measured SAFE_DISPATCH overhead on Chromium over six demanding benchmarks: three industry-standard JavaScript performance suites (octane, kraken, and sunspider) and three HTML rendering performance tests (balls, linelayout, and html5). All results are reported from the average of five runs, using percentage overhead compared to a baseline with no instrumentation. “mchk” is the unoptimized method pointer checking from Section III “vtchk” is the unoptimized vtable checking from Section IV. “inline” combines method pointer checking and vtable checking. Note that two bars did not fit in the graph with the scale we chose for the y axis, namely “vtchk” and “vtchk_inline_rand” for html5; we shortened those bars, and show their values right on top of the bars (rather than change the scale and make all the other bars more difficult to read).

![SAFE_DISPATCH Overhead](image)

Fig. 10. **SAFE_DISPATCH Overhead.** We measured the overhead of SAFE_DISPATCH on the Google Chromium browser over six demanding benchmarks: three industry standard JavaScript performance suites (octane, kraken, and sunspider) and three HTML rendering performance tests (balls, linelayout, and html5). All results are reported from the average of five runs, using percentage overhead compared to a baseline with no instrumentation. “mchk” is the unoptimized method pointer checking from Section III “vtchk” is the unoptimized vtable checking from Section IV “inline_rand” indicates that we inline all checks that our Class Hierarchy Analysis tells us are needed for safety, but we inline them in a random order (i.e. no profile information). “inline_prof” indicates that we inline the checks observed during profiling in order of how frequently they occur. “hybrid” is the hybrid approach from Section V, which does profile-based inlining, but also combines method pointer checking and vtable checking. Note that two bars did not fit in the graph with the scale we chose for the y axis, namely “vtchk” and “vtchk_inline_rand” for html5; we shortened those bars, and show their values right on top of the bars (rather than change the scale and make all the other bars more difficult to read).

Benchmarks. We measured SAFE_DISPATCH overhead on Chromium over six demanding benchmarks: three industry-standard JavaScript performance suites (octane, kraken, and sunspider), and three HTML rendering performance tests (balls, linelayout, and html5). The three HTML rendering benchmarks are drawn from the WebKit performance test suite, the engine underlying several major web browsers including Google Chrome, Apple Safari, and Opera. We selected these benchmarks from the suite as three of the most important for performance and rendering correctness. We briefly describe the benchmarks below:

**octane**, **kraken**, and **sunspider** are the JavaScript performance benchmarking suites from the Google Chrome, Mozilla Firefox, and Apple WebKit teams respectively. These benchmarks strive to measure real-world workloads and exercise the most important browser functionality, while remaining statistically sound and pushing for improvement on bleeding-edge features. For octane we report the benchmark score where higher is better and for kraken and sunspider we measure running time in milliseconds where smaller is better.

**balls** creates thousands of small ball-shaped DOM elements, moves them around on the screen, measures how many of them can be moved in a fixed amount of time, and reports frames per second as its output. We report frames per second (fps); higher is better.

**linelayout** creates multiple DOM objects containing copious text. The renderer must draw many text lines, automatically inserting line breaks and allocating DOM objects efficiently on the screen, ensuring the renderer correctly handles the layout of DOM elements on the screen. We report number of complete runs in a fixed period; higher is better.

**html5** performs millions of DOM manipulations to test numerous HTML5 features and is one of the most demanding WebKit performance tests. Each complex rendering is compared to an industry-standard reference rendering, thus ensuring optimizations have not introduced incorrect behavior. We report timing results in milliseconds; smaller is better.

Runtime Overhead. Figure [10] presents the runtime overhead percentage of SAFE_DISPATCH on benchmarks using a number of different approaches and optimizations, whereas Figure [11] presents the raw numbers, including memory overhead. See the caption of Figure [10] for what each configuration of SAFE_DISPATCH corresponds to (e.g., “mchk_inline_rand”). All our results are the average of five runs on an otherwise quiescent system running Ubuntu 12.04 on an Intel i7 Quad Core machine with 8GB of RAM.

