# SPAM: Stateless Permutation of Application Memory

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Abstract—In this paper, we propose the Stateless Permutation of Application Memory (SPAM), a software defense that enables fine-grained data permutation for C programs. The key benefits include resilience against attacks that directly exploit software errors (i.e., spatial and temporal memory safety violations) in addition to attacks that exploit hardware vulnerabilities such as ColdBoot, RowHammer or hardware side-channels to disclose or corrupt memory using a single cohesive technique. Unlike prior work, SPAM is stateless by design making it automatically applicable to multi-threaded applications.

We implement SPAM as an LLVM compiler pass with an extension to the compiler-rt runtime. We evaluate it on the C subset of the SPEC2017 benchmark suite and three real-world applications: the Nginx web server, the Duktape Javascript interpreter, and the WolfSSL cryptographic library. We further show SPAM's scalability by running a multi-threaded benchmark suite. SPAM has greater security coverage and comparable performance overheads to state-of-the-art software techniques for memory safety on contemporary x86\_64 processors. Our security evaluation confirms SPAM's effectiveness in preventing intra/inter spatial/temporal memory violations by making the attacker success chances as low as  $\frac{1}{16!}$ .

## I. INTRODUCTION

As reported by the Project Zero team at Google, memory corruption issues are the root-cause of 68% of listed CVEs for zero-day vulnerabilities within the last five years [31]. While current solutions can be used to detect spatial and temporal software memory safety violations during testing [70], [21], [22] and/or post-deployment [54], [55], [19], [62], [58], [41], the recent development of hardware vulnerabilities that can leak secrets (e.g., hardware side-channels [33], [34], [84], ColdBoot [35]) or corrupt memory (e.g., RowHammer [45]) need different specialized approaches. The use of multiple security countermeasures complicates the deployment of hardened software especially when operational resources and budgets for security are limited. As pointed out by Saltzer and Schroeder [67], an economy of mechanism is valuable to handle multiple software and hardware memory security issues.

In this paper, we present the Stateless Permutation of Application Memory (SPAM), a post-deployment defense that provides cohesive protection against software and hardware memory corruptions with no explicit metadata. To better understand how SPAM works, let us consider the lifetime of an object from allocation to deallocation as shown in Figure 1.

SPAM permutes the layout of data in program memory based on its location in the virtual address space. When a new region of memory is allocated by the program, SPAM specifies a permutation for the data of this allocation. Thus, the mapping between memory instances (e.g., C structs) and their actual layout in memory is unknown to an attacker. The allocation base address and size are used to derive one specific permutation out of  $(\frac{S}{G})!$  different permutations, where S is the allocation size and G is the permutation granularity in number of bytes. SPAM also uses a unique per-process key and a disclosure-resistant pseudo-random number generator to mitigate record-and-reply attacks. As illustrated in Figure 1 (1), with SPAM even if attackers have access to a memory safety vulnerability that leads to an arbitrary read/write capability, they can no longer infer the order or offsets of the victim data within the allocated region.

If the allocated object is multi-dimensional (i.e., a compound data structure with one or more buffer fields), SPAM converts them to one-dimension using a novel source-to-source transformation, Buf2Ptr, that promotes struct buffer fields into their own allocations. An example transformation for a struct is shown in Figure 1 (2). Here, the buffer field c is promoted to a pointer c\_ptr that points to a standalone allocation containing the original buffer field data. Both allocations, A1 and c\_ptr, are permuted independently using their corresponding base addresses and sizes. In other words, Buf2Ptr reduces the intra-object memory safety problem to be equivalent to an inter-object one.

When an object is freed the same memory region may be allocated for a new object, posing a security concern. To mitigate this, SPAM generates a random value that is embedded within each pointer returned by the memory allocator. Thus, a single memory region can have multiple different permutations dependent on the random value. For example, in Figure 1 (3) when A1 is freed, the memory allocator will use the same memory again to satisfy the next allocation (i.e., A3). SPAM embeds a different random value in A3 resulting in a new permutation. As a result, even if the same memory is allocated to a different object during the program lifetime, the attacker has no guarantee that the data would be at the same location as the freed object. Thus, SPAM provides complete coverage against software memory corruptions.

