A Turning Point for Verified Spectre Sandboxing

Sunjay Cauligi
UC San Diego, USA

Marco Guarnieri
IMDEA Software Institute, Spain

Daniel Moghimi
UC San Diego, USA

Deian Stefan
UC San Diego, USA

Marco Vassena
CISPA Helmholtz Center for Information Security, Germany

Abstract

Spectre attacks enable an attacker to access restricted data in an application’s memory. Both the academic community and industry veterans have developed several mitigations to block Spectre attacks, but to date, very few have been formally vetted; most are “best effort” strategies. Formal guarantees are particularly crucial for protecting isolated environments like sandboxing against Spectre attacks. In such environments, a subtle flaw in the mitigation would allow untrusted code to break out of the sandbox and access trusted memory regions.

In our work, we develop principled foundations to build isolated environments resistant against Spectre attacks. We propose a formal framework for reasoning about sandbox execution and Spectre attacks. We formalize properties that sound mitigation strategies must fulfill and we show how various existing mitigations satisfy (or fail to satisfy!) these properties.

1 Introduction

Software-based Fault Isolation (SFI) is a popular technique for efficiently confining untrusted code to a software sandbox [15]. For example, web browsers and cloud providers rely on SFI-based sandboxes to prevent buggy or malicious code from corrupting the memory of the host and other sandboxes [5, 9, 18]. Unfortunately, untrusted code can leverage speculative execution to break out of the sandbox and access trusted memory regions, thus making existing SFI implementations vulnerable to Spectre attacks [6, 8].

Researchers have proposed different approaches to mitigate Spectre attacks in SFI-style sandboxes [7, 11, 14]. However, these are best-effort proposals: They rely on carefully combining several intricate software protections and hardware extensions to prevent unsafe speculative behaviors. It is unclear whether the combination of these countermeasures work as intended and so, in practice, these approaches may fail to provide the expected security guarantees against Spectre attacks. This gap is apparent in the security guarantees of Swivel [11], a WebAssembly sandboxing system—although Swivel indeed prevents many Spectre attacks, its security guarantees are conditioned on several underlying assumptions and constraints. As one example, the Swivel-CET implementation prevents speculative leakage via the data cache, but does not stop leakage via control flow.

2 Background

We begin with an overview of speculative attacks on SFI sandbox systems and a brief description of the mitigation techniques that Swivel employs to enforce speculative sandbox isolation and control-flow integrity.

2.1 Speculative SFI attacks

Swivel identifies two distinct classes of speculative attacks on SFI sandboxes: Breakout attacks and poisoning attacks [11]. First, the sandbox host system does not trust the individual sandboxes: Swivel prevents breakout attacks, where a sandbox accesses data outside of its defined memory regions. Second, Swivel’s sandboxes themselves are mutually distrusting: Swivel prevents poisoning attacks, where an attacker is able to leak secrets from a victim sandbox.

Breakout attacks. A sandbox breakout occurs when a malicious sandbox is able to directly access the contents of memory outside of its own memory segments, e.g., from the host application or from another sandbox. As an example, the following pseudo-assembly program is vulnerable to a breakout attack:

```assembly
jmp end if e_check
*(r_stk + 4) := r_heap  ; spill r_heap to the stack
r_heap := r_A           ; and replace its contents with r_A
jmp end if ¬e_check     ; else
r_{y} := *(r_heap + 24) ; load a value from the heap
end:
```

Even though architecturally the final load is safe—as the two conditions are mutually exclusive—we might (mis)predict and enter both conditional blocks anyway. Under these conditions, the value in r_A is incorrectly used as the heap base address, so an attacker that controls the value of r_A can exploit this behavior to access arbitrary memory—including memory outside the sandbox.
Poisoning attacks. Even if a sandbox protects its own secrets from leaking architecturally, it may be speculatively poisoned and still leak these secrets on mispredicted execution paths. We present the following simple example, where X and Y are arrays of length 64 in the sandbox’s heap and \( r_A \) is an index into X.

\[\begin{align*}
\text{jmp end if } r_A \geq 64 & \quad ; \text{ check bound for heap array } X \\
    r_B & \leftarrow (r_{\text{Heap}} + X + r_A) \quad ; \text{ out of bounds if mispredicted} \\
    r_C & \leftarrow (r_{\text{Heap}} + Y + r_B) \quad ; \text{ leak } r_B \text{ via memory address}
\end{align*}\]

Under architectural execution, any value within X may be leaked due to the final memory access, but values outside of X are not leaked due to the initial conditional check. However, during speculative execution, we may incorrectly predict that the branch should fall through even when \( r_A \) is out-of-bounds for X. If an attacker is able to control the value of \( r_A \), they can then leak any value in the victim sandbox’s heap.