From Figure [10] we can see that in general, all the “mchk” overheads are smaller than the “vtchk” overheads. This is consistent with the fact that, as described in Section III, the number of valid vtables at a given method callsite is often 2x greater than the number of valid method implementations. Figure [10] shows the effectiveness of partial inlining of checks...
Fig. 11.  **SAFE_DISPATCH Benchmarking Results and Code Size Overhead.** The table above shows our benchmarking measurements for **SAFE_DISPATCH** which correspond to the runtime overhead graph in Figure 10 for times reported in milliseconds, smaller is better, for other reported quantities (score, fps, and runs), larger is better. We additionally measured average code size increase due to **SAFE_DISPATCH** data structures and instrumentation, and observed overheads typically well under 10%.

<table>
<thead>
<tr>
<th>Instrumentation</th>
<th>octane (score)</th>
<th>kraken (ms)</th>
<th>sunspider (ms)</th>
<th>balls (fps)</th>
<th>linlayout (runs)</th>
<th>html5 (ms)</th>
<th>Code Size Overhead %</th>
</tr>
</thead>
<tbody>
<tr>
<td>none</td>
<td>15353</td>
<td>1556</td>
<td>254</td>
<td>14.95</td>
<td>106.26</td>
<td>3543</td>
<td>-</td>
</tr>
<tr>
<td>mchk</td>
<td>14454</td>
<td>1643</td>
<td>285</td>
<td>12.73</td>
<td>90.43</td>
<td>4233</td>
<td>7.20</td>
</tr>
<tr>
<td>mchk_inline_rand</td>
<td>14897</td>
<td>1599</td>
<td>272</td>
<td>13.84</td>
<td>94.47</td>
<td>3974</td>
<td>14.11</td>
</tr>
<tr>
<td>mchk_inline_prof</td>
<td>15278</td>
<td>1570</td>
<td>263</td>
<td>14.50</td>
<td>100.71</td>
<td>3830</td>
<td>7.48</td>
</tr>
<tr>
<td>vtchk</td>
<td>14101</td>
<td>1782</td>
<td>310</td>
<td>11.47</td>
<td>88.10</td>
<td>5294</td>
<td>7.31</td>
</tr>
<tr>
<td>vtchk_inline_rand</td>
<td>14969</td>
<td>1725</td>
<td>304</td>
<td>11.24</td>
<td>74.91</td>
<td>6793</td>
<td>44.18</td>
</tr>
<tr>
<td>vtchk_inline_prof</td>
<td>15228</td>
<td>1574</td>
<td>270</td>
<td>13.42</td>
<td>97.43</td>
<td>3892</td>
<td>7.85</td>
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<tr>
<td>hybrid</td>
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<td>1570</td>
<td>256</td>
<td>14.71</td>
<td>102.39</td>
<td>3721</td>
<td>7.48</td>
</tr>
</tbody>
</table>

Fig. 12.  **Cross Profiling.** To evaluate the effect of profiling across benchmarks, we measured the overhead of running each binary optimized for one JavaScript performance suite on the other suites. The numbers reported are percentage overhead for the hybrid approach. We can see that inlining alone, without profile information ("mchk_inline_rand" and "vtchk_inline_rand") improves performance compared to the unoptimized instrumentation, but only for method checking. For vtable checking, the random-order inlining causes a slowdown because there were too many checks to inline, which affected performance negatively (this is confirmed by the memory overhead shown in Figure 11). Inlining with profile information ("mchk_inline_prof" and "vtchk_inline_prof") provides a significant reduction in percentage overhead compared to the unoptimized instrumentation. Finally, Figure 12 also shows that the hybrid approach from Section V has the lowest overhead by far, about 2% on average.

<table>
<thead>
<tr>
<th>Profile</th>
<th>Benchmark Overhead %</th>
<th>octane</th>
<th>kraken</th>
<th>sunspider</th>
</tr>
</thead>
<tbody>
<tr>
<td>octave</td>
<td>0.30</td>
<td>2.51</td>
<td>6.30</td>
<td></td>
</tr>
<tr>
<td>kraken</td>
<td>0.79</td>
<td>1.22</td>
<td>6.69</td>
<td></td>
</tr>
<tr>
<td>sunspider</td>
<td>1.15</td>
<td>2.25</td>
<td>1.97</td>
<td></td>
</tr>
</tbody>
</table>