Additionally, SPAM provides resilience against hardware memory corruptions by keeping the data permuted across the memory hierarchy (i.e., caches and DRAM). For example, sensitive data leaked by a ColdBoot attack is indistinguishable from random as it would be permuted. Similarly, the randomness of physical memory increases the complexity of a RowHammer attack as the attacker needs to know the exact layout of adjacent data to decide where to trigger a bit flip. Moreover, SPAM provides a natural protection against speculative side-channels as speculatively executed loads will always return permuted data making it harder for an attacker to recover the original memory layout. More importantly, combinations of techniques that aim to provide a similar level of protection to SPAM may not build on top of each other

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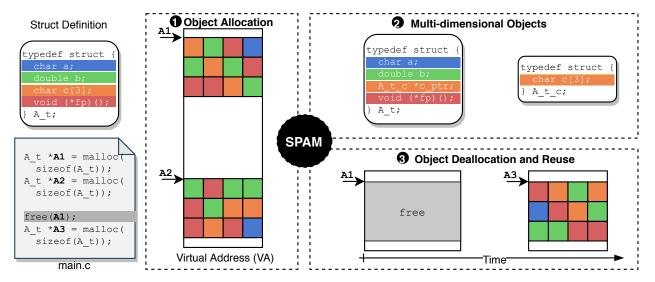


Fig. 1: A sample program highlighting the lifecycle of an object in SPAM: **1** every object has a unique permutation, **2** buffer to pointer promotion (Buf2Ptr) for multi-dimensional objects and **3** deallocation of objects.

or may incur higher performance costs. As we argue in this work, there is no single cohesive solution that can address both software and hardware memory violations.

One important aspect of SPAM is that it does not store any metadata separately in protected memory regions [44], [1] or as part of the object itself [3], [22]. SPAM dynamically calculates permutations for every load and store. Thus, it neither introduces additional storage overheads nor provides the opportunity to be manipulated by an attacker. Especially in the context of multi-threaded programs, the lack of metadata in SPAM allows scalable performance of application code. In contrast, memory safety techniques that rely on explicit metadata require proper synchronization to maintain correct and secure behavior which negatively impacts scalability.

SPAM is implemented within the LLVM compiler framework and currently targets the x86\_64 architecture. The experimental results show that SPAM has comparable performance overheads to state-of-the-art software techniques for memory safety on the C subset of SPEC2017 benchmark suite [8], a web server [78], a Javascript interpreter [81], and a cryptographic library [90]. We further show SPAM's scalability by running a multi-threaded benchmark suite [2]. Additionally, we conduct a quantitative security analysis to demonstrate SPAM's effectiveness in preventing intra/inter spatial/temporal memory safety corruptions.

The remainder of the paper is organized as follows. We specify the threat model and assumptions in Section II. We introduce SPAM in Section III and discuss our prototype implementation in Section IV. We then analyze the security of SPAM in Section V. Section VI highlights the main performance optimizations, while Section VII extensively evaluates SPAM and compares it against state-of-the-art techniques. We summarize SPAM deployment considerations in Section VIII and discuss the current prototype limitations in Section IX. Section X summarizes the related work. Finally, we conclude in Section XI.

#### II. THREAT MODEL & ASSUMPTIONS

Adversarial Capabilities. We consider a powerful, yet realistic adversary model that is consistent with previous work on software memory safety [54], [55], [21], [22], [70], [58] with stronger assumptions against side-channel capable adversaries. We assume that the adversary is aware of the applied defenses and has access to the source code or binary image of the target program. Furthermore, the target program suffers from a memory vulnerability that allows the adversary to read from, and write to, arbitrary memory addresses. We further assume that the attacker can disclose information at run time [74] and use side-channels [47] as part of the attack to read or manipulate memory contents.