2.2 Speculative SFI enforcement

To enforce speculative SFI and prevent breakout and poisoning attacks, Swivel uses a number of compilation techniques. In addition, Swivel’s SFI system operates on WebAssembly (Wasm) programs; as such, it can rely on security properties conferred by well-formed Wasm programs, such as Wasm’s memory regions and its reliance on indirect jump tables. We describe these properties as well as Swivel’s own techniques for enforcing speculative SFI.

WebAssembly guarantees. A Wasm program’s memory at runtime is divided into several distinct regions: The heap, the stack, and global memory. The heap in a Wasm program is the only region that can be explicitly “addressed”; although Wasm has no pointers, its load and store operations take an offset into the heap region. The base address of the heap is kept in a register. The Wasm stack is only used for register spills and function return addresses; it cannot be arbitrarily accessed by a program. All stack spills are known at compile-time, so all stack accesses are compile-time constant offsets from the current stack frame, which is kept in a register. The Wasm global memory holds a program’s jump tables as well as other global constants. As such, with the exception of jump table entries, all global accesses are also compile-time constant offsets into the global region. Finally, all indirect jumps (or indirect calls) in a Wasm program happen explicitly via these jump tables; The target is given by an index into the program’s jump table rather than as a direct address.

Memory safety. Swivel employs several techniques, both at compile-time and runtime, to provide coarse-grained memory safety to sandbox programs even in the face of speculation. First, it “pins” the heap base register—it prevents this register from being spilled to the stack and from being used in general computation—so that the heap base cannot be corrupted. Next, it hardens heap and jump table loads: Any values used as offsets into the heap are first truncated to the size of the heap region before they are added to the heap base—offsets into the jump table are similarly truncated. Other memory accesses, such as for the stack or global constant, do not need to be hardened, as they only use compile-time constant offsets. Finally, Swivel’s runtime system places guard pages around each of the distinct memory regions, so that any region over- or underflow (e.g., by returning too many times) will immediately halt the program.

2.3 Speculative CFI and linear blocks

Swivel offers two distinct approaches for how it enforces speculative CFI. The first approach, Swivel-SFI, is intended for current x86 processors and relies heavily on rewriting control flow constructs. The second approach, Swivel-CET, relies on the Control-flow Enforcement Technology (CET) extensions developed by Intel in their latest hardware [13]. Both of these approaches depend on Swivel’s concept of linear blocks.

Linear blocks. A linear block consists of a sequence of instructions ending in any control flow instruction, and with no other control flow instructions in the block. When compiling a sandbox program, Swivel first breaks the program into a collection of such linear blocks. Swivel then enforces speculative control-flow integrity (CFI) at the granularity of these linear blocks: It ensures that all control flow transfers—which always take place at the end of a linear block—always land at the start of another linear block.

Swivel-SFI. Swivel-SFI’s approach provides security, somewhat counterintuitively, by replacing all non-trivial control flow with indirect jumps. Conditional jumps, for instance, are emulated by selecting the target block’s address based on the relevant condition; calls and returns are replaced with instructions that save return addresses to a separate stack—distinct from the existing stack memory region and with its own (pinned) stack pointer register. Swivel-SFI then protects speculative control flow by flushing the indirect jump predictor (or BTB for Branch Target Buffer [1]) upon entering the sandbox.