Fig. 13.  **SAFE_DISPATCH Prototype LOC.** The table above characterizes the major components in our **SAFE_DISPATCH** implementation. The basic instrumentation module is implemented as a Clang++ compiler pass and inserts calls to the check() function as described in Section III function at each method call site, additionally logging some type data. These logs are used by the CHA module, written in Python, to build the ValidM and ValidVT used during checking at runtime. The final module is implemented as a set of low-level LLVM passes to inline checks based on profiling information to profile all three rendering benchmarks to get a representative set, but then this would not evaluate cross-profiling). Figure 12 shows the results of cross-profiling for the hybrid approach. Each row and each column is a benchmark, and at row y and column x, we show the percentage overhead of running the x benchmark using the binary optimized for y’s profile information. While we can see that in some cases the overhead jumps to 6%, if we profile with **sunspider**, the overhead still remains in the vicinity of 2%. This may indicate that **sunspider** is a more representative Javascript benchmark, which is better suited for generating good profile information.

**Code Size Overhead.** We also measured the increase to code size resulting from **SAFE_DISPATCH** data structures and instrumentation in the generated executable, shown in the final column of the table from Figure 11. For the hybrid approach, the generated executable size was within 10% of the corresponding unprotected executable. Note that the memory overhead for “vtchk_inline_rand” is substantial, which is consistent with the run-time overhead for “vtchk_inline_rand” from Figure 10.

B. Development Effort

Our prototype implementation of **SAFE_DISPATCH** has three major components: (1) the basic instrumentation compiler pass,
(2) CHA analysis to generate the ValidM and ValidVT internal SAFE DISPATCH checking data structures, and (3) inlining optimizations. The size of each component is listed in Figure 13.

The basic instrumentation pass is implemented as a pass in Clang++ while the compiler has access to source-level type information which is erased once a program is translated into the lower level LLVM representation. This pass also produces information used in our second major component, the CHA analysis, which we implemented in a set of Python scripts to build the intermediate ValidM and ValidVT tables. Finally, we implemented our inlining passes as an optimization in LLVM which can take advantage of profiling information to order checking branches by how frequently they were taken in profile runs.

C. Compatibility

In principle, SAFE DISPATCH only incurs minimal compile time overhead to build the ValidM and ValidVT tables and instrument virtual method call sites as described in Sections III [14] and [15]. Thus, the programmer should be able to use SAFE DISPATCH on every compilation without disrupting the typical edit, compile, test workflow. However, in our current prototype implementation, SAFE DISPATCH performs two full compilations to gather necessary analysis results before instrumenting the code, leading to a roughly 2x increase in compile time. As mentioned above, this is an artifact of our prototype implementation which can easily be fixed and is not an inherent limitation of SAFE DISPATCH.

The SAFE DISPATCH prototype also requires a whole-program CHA to perform instrumentation, and does not currently support separate compilation. There are two main challenges in supporting separate compilation. The first challenge is to make CHA modular. In particular, the compiler would have to generate CHA information per-compilation unit, which the linker would then combine into whole-program information. This approach to CHA is very similar to the approach taken in GCC’s vtable verification branch [27], [28], more details of which are discussed in Section VII. The second challenge is to inline checks in a modular way. In particular, editing code in one file could require additional checks in another file. To address this challenge, the compiler could insert calls to check at compile time, and then replace these calls with inserted inlined checks at link-time (similarly to link-time inlining of function calls). Finally, profiling data for inlining optimizations can be collected using a profile build in which the check function collects the required function/vtable pointers. This profile build can easily support separate compilation, as it does not require inlining or CHA.

VII. SAFE DISPATCH SECURITY ANALYSIS

In this section we consider the security implications of SAFE DISPATCH including the class of attacks SAFE DISPATCH prevents and some limitations of our approach.

A. SAFE DISPATCH Guarantee

The instrumentation inserted by the SAFE DISPATCH compiler guarantees that each virtual method call made at runtime jumps to a valid implementation of that method according to C++ dynamic dispatch rules. This guarantee immediately eliminates an attacker’s ability to arbitrarily compromise the control flow of an application using a vtable hijacking attack. Our defense would prevent crucial steps in many recent, high profile vtable hijacking attacks, e.g. Pinkie Pie’s 2012 Zero-day exploit of Google Chrome which escaped the tab sandbox and allowed an adversary to compromise the underlying system. In addition to preventing many attacks, SAFE DISPATCH provides an intuitive guarantee in terms of the C++ type system, which is easy to understand for programmers who are familiar with the type system. Furthermore, the programmer cannot inadvertently nullify the SAFE DISPATCH guarantee through a programming mistake; the checks inserted by SAFE DISPATCH will detect errors such as incorrect type casts which would otherwise lead to a method call invoking an invalid method implementation.