Assumptions. SPAM requires the availability of source code for the target program. This requirement is true for the majority of state-of-the-art techniques (see Table VI). We also assume that the underlying operating system (OS) enables W^X—i.e., no code injection is allowed (non-executable data), and all code sections are non-writable (immutable code). SPAM protection applies to all instrumented code and libraries. Uninstrumented codes, such as third party libraries and the operating system runtime, can be fully utilized without limitations, but are not protected by SPAM. This model offers a path to incremental adoption of SPAM. Additionally, the SPAM runtime is considered part of the trusted-computing base (TCB). A number of low-overhead intra-process isolation mechanisms can be utilized to harden the runtime [82], [36]. We leave the exploration of runtime hardening for future work.

## III. STATELESS PERMUTATION OF APPLICATION MEMORY (SPAM)

Our proposal to guarantee complete memory safety is to ensure that the data layout is always permuted at a very fine granularity. This permutation is meant to ensure that an attacker cannot leak useful information or overwrite critical data within the program even in the presence of memory safety vulnerabilities. To address our powerful threat model, we require that information about permuted objects is neither stored as part of the object itself, nor encoded in the binary version that can be accessed by an attacker.

#### A. Spatial Memory Safety

When a new memory region of size S is allocated by the program, typically by calling malloc, SPAM uses the base address (BA), size (S), and a 64-bit per-process key (K) to compute its permutation. As shown in Figure 1 ( $\bigcirc$ ), the struct A\_t is permuted differently for each allocation instance (i.e., A1 and A2). This new permutation defines the new offsets for the individual data bytes within the struct. This runtime per-instance layout makes it harder for attackers to construct a reliable exploit as they need to guess the correct permutation.

Generating a permutation. SPAM is a format-preserving encryption (FPE) scheme [32], [64] which uses the Fisher-Yates shuffle [27] algorithm (modernized in [25] and popularly known as the Knuth shuffle [46]) to produce an unbiased permutation (i.e., every permutation is equally likely) <sup>2</sup>. To generate SPAM permutations we follow the approach described in Algorithm 1: (1) a PRNG is seeded with a per-process key, the base address of an allocation, and the allocation size (2) the Fisher-Yates shuffle algorithm is then executed to completion resulting in the set of permutations that are used to access memory. Algorithm 2 details the Fisher-Yates shuffle algorithm which permutes an initialized array of elements in-place and returns the array. The permutation generated by SPAM can be viewed as a block cipher, where cryptographically speaking, the strength of the scheme depends on the PRNG. PRNGs only provide numbers in a fixed range. For Fisher-Yates, we bound the PRNG's output using a modulo operation according to the number of elements to be shuffled. While Fisher-Yates is unbiased, the modulo operation may introduces bias affecting uniformity. We evaluate the uniformity of the permutations generated by our implementation in Section VII-E.

#### **Algorithm 1** Generating SPAM Permutation

```
Requires: G—Permutation Granularity, B—Permutation Boundary
Inputs: K—Per-Process Key, BA—Base Address, S—Allocation Size
Outputs: P—Permutation
1: function GENPERM(K, BA, S)
                                                           ▷ Initialize PRNG
2.
       R \leftarrow \text{PRNGSEED}(K, BA, S)
3:
       C \leftarrow B/G
                                                ▶ Define permutation chunks
4.
       P \leftarrow \text{FISHER-YATES}(R, C)
                                                           ⊳ Get permutation
5:
       return P
6: end function
```

**Updating pointers.** A new pointer to access the appropriate memory location is computed given a pointer and the provided permutation. This process is shown in more detail in Figure 2. SPAM only changes the block offset bits that define the permuted location of a data chunk. The choice of permutation boundary, *B*, is arbitrary, but defines the minimum allocation

#### Algorithm 2 Fisher-Yates Shuffle

Inputs: R—Random Number Generator, C—Permutation Chunks Outputs: P—Permutation 1: function Fisher-Yates(R,C)  $P \leftarrow \text{INIT}(C)$  $\triangleright$  Initialize array of C elements 2: 3: **for** i from C-1 to 1 **do** 4:  $i \leftarrow R() \% i$  $\triangleright$  Generate number s.t.  $0 \le j \le i$ 5: SWAP(P[i],P[j])6: end for return P ▶ The permuted indexes. 8: end function