Swivel-CET. The Swivel-CET implementation makes use of two features from Intel’s CET hardware extensions: The endbranch instruction and the hardware shadow stack. The endbranch instruction provides forward-edge CFI: Every control flow instruction (except returns) must land on an endbranch instruction, even when executing speculatively. For call and return instructions, CET provides a hardware-enforced shadow stack: All calls and returns, in addition to pushing and popping return addresses off the regular stack, also push and pop return addresses on a separate protected memory region. When returning, the processor only jumps to a predicted return location if the prediction agrees with the
address popped from the shadow stack [13]. Finally, Swivel-CET inserts a register interlock at every linear block transition: The register interlock is a sequence of instructions that detects whether speculative control flow has been mispredicted, and if so, clears all the memory base registers (i.e., the heap base and stack frame registers). By doing so, all memory operations following a misprediction are directed to invalid addresses.

3 Formal model

To study SFI in the context of speculative execution attacks, we develop a simple assembly-like language, ZFI-$\mathbb{Q}$. We present the syntax of ZFI-$\mathbb{Q}$, then formalize its architectural and speculative semantics.

3.1 Syntax

The syntax of ZFI-$\mathbb{Q}$ programs is given in Figure 1. In ZFI-$\mathbb{Q}$, expressions are constructed by combining immediate values $v$ and registers $r$ using basic arithmetic operations $\oplus$. ZFI-$\mathbb{Q}$ supports standard control-flow instructions (conditional and indirect jumps, function calls and returns), register assignments ($r := e$), memory loads ($r' := \ast (r + e)$), and stores ($\ast (r + e) := e'$). Memory instructions always access memory at an offset $e$ from a base register $r$; we mirror Wasm, which only allows accessing offsets into the distinct memory regions. To model Swivel implementations, ZFI-$\mathbb{Q}$ also supports dedicated instructions flush (to flush the BTB) and endbranch (for hardware CFI).

3.2 Architectural semantics

We first cover the architectural semantics of ZFI-$\mathbb{Q}$, which models the execution of our basic assembly programs without any speculative behavior. The semantics is defined in terms of architectural configurations $\Psi$. Each configuration $\Psi$ is a quadruple consisting of a program $P$ mapping values to instructions, a program counter $pc \in \mathbb{V}$, a register file $\text{Reg} : \mathbb{R} \rightarrow \mathbb{V}$ mapping registers to values, and a memory $\text{Mem} : \mathbb{V} \rightarrow \mathbb{V}$ that maps memory addresses to values. We use dot-notation to access a context’s elements, e.g., $\Psi.(\text{Mem})$ denotes the memory associated with $\Psi$. We use bracket-notation to update an element within a context, e.g., $\Psi[(\text{Reg}) := (\text{Reg})']$ denotes the context obtained by updating the register file to $\text{Reg}'$. Furthermore, $\Psi[\text{insn}]$ denotes that $\text{insn}$ is the instruction pointed by the current program counter $\Psi.pc$; and $\Psi^+$ denotes the context obtained by incrementing the program counter of $\Psi$ by 1.

Our architectural semantics is formalized by the $\rightarrow$ relation in Figure 2, which describes how architectural contexts are modified during the computation. In the rules, $\|e\|_{\Psi}$ denotes the value of expression $e$ in the context of $\Psi$, and $r_{\text{stk}}$ and $r_{\text{heap}}$ represent the unique stack pointer and heap pointer registers. The architectural semantics are straightforward; for example, to initiate the function call $\text{call } i$, rule

![Figure 1. Syntax of the ZFI-$\mathbb{Q}$ language.](image-url)

| Basic types | $(\text{Values})$ $i, v \in \mathbb{V}$ | $(\text{Registers})$ $r \in \mathbb{R}$ | $(\text{Operators})$ $\oplus \in \oplus$ |
|------------|-----------------------------------|-----------------------------------|-----------------------------------|
| Syntax     | $(\text{Expressions})$ $e \in v \mid r \mid e \oplus e$ | $(\text{Instructions})$ $\text{insn} \in r := e$ | $(\text{assignments})$ $\mid \text{ret}$ | $(\text{return})$ |
|            | $(\text{memory load})$ $\mid \text{call} \pm i$ | $(\text{memory store})$ $\mid \text{call } i$ | $(\text{direct call})$ $\mid \text{flush}$ | $(\text{BTB state flush})$ |
|            | $(\text{conditional jump})$ $\mid \text{ret}$ | $(\text{indirect jump})$ $\mid \text{endbranch}$ | $(\text{CET } \text{"endbranch"})$ |
We refer to this extended relation as \( \rightarrow_{\text{trace}} \) for brevity, as it merely adds bookkeeping to the semantics.