The SAFE DISPATCH guarantee provides strong defense against vtable hijacking attacks, regardless of how the attack is mounted, e.g. use-after-free error, heap based buffer overflow, type confusion, etc. As discussed further in the next section on related work, other defenses only focus on particular styles of attack (for example mitigating use-after-free errors by reference counting), or incur non-trivial overhead (for example using a custom allocator to ensure the memory safety properties necessary to prevent vtable hijacking). Furthermore, SAFE DISPATCH protection is always safe to apply: all programs should already satisfy the SAFE DISPATCH guarantee – we are simply enforcing it.

SAFE DISPATCH also defends against potentially exploitable, invalid types made by the programmer [29]. If a programmer incorrectly casts an object of static type c to another type c‘, then methods invoked on the object will not be valid implementation and SAFE DISPATCH will signal an error.

The astute reader may wonder why the checks inserted by SAFE DISPATCH instrumentation are any more secure than the vtable pointer stored in a runtime object. Unlike such heap pointers, the checks inserted by SAFE DISPATCH and their associated data structures are embedded in the generated executable which resides in read-only memory, ensuring that an attacker will not be able to corrupt SAFE DISPATCH inserted checks at runtime. Of course, this assumes the attacker will not be able to remap the program’s text segment, or portion of memory containing the application’s executable code, to be writable.

B. SAFE DISPATCH Limitations

SAFE DISPATCH guarantees that one of the valid method implementations for a given call site will be invoked at runtime, not that the correct method will be called. For example, an attacker could still corrupt an object’s vtable pointer to point to the vtable of a child class, causing an object to invoke a child class’s implementation of a method instead of it’s own. While this call would technically satisfy the static C++ dynamic dispatch rules, it could lead to further memory corruption or other undesirable effects. However, we are not aware of any exploits in the wild which take advantage of such behavior.

SAFE DISPATCH detects vtable pointer corruption precisely when it would result in an invalid method invocation. This does
not prevent other memory corruption attacks, such as overwriting the return address stored in a function’s activation record on the stack. SAFE_DISPATCH also does not currently prevent corrupting arbitrary (non-object) function pointer values. Such function pointers are important in systems making extensive use of callbacks or continuations. SAFE_DISPATCH could be extended to protect such calls through function pointers by conceptually treating them as method invocations of a special ghost class introduced by the compiler. This change, which we will explore in future work, would also be transparent to the programmer and would further strengthen our guarantee.

SAFE_DISPATCH only protects the code it compiles. Thus, if an application dynamically loads unprotected system libraries, an attacker may be able to compromise control flow within the library code via vtable hijacking. While such libraries can be compiled with SAFE_DISPATCH to prevent such attacks, it’s important to note that SAFE_DISPATCH requires performing a whole program Class Hierarchy Analysis on the entire program, including all application libraries and all system libraries. Unfortunately, it is well known that such whole program analyses present challenges in the face of separate compilation, dynamically linked libraries, and shared libraries. As a result, our current SAFE_DISPATCH prototype protects the entire application code, including all application libraries, but it does not protect shared system libraries such as the C++ standard library.

Dynamically linked libraries are also a possible source of incompatibility with the current SAFE_DISPATCH prototype. For example, consider an application that uses a subclass implemented in an external, dynamically linked library. Since the subclass information is not statically available to SAFE_DISPATCH’s CHA, any such dynamically loaded subclass method implementations will be reported as invalid by check at runtime. To overcome this limitation, SAFE_DISPATCH would be required to dynamically update its ValidM and ValidVT tables as dynamic libraries are loaded at runtime by instrumentation of certain system calls (e.g., diopen). In future work, we hope to address this limitation by developing better techniques for performing our CHA analysis in the face of separate compilation and dynamically linked libraries.