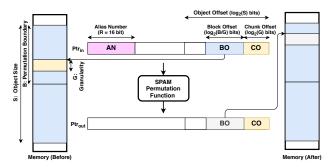


Fig. 2: The process of updating pointers in SPAM.

size. For example as shown in Figure 3, an object of size S bytes will consist of  $\frac{S}{B}$  permutation blocks, where each block consists of  $\frac{B}{G}$  chunks. Each block is then permuted given a per-process key, the object base address and size. For objects greater in size than the permutation boundary, we divide them into permutation blocks and permute them separately.

(Un-)permuting memory. External library calls (e.g., the ones made to libc) are quite common. To maintain compatibility with uninstrumented external code, SPAM provides UNPERMUTE and PERMUTE primitives. The UNPERMUTE and PERMUTE primitives are emitted for pointer arguments before and after external calls, respectively.

#### B. Sub-object Memory Safety

To provide intra-object memory safety, SPAM proposes a novel application of an idea called, Buf2Ptr, that has been previously used in the area of data layout optimizations for enhancing performance [40], [66], [94]. Buf2Ptr promotes array or buffer fields defined in C/C++ structures

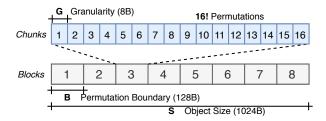


Fig. 3: An example of how permutations are computed for an object of size, S=1024 bytes. We use a permutation boundry, B=128 bytes with a G=8 bytes permutation granularity, resulting in  $\frac{B}{G}=16!$  possible permutations.

<sup>&</sup>lt;sup>1</sup>Without loss of generality, we focus the discussion here about heap objects (C structs) allocated by a memory allocator. In Section IV, we discuss how we support stack & globals.

<sup>&</sup>lt;sup>2</sup>Prior work uses Fisher-Yates shuffle to randomize allocations on the heap. Unlike SPAM, which randomizes the layout of each allocation independently, STABILIZER [17] picks a random base address for each new allocation from a pool of N addresses per each size class, while MESH [61] uses shuffle vectors to perform randomized allocation with low space overhead.

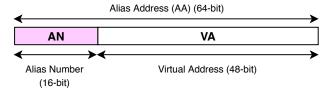


Fig. 4: The construction of alias addresses created by SPAM to provide probabilistic temporal memory safety.

to be independent, reducing the problem of intra-object allocation to be equivalent to inter-object allocation. This allows SPAM to rely on the same security guarantees discussed in Section III-A. Buf2Ptr eliminates all security concerns about structs contiguously laid out in memory (e.g., malloc(10\*sizeof(struct Foo))) as they would no longer contain arrays to overflow. To illustrate a Buf2Ptr transformation, consider the example in Listing 2. Array fields within a structure are replaced with a promoted pointer (e.g., p\_buf) and a new structure containing the original array is defined (e.g., Foo\_buf). As a result of this transformation, allocations, deallocations, and usages of the original field must also be properly promoted. For example, an allocation for a composite data type (e.g., Foo) becomes separate allocations based on the number of fields promoted (e.g., Foo\_buf).

```
// Promoted Type
                              struct Foo_buf {
2 struct Foo {
   char buf[10];
                                 char buf[10];
4 } ;
                              };
                              struct Foo {
                                 struct Foo_buf *p_buf;
                                 Promoted Allocations
9struct Foo *f = malloc(
                              struct Foo *f = malloc(
10
   sizeof(struct Foo));
                                 sizeof(struct Foo));
11
                              f \rightarrow p_buf = malloc(
                                 sizeof(struct Foo_buf));
12
                                 Promoted Usages
14 f->buf[7] = 'A';
                              f \rightarrow p_buf \rightarrow buf[7] = 'A';
15
                               // Promoted Deallocations
                              free(f->p_buf);
16 free (f);
                              free(f);
17
          (a) Original
                                     (b) Transformed
```

Listing 2: An example of Buf2Ptr transformation.