### Table 1

| Effect(s) of \( \Psi[\text{insn}] \rightarrow \Psi' \) | Leakage model |
|--------------------------------------------------|---------------|
| dmem ct arch                                     |               |
| any jump \( (pc := v) \)                         | \( \Psi \)     |
| any load \( (v = \Psi[\text{mem}] \)            | \( \Psi \)     |
| any store \( (\Psi[\text{mem}] := v) \)        | \( \Psi \)     |

all values loaded from memory. Since the initial memory is the source of all values in the program, an attacker observing all loaded values during execution is equivalent to an attacker that sees the complete trace of all values in registers and memory [4].

We expose these leakage models via a function \( \text{Leaks}(\Psi) \) (informally illustrated by Table 1) that takes as input a configuration \( \Psi[\text{insn}] \) and outputs observations for each jump, load, or store operation that occurs during the semantic execution rule for \( \text{insn} \). For example, the execution of \( \Psi[\text{ret}] \) (rule \( \text{return} \) in Figure 2) contains both a load \( (v_{\text{stk}} = \Psi[\text{stk}] \) and a jump \( (pc := \Psi[\text{stk}] \) and \( \Psi[\text{ret}] \) will result in two observations: \( v_{\text{stk}} \), for loading the return address; and \( \Psi[\text{stk}] \), for jumping to that location.

Finally, we include a structure \( \text{Obs} \) in our configuration to collect the sequence of leakage observations during execution. We update \( \text{Obs} \) with each architectural step using the relation \( \rightarrow_{\text{trace}} \) induced by the following rule:

\[
\begin{align*}
\text{TRACE} & \quad \Psi \rightarrow \Psi' \quad \text{Obs}' = \Psi.\text{Obs} \uplus \text{Leaks}(\Psi) \\
\Psi[\text{insn}] & \rightarrow_{\text{trace}} \Psi'[\{\text{Obs}'\}]
\end{align*}
\]

We refer to this extended relation as \( \rightarrow \), as it merely adds bookkeeping to the semantics.
starts executing instructions along a mispredicted path, as recorded by the flag \textit{mispredicted}. Finally, rule \texttt{spec-trace} defines \texttt{\rightarrow trace} analogously to \textit{\rightarrow}. As before, we refer to this extended relation as \texttt{\rightarrow} for brevity.

4 Formalizing speculative SFI security

With the semantics for \texttt{ZFI}\texttt{-f2}, we investigate what it means for SFI sandboxing to be \textit{speculatively secure}. We examine the mitigations implemented by Swivel in terms of our semantics and we formally define the security properties that Swivel claims to provide.

4.1 Speculative SFI security properties

We present the formal security statements of \texttt{ZFI}\texttt{-f2} programs in terms of \textit{non-interference properties}. Generally, a program is \textit{non-interferent} if, for all pairs of initial contexts that may differ only in sensitive values (i.e., any values we don’t want to leak to an attacker), the attacker cannot distinguish the two resulting executions. Otherwise, the attacker can learn some information about the sensitive values.

Furthermore, we define security with respect to a \textit{class of oracles} \(\Omega\). This allows us to model assumptions about microarchitectural predictors while remaining abstract over specific predictor implementations: For example, we can exclude from \(\Omega\) any oracles that predict based on memory contents; or only consider oracles that, for conditional jumps, will predict one of the two resulting branches.

\textbf{Breakout security}. A breakout attack occurs when an attacker is able to (speculatively or otherwise) load values from outside its defined memory regions. In our semantics, we can capture this notion with the \textit{arch} leakage model: If we consider the sandbox program’s own memory regions as benign and all other memory as sensitive, then a successful breakout attack is equivalent to a sensitive value appearing in the program’s observation trace.