C. Performance and Security Tradeoffs

As discussed in previous sections, there are multiple strategies for enforcing the SAFE_DISPATCH guarantee which lead to different security and performance tradeoffs. Vtable checking provides additional data integrity guarantees over method checking, in particular for this pointer offsets in the face of multiple inheritance, but at the cost of additional runtime overhead. Our hybrid approach adopts vtable checking at method pointer call sites to reduce runtime overhead, but uses method checking at non-method-pointer call sites, and so does not provide the same data integrity guarantees as vtable checking. Although the additional data integrity guarantee provided by vtable checking may mitigate some attacks, we feel that the significantly reduced overhead of our method checking and hybrid approaches offer a more realistic tradeoff for complex, high performance applications like web browsers.

VIII. Related Work

The research community has developed numerous defenses to increase the cost of mounting low-level attacks that corrupt control data, steadily driving attackers to discover new classes of exploitable programming errors like vtable hijacking. In this section we survey the existing defenses most relevant to vtable hijacking, consider their effectiveness at mitigating such attacks, and compare them to SAFE_DISPATCH.

Reference Counting. Reference counting [20, 21, 32] is a memory management technique used in garbage collectors and complex applications to track how many references point to an object during program execution. When the number of references reaches zero, the object may safely be freed. Use-after-free errors can be avoided using reference counting by checking that an object has a non-zero number of references before calling any methods with the object. While this may help increase the attack complexity of vtable hijacking attacks mounted by exploiting use-after-free bugs, reference counting can have a non-trivial run-time overhead, and it also makes reclaiming cyclic data-structures complicated. Most importantly, however, reference counting cannot fundamentally prevent such attacks. In reference counting, the number of references to an object is stored in the heap, and thus an adversary capable of corrupting vtable pointers would also be able to corrupt reference counts, thereby circumventing any reference counting based defense. In contrast, SAFE_DISPATCH instrumentation is placed in the program binary which resides in read-only memory and thus is not susceptible to corruption by an attacker.

Memory Safety. Programs written in memory safe languages are guaranteed, by construction, to be free of exploitable, low-level memory errors. This kind of memory safety guarantee is clearly stronger than the guarantee that SAFE_DISPATCH provides. However, unfortunately programs written in such languages often suffer significant performance overhead from runtime checking to ensure that all memory operations are safe. This overhead is sufficient to preclude the use of memory safe languages in many performance critical applications. In contrast, SAFE_DISPATCH provides strong security guarantees without any assumptions about memory safety and incurs only minimal overhead.

There has also been extensive research on C compilers which insert additional checks or modify language features to ensure memory safety, for example CCured [33, 34], Cyclone [35], Purify [36], and Deputy [37]. While these techniques can help prevent vtable hijacking, they often require some amount of user annotations, and even if they don’t, their run-time overheads are bigger than SAFE_DISPATCH, especially on large-scale applications like Chrome.

Control Flow Integrity. Control flow integrity (CFI) is a technique that inserts sufficient checks in a program to ensure that every control flow transfer jumps to a valid program location [13]. Recent advances have greatly reduced the overhead of CFI, in some cases to as low as 5%, by adapting efficient checks for indirect targets [14], using static analysis [15], harnessing further compiler optimizations from a trustworthy high-level inline-reference monitor representation [16], or incorporating low-level optimizations [17]. The main difference between our work and these previous CFI approaches lies in
the particular point in design space that we chose to explore. Broadly speaking, previous CFI approaches are designed to secure all indirect jumps whereas we focus specifically on protecting C++ dynamic dispatch, which has become a popular target for exploits. In this more specific setting, we provide stronger guarantees than recent CFI approaches while incurring very low performance overhead.

**VTable Hijacking Prevention.** The GCC compiler has recently been extended with a promising new “vtable verification” feature developed by Google [27], concurrently and independently from SAFE_DISPATCH. The GCC approach compiles each C++ source file to an object file extended with local vtable checking data, and the local checking data is combined at load-time into a program-wide checking table. Each virtual method call site is then instrumented with a call to a checking function which uses the program-wide table to determine if the control-flow transfer should be allowed. In many respects, the GCC approach is roughly equivalent to our unoptimized vtable checking approach. In this light, our work extends GCC’s approach in the following ways: (1) we explore and empirically evaluate not only vtable checking, but also method checking (2) through this evaluation, we discover and propose a new optimization opportunity in the form of a hybrid approach and (3) we inline common checks. In our implementation, vtable checking without inlining (which is roughly what GCC does) leads to an overhead of about 25%. Through optimizations 2 and 3 above, we reduce the overhead to only 2%. On the other hand, the GCC approach supports separate compilation much more easily than our approach, which requires whole program analysis and profiling.