#### C. Temporal Memory Safety

Permuting the object layout alone as described in Section III-A is not sufficient to prevent temporal attacks such as use-after-free. This is primarily due to the fact that the attacker's object and the victim one share the same base address (i.e., due to the deterministic allocator behavior) and key (i.e., as both objects correspond to the same process). We observe that the problem is due to address reuse among allocations. We avoid this problem by re-purposing the currently unused high order bits of the virtual address (VA). As shown in Figure 4, SPAM randomly chooses a *R*-bit alias number (AN) and encodes it within the most significant *R*-bits of the base address. As SPAM generates permutations based on the entire address, named alias address (AA), we get a new

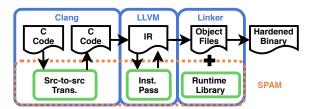


Fig. 5: The SPAM compiler infrastructure framework.

permutation for the same memory region (even if the lower order bits of the VA remains the same).

Figure 1 (3) shows how SPAM generates a new permutation for the same object after freeing the old one. Each allocation can have up to  $2^R$  different aliases (where R depends on the hardware architecture), with each alias having its own permutation. SPAM drops the AN bits whenever the alias address is passed to the free function so that the processor functionality for address handling remains unaffected by our security modification. Algorithms 3 to 5 summarize the steps needed for SPAM to provide its spatial and temporal memory safety guarantees.

#### Algorithm 3 Allocation Creation

```
      Requires: M—Memory Allocator, RNG—Random Number Generator

      Inputs: S—Allocation Size

      Outputs: AA—Alias Address

      1: function ALLOC(S)

      2: VA \leftarrow M(S)
      \triangleright Returns Virtual Address

      3: AN \leftarrow RNG()
      \triangleright Generate 16-bit random number

      4: AA \leftarrow \{AN, VA[47:0]\}
      \triangleright Assemble Alias Address

      5: return AA

      6: end function
```

## Algorithm 4 Allocation Access

```
Requires: K—Per-Process Key, G—Permutation Granularity
Inputs: AA—Alias Address
Outputs: VA_{new}-Virtual Address
1: function ACCESS(AA)
      BA \leftarrow GETBASEPTR(AA)
                                       2.
3:
      S \leftarrow \text{GETSIZE}(BA)
                                              4:
      P \leftarrow \text{GENPERM}(K,BA,S)
                                                 5.
      VA \leftarrow STRIP(AA)
                                              VA_{new} \leftarrow \text{GETPERMPTR}(VA,P)
                                                return VA<sub>new</sub>
 7.
8: end function
```

## Algorithm 5 Allocation Delete

#### IV. IMPLEMENTATION

Figure 5 provides an overview of our SPAM framework. In this section, we discuss the different components.

**Source-to-Source Transformation.** We implement Buf2Ptr as a source-to-source transformation pass using Clang's rewriter

interface. The pass performs two main traversals over the AST. The first traversal analyzes each translation unit to collect a whole program view of composite data types (e.g., structs) and their usages. This information is used to determine what can be legally promoted, as explained in Section III-B. The second traversal performs the actual rewriting.

**Instrumentation Pass.** To handle heap memory, we implement an instrumentation pass at the LLVM IR level augmenting all the necessary loads and stores to invoke the runtime, which computes accesses to the appropriate permuted memory locations. We iterate over all loads and stores and emit a call to the runtime to resolve the permuted memory location to be accessed. Then, we determine whether calls refer to externally linked functions or functions defined in other translation units. Finally, external calls are broken down into two categories wrapped and unwrapped. Wrapped calls are simply replaced with SPAM specific variants that operate on permuted memory to improve performance. Unwrapped calls are guarded by a pair of UNPERMUTE and PERMUTE runtime functions if pointer arguments are used in the relevant call. These operations ensure compatibility with uninstrumented code by unpermuting/permuting data before/after executing uninstrumented code. Table VII (in Appendix B) includes a list of SPAM wrappers.