Formally, to prevent breakout attacks, we must show that all sandboxed programs satisfy non-interference under the \textit{arch} leakage model. We consider two initial contexts for a program \(\texttt{equivalent}\) if their respective memories agree for all sandboxed memory regions; we write this relation as \(\approx_{\text{MR}}\). A program, then, is \textit{breakout secure} (up to \(n\) steps) against a class of oracles \(\Omega\) if, for all Oracle \(\in \Omega\) (and with resulting \(\Rightarrow\)), for all initial contexts \(\Psi_1\) and \(\Psi_2\):

\[
\Psi_1 \approx_{\text{MR}} \Psi_2 \quad \text{and} \quad \Psi_1 \Rightarrow^n \Psi_1' \quad \text{and} \quad \Psi_2 \Rightarrow^n \Psi_2'
\]

\[
\Rightarrow \quad \Psi_1'.\text{Obs}_{arch} = \Psi_2'.\text{Obs}_{arch}
\]

where \(\text{Obs}_{arch}\) is the observation trace given by \(\text{Leaks}(\cdot)\) for the \textit{arch} model.

\textbf{Poisoning security}. A poisoning attack occurs when a victim sandbox is coerced into leaking a value during speculative execution that it would not have leaked architecturally. We capture this notion in our semantics by comparing the architectural and speculative observation traces of a program: Formally, a program is \textit{poisoning secure} (up to \(n\) steps) against a class of oracles \(\Omega\) if, for all Oracle \(\in \Omega\) (and with resulting \(\Rightarrow\)), for all initial contexts \(\Psi_1\) and \(\Psi_2\):

\[
\text{If } \Psi_1 \rightarrow \Psi_1' \quad \text{and} \quad \Psi_2 \rightarrow \Psi_2' \quad \text{and} \quad \Psi_1' \Rightarrow^n \Psi_1' \quad \text{and} \quad \Psi_2' \Rightarrow^n \Psi_2'
\]

\[
\Rightarrow \quad \Psi_1'.\text{Obs}_{ct} = \Psi_2'.\text{Obs}_{ct}
\]

\[
\text{then } \Psi_1'.\text{Obs}_{ct} = \Psi_2'.\text{Obs}_{ct}
\]

where \(\text{Obs}_{ct}\) is the observation trace given by \(\text{Leaks}(\cdot)\) for the \textit{ct} model.

4.2 Analyzing Swivel with \texttt{ZFI}\texttt{-f2}

Since Swivel only operates on valid WebAssembly programs, we can make certain assumptions about the structure of our input programs. For example, the stack region (represented in \texttt{ZFI}\texttt{-f2} as \texttt{Mem}([\(r_{\text{stk}} + e_{\text{off}}\)]) is only used for local variables and register spills; all stack loads and stores use constant (immediate) offsets from the stack pointer (i.e., \(e_{off}\) for \(r_{\text{stk}}\) is always a simple value). Furthermore, the heap pointer \(r_{\text{heap}}\) in \texttt{ZFI}\texttt{-f2} is never spilled to the stack, and the stack pointer \(r_{\text{stk}}\) is only modified when establishing function stack frames. Finally, since Swivel’s runtime surrounds each memory region with guard pages, we consider any over- or underflow (e.g., of the stack) to get stuck.

We analyze both the Swivel-SFI and Swivel-CET implementations on whether or not they soundly prevent breakout and poisoning attacks. In general, we want to show that a program, upon leaving any linear block, will always land on
the start of a new linear block. We can use this to inductively extend local block invariants to cover the whole program.

4.2.1 Swivel-SFI

Swivel-SFI replaces all (non-trivial) control flow with indirect jumps, flushing the BTB predictor upon the program’s entry. Since the only relevant predictor in Swivel-SFI is the BTB, we model the flush instruction by clearing the entire µstate to the empty state ⊥:

\[
\text{SPEC-FLUSH} \quad \Psi[\text{flush}] \rightsquigarrow \Psi^\top \{ \mustate := \bot \}.
\]

Flushing µstate will not prevent misprediction: For example, depending on the choice of Oracle ∈ Ω, the prediction oracle may still predict an incorrect target when µstate = ⊥. It may, however, limit an attacker attempting to mistrain victim predictors. After a flush, BTB predictions have no state to rely on beyond the program itself; Swivel thus assumes that any given jump instruction can only be trained to historically valid targets from that pc location. For our analysis, we limit Ω to such oracles.