Another technique for preventing vtable hijacking is VTGuard [33], a feature of the Visual Studio C++ compiler. This approach inserts a secret cookie into each vtable and checks the cookie before the vtable is used at runtime. While this approach has very low performance overhead, it is less secure than ours: the attacker can still overwrite a vtable pointer to make it point to any vtable generated by the compiler, something we prevent. Moreover, if the secret cookie is revealed through an information disclosure attack, then the VTGuard protection mechanism can be circumvented.

**Memory Allocators and Dynamic Heap Monitoring.** Dynamic heap monitoring, like that used in Undangle [39] and Valgrind [40], can help discover memory errors during testing, but are not suitable for deployment as they can impose up to 25x performance overhead, which is unacceptable for the applications we aim to protect. The DieHard [3, 41] custom memory manager has proven effective at providing probabilistic guarantees against several classes of memory errors, including heap-based buffer overflows and use-after-free errors by randomizing and spreading out the heap. While DieHard overhead is often as low as 8%, it demands a heap at least 2x larger than what the protected application would normally require, which is unacceptable for the applications we aim to protect. Furthermore, large applications like a browser often use multiple custom memory allocators for performance, whereas DieHard requires the entire application to use a single allocator.

**Data Execution Prevention (DEP).** After an adversary has compromised program control flow, they must arrange for their attack code to be executed. DEP [2] seeks to prevent an attacker from writing malicious shellcode directly to memory and then jumping to that code. Conceptually every memory page is either writable or executable, but never both. DEP can mitigate vtable hijacking after the attack has been mounted by preventing the attacker from executing code they’ve allocated somewhere in memory. However, attackers can still employ techniques like Return Oriented Programming (ROP) to circumvent DEP after control flow has been compromised from a vtable hijacking attack. DEP is also often disabled for JIT. While DEP tries to mitigate the damage an attacker can do after compromising control flow, SAFE_DISPATCH seeks to prevent a class of control flow compromises (those due to vtable hijacking) from arising in the first place.

**Address Space Layout Randomization (ASLR).** Like DEP, ASLR [43] seeks to severely limit an attackers ability to execute their attack code after control flow has been compromised. It does this by randomly laying out pages in memory so that program and library code will not reside at predictable addresses, making it difficult to mount ROP and other attacks. Unfortunately, for compatibility, many prevalent, complex applications are still forced to load key libraries at predictable addresses, limiting the effectiveness for ASLR in these applications. SAFE_DISPATCH helps secure such applications by preventing vtable-hijacking-based control flow compromises from arising in the first place.

**IX. CONCLUSION**

Robust vtable hijacking attacks are increasingly common, as seen in sophisticated, high profile attacks like Pinkie Pie’s recent exploits of the Chrome browser [12]. In this paper, we addressed the growing threat of vtable hijacking with SAFE_DISPATCH, an enhanced C++ compiler to ensure that control flow transfers at method invocations are valid according to the static C++ semantics.

SAFE_DISPATCH first performs class hierarchy analysis (CHA) to determine, for each class c in the program, the set of valid method implementations that may be invoked by an object of static type c, according to C++ semantics. SAFE_DISPATCH then uses the information produced by CHA to instrument the program with dynamic checks, ensuring that, at runtime, all method calls invoke a valid method implementation according to C++ dynamic dispatch rules.

To minimize performance overhead, SAFE_DISPATCH performs optimizations to inline and order checks based on profiling data and adopts a hybrid approach which combines method checking and vtable checking. We were able to reduce runtime overhead to just 2.1% and memory overhead to just 7.5% in the first vtable-safe version of the Google Chromium browser which we built with the SAFE_DISPATCH compiler.

We believe that these results are a solid first step towards hardening method dispatch against attack, and that they provide a good foundation for future exploration in this space, including ways of handling separate compilation, and additionally protecting indirect control flow through arbitrary functions pointers.

**ACKNOWLEDGMENT**

We would like to thank Hovav Shacham and Stephen Checkoway for clarifying the importance of vtable hijacking...
attacks in the initial stage of the project. We would also like
to thank the anonymous reviewers for helping us improve our
paper. This work was supported in part by the National Science
Foundation through grants 1228967 and 1219172.

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