Our current prototype support for global and stack memory builds on top of LowFat [23], [24]. In addition to the features provided by LowFat, for constant globals (i.e., those typically in the .data section) we emit a call to a REGISTERGLOBAL runtime function. The REGISTERGLOBAL function is appended to the global constructors (i.e., .ctor) to permute each global variable on program load. Similarly, for stack variables usually passed by the OS (e.g., argv), we emit a call to the REGISTERSTACK runtime function in order to permute memory on program start (i.e., main).

Runtime. SPAM's runtime, implemented as an extension to LLVM's compiler-rt, encompasses the following functionality: (1) getting an allocation's base address (2) looking up the allocation's size (3) generating a permutation (4) calculating the memory location to be accessed and (5) unpermuting and permuting memory for compatibility with uninstrumented code. Our current implementation builds on top of the LowFat [21] allocator. Support for other allocators is possible as long as they provide (1) and (2) making our approach allocator agnostic. Appendix D provides an overview of the runtime API.

**Permutation Parameters.** In our current prototype, we use a permutation granularity of 8B (i.e., every successive 8B in memory will remain unpermuted while an entire 8B chunk can be stored in any place within a permutation boundary). The main reason for this choice is that 8B accesses are common on 64-bit systems. Using a smaller chunk size, while supported by our implementation, will add additional overheads. We use a permutation boundary of 128B to match the cache line size of the Last Level Cache <sup>3</sup>. Our current prototype targets the x86\_64 architecture, which can have a maximum alias number of 16-bits as the virtual address consumes 48-bits of the total 64-bit address space.

#### V. SECURITY ANALYSIS

In this section, we first discuss the security guarantees provided by SPAM then we evaluate them quantitatively.

TABLE I: The basic primitives that define a program and how SPAM affects them.

	τ	Ininstrumented	SPAM			
Memory	addr ←	malloc(S)	baddr ← perm ← paddr ←	SPAM_malloc(S) genperm(K, baddr, S) getaddr(addr, perm)		
	val ←	free(addr) load(addr) store(addr, val)	val ←	SPAM_free(paddr) load(paddr) store(paddr, val)		
Compute	val ←	arith(val)	val ←	arith(val)		
Control-Flow		branch(addr)		branch(addr)		

Table I shows the primitives that define a program. SPAM's mechanism for protecting memory involves introducing new secure primitives that act as a shell to guard memory operations as introduced in Section III. The permutation shell around the memory operations guarantees that input and output operations that attackers can use to subvert/control programs have uncontrollable behavior. Memory operations can be used in two modes: relative or absolute. With absolute read/write capability, an attacker can control the addr supplied to a load or store. A relative read/write capability returns/updates a value at an arbitrary offset from a known address (e.g., f->buf[7] where 7 is an example of an attacker controlled offset). An overflow in the buffer field, buf, can corrupt other fields in object, f.

SPAM revokes absolute capabilities as now every load/store instruction depends on a secret permutation (perm) that is not available to the attacker. This permutation is derived using a secure key (K) and is computed at runtime (using genperm and getaddr) for every access. Alternatively, an attacker can read/write memory via an external mechanism (e.g., sidechannels) to bypass the secure primitives. SPAM nullifies this external capability by keeping data permuted across the entire memory hierarchy. This makes it impractical for an attacker to recover the memory contents. In addition to that, SPAM revokes relative capabilities using Buf2Ptr which reduces them into absolute read/write capabilities.

Common exploits build upon the absolute/relative read-/write capabilities as discussed above. We briefly describe how these exploits are each specifically handled by SPAM.

#### A. Resilience to Common Exploits

**Buffer under-/over-flows.** SPAM can defend against the exploitation of buffer overflows (and underflows) by hiding the mapping between program objects and their actual layout in memory. Even if the attacker has access to the source code and/or binary image of the victim program, they cannot infer the layout of the victim object. The same object can have multiple layouts based on its location in memory. With high probability, with SPAM in place, the attacker cannot corrupt or leak information that can be used to mount many exploit variants. SPAM's protection applies to both inter- and intra-object safety (as Buf2Ptr reduces the intra-object problem to

<sup>&</sup>lt;sup>3</sup>Permutation boundary can be easily tuned to match the requirements of different processors (e.g., 64B LLC cachelines on recent AMD processors).

inter-object).