**Breakout security.** Swivel-SFI hardens all memory operations; thus if we execute a linear block, we know the block itself will be secure from breakout attacks. We thus need only show that when a Swivel-SFI program exits one linear block, it will always start at the top of another linear block.

Architecturally, since all (forward-edge) indirect jumps are implemented via hardened jump table lookups, all such control flow will always target valid linear blocks. All backward-edge jumps (i.e., returns) are implemented via popping and jumping to an address from the separate stack, which itself is only accessible via the pinned separate stack register. Thus addresses on this separate stack cannot be otherwise overwritten, and so will always point to valid linear blocks.

**Poisoning security.** Unfortunately, even with our selection of Ω, we cannot soundly prove that Swivel-SFI programs are secure from poisoning attacks. As a trivial example, consider the program demonstrating a poisoning attack in Section 2.1. Even after it is converted to use an indirect jump to replace the conditional branch, it may still mispredict the direction of the condition and execute the vulnerable loads—flushing the BTB does not prevent mispredictions from happening. However, by flushing the BTB, Swivel-SFI claims to prevent an attacker from actively mistraining a predictor—i.e., an attacker cannot force the victim sandbox to mispredict, and any secret leakage would be purely opportunistic [11]. Our current framework does not distinguish active attackers in its security model; we leave formal analysis of active attackers to future work.

4.2.2 Swivel-CET

We formalize the CET hardware extensions as an augmented step relation \( \rightsquigarrow_{\text{cet}} \) built on top of our prior speculative relation \( \rightsquigarrow \), shown in Figure 4. The special semantics for CET only affect control-flow instructions (rule SPEC-CET-STEP).

For all forward-edge control flow, the CET hardware checks that the instruction at the target address—even when speculatively predicted—is the special endbranch instruction. We represent this in rules SPEC-CET-ENDBRANCH and SPEC-CET-CALL with the clauses \( \Psi \rightsquigarrow \Psi' \) and \( \Psi'[\text{endbranch}] \).

The CET hardware protects backward-edge jumps using a special hardware-managed shadow stack—similar to Swivel-SFI’s separate stack—and which is indexed through an otherwise-inaccessible shadow stack register \( r_{\text{SSk}} \). Furthermore, upon a return, the shadow stack value must agree with the predicted return value for execution to proceed. We formalize this in rules SPEC-CET-CALL and SPEC-CET-RETURN.

**Breakout security.** As with Swivel-SFI, Swivel-CET masks all memory operations within a linear block. By placing endbranch instructions only at the tops of linear blocks, and by relying on the CET shadow stack, Swivel-CET provides CFI at the linear block level.

**Poisoning security.** To prevent poisoning attacks, Swivel-CET inserts instructions at the beginning and end of every
linear block to form a register interlock, implemented as follows: Each linear block in the program is given a unique label. At the end of each block, Swivel-CET inserts instructions to dynamically calculate and save the label of the target block. For example, just before a conditional branch, the condition expression is used to select between the two target block labels. Then, at the start of each block, Swivel-CET inserts instructions to compare the stored target label to the label of current block. If the labels do not match, all memory base registers (i.e., \( r_{\text{Heap}} \) and \( r_{\text{Skt}} \)) are set to a guard page address \( \bot \). Thus any further (data) memory accesses will be stuck and cannot leak any values. With register interlocks in place, we can show that if \( \Psi \) mispredicted, then all following memory operations cannot leak.

However, while this prevents leaking via memory operations, this does not stop leakages via control flow. For example, if a sandbox secret is already in a register before we mispredict, then a later linear block may still branch on this register, leaking the secret value. Thus we can only prove poisoning security for Swivel-CET with respect to the weaker dmem leakage model instead of the stronger ct leakage model.

## 5 Conclusion

We present the first formal framework for SFI security in the face of Spectre attacks. Our language, ZFI\( \lambda \), is expressive enough to verify the security claims of the Swivel sandbox system; by formalizing Swivel’s security properties, we reveal which of its security claims it soundly upholds, as well as the explicit assumptions about hardware execution that Swivel relies on. We plan to extend and apply our framework to analyze the security claims of other sandboxing techniques that claim security against Spectre attacks [7, 12, 14].

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