Use-after-frees. As described in Section III-C, SPAM provides temporal memory safety via the alias address space. The same allocated virtual/physical memory region can have up to 2<sup>16</sup> different aliases (each alias having its own permutation). This alias address space is sufficient to thwart use-after-free attacks, in which the type of the freed object aligns with the confused type of the new object, having a big impact on the reliability of these exploits [30]. Heap Feng Shui attacks exploit a memory allocator's determinism to arrange memory so that it is favorable for an attacker to manipulate a victim allocation [75]. Similarly, SPAM relies on the alias address space to generate multiple permutations for the same memory region, making it impractical to infer any information about an object layout based on another object, even if both have the same type.

Uninitialized Reads. While SPAM does not explicitly zero out memory that may have held security sensitive data, the fact that the memory is left permuted after a free is sufficient in many cases. The next program to use the same memory region will be assigned a different permutation key by default, making it impractical to recover the data by mistake. Additionally, an attacker trying to access this sensitive data would need the appropriate permutation in order to unscramble the memory. The same applies when peeking at memory with a variadic function misuse attack [26].

Control-Flow Hijacking and Data-Oriented Attacks. Given a memory error, attackers can gain arbitrary memory read/write primitives. Attackers can then leverage such primitives to launch different attacks, such as control-flow hijacking [7], [74], [69], [83], information leakage [77], or data-only attacks [13], [39], [60], [14]. SPAM effectively mitigates all of those attacks as it makes it harder for the attacker to utilize the memory read/write primitives. For instance, it is impractical to hijack the control-flow of the program (e.g., by overwriting a function pointer in a C struct) if the whole struct is permuted with  $\left(\frac{S}{G}\right)$ ! different permutations. The same argument holds even for the more critical data-only attacks that corrupt the program without changing its control-flow. SPAM provides sufficient probabilistic guarantees for protecting the security-critical data structures of a program.

Memory errors in uninstrumented code. SPAM unpermutes the data that is passed to uninstrumented code (e.g., library functions) while the rest of the program data remains permuted. So, if the uninstrumented code has a memory vulnerability it may only reliably corrupt the portion of data that is passed to it. Unlike other techniques that provide no security guarantees for uninstrumented code, SPAM reduces the attack surface by keeping the rest of the program data permuted.

```
if (i < sizeof(a)) { // mispredicted branch
secret = a[i];
val = b[64 * secret]; // secret is leaked</pre>
```

Listing 3: Example speculative execution attack.

**Speculative Execution Attacks.** With SPAM, utilizing speculative exploits is more challenging for an attacker. Not

TABLE II: RIPE Results

	ASAN	MPX	SPAM
Working Attacks	2/20	0/20	0/20

only is the data permuted, but the speculative (instrumented) load additionally uses a different permutation to access the permuted data. Consider an attacker that tries to speculatively load the secret value a [i] using an out-of-bound index, i, as shown in Listing 3. In this case, they will end up with an unpredictable value in secret due to SPAM's security primitives which permute the address of a [i].

Hardware Memory Violations. Let us consider an attacker wants to leak a function pointer from a struct that has ten other fields. Using a side-channel, the attacker leaks the entire struct. However, due to SPAM's permutation they would not be able to recognize the needed function pointer (or even reconstruct the struct layout)<sup>4</sup>. By the same principal, SPAM provides indirect protection against other types of attacks such as RowHammer and ColdBoot attacks.

Chosen Data Attacks. One natural question to ask is whether an attacker can use data from a computation to recover the data structure layout and therefore gain an insight into the permutation. Let us assume that an attacker can inject N unique values into N fields of a struct. Let us further assume that the attacker can read/leak the permutation. This read will give the attacker a permutation that is valid only for the address allocated to the instance of the struct that has been primed with unique known values. A different allocation (address) will have a different permutation. To be able to predict the permutation for any address, the attacker would have to do AES-inverse(key, alias|address) based on several reads of permuted locations. The complexity of this attack is the complexity of reversing AES with chosen plaintexts. Alternatively, an attacker may perform *Heap Feng Shui* [75] style exploit and place a similar vulnerable data structure at a location for which they know the permutation. To carry out this attack, the attacker has to make at least 2<sup>16</sup> attempts because the alias number is chosen randomly for each allocation at the same address.

## B. Security Litmus Tests

Here, we quantitatively evaluate the security guarantees provided by SPAM and compare it against two state-of-the-art techniques: AddressSanitizer (ASAN) and Intel MPX, as representatives of pre- and post-deployment memory safety solutions, respectively.

RIPE. We quantitatively evaluate security by using RIPE [88], an open source intrusion prevention benchmark suite. We first ported RIPE to 64-bit systems and compiled it with SPAM. While RIPE can support attacks on stack, globals and the heap, we focus solely on heap-related attacks due to its additional temporal nature. For our baseline, the total number of attacks

 $<sup>^4</sup>$ One may argue that using permutation granularity, G=8 bytes, might help the attacker distinguish between pointer and non-pointer data items in a leaked struct. This can be thwarted by configuring our framework to use smaller values for G in such cases.

TABLE III: Security Microbenchmarks

	ASAN	MPX <sup>5</sup>	SPAM	
Intra-Overflow	Х	1	<b>✓</b>	
Inter-Overflow	✓	✓	1	
Use-after-free	✓	X	1	
Type Confusion	✓	✓	✓	
Buffer Over-read	✓	✓	✓	
Uninitialized Read	X	X	✓	

that survive with a native (non-protected) GCC and Clang is 20 attacks. The results for all tools are summarized in Table II. As expected, MPX<sup>5</sup> and SPAM are able to prevent all attacks due to providing intra-object protection. ASAN overlooks two intra-object attacks in which a function pointer is corrupted.

**Microbenchmarks.** In addition to RIPE, we implement a small set of security microbenchmarks. While RIPE tests for control-flow hijacking attacks, our set of microbenchmarks aims to provide wider coverage. Thus, our set tests against equally important categories of attacks, such as type-confusion and information leakage. The complete set of results denoting the ability for a given tool to detect specific vulnerabilities is summarized in Table III. The results highlight the scope of each tool. SPAM is the only solution of those evaluated that is comprehensive enough to provide coverage over the spectrum of these vulnerabilities.

Cohesiveness. We evaluate the security trade-offs between the different tools. We use the security microbenchmarks and RIPE (shown as Control-Flow) as indications of a tool's security coverage. The results are summarized in Figure 6 with the overall area of the polygon indicating the number of categories covered (i.e., the larger the area the greater the coverage). As we argue in this work, no single tool can provide a cohesive solution for memory violations as SPAM highlighting the notability of its approach. In Section X, we discuss additional hardware security related aspects of SPAM in comparison to other state-of-the-art techniques further highlighting its cohesiveness.

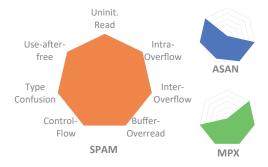


Fig. 6: Quantitative security trade-offs for different tools.

#### VI. SPAM PERFORMANCE OPTIMIZATIONS

In this section, we explain a set of optimizations that we enable in our current prototype for enhancing its performance.<sup>6</sup>

**Permutation Deduplication.** To avoid repeating the work of generating permutations multiple times, at the beginning of a function we generate the permutations for any pointer that is passed as a function input. We propagate a permutation across multiple loads and stores (if they share the same base address) instead of recomputing it. We pack this permutation into an integer of an appropriate size depending on the permutation granularity to efficiently pass it around. This integer is taken as an argument to our runtime function (GETPERMPTR) to avoid re-generating a permutation for each load/store. Similarly, for pointers defined later in the function's scope, a call to our generate permutation function is emitted and the packed integer holding the permutation is propagated.

**Software Caching.** Since all accesses to the same object have the same base address, we exploit this locality by using a small lookup cache before accessing the permutation function. We implement a direct-mapped software cache in our runtime to store the corresponding permutation for a given base address.<sup>7</sup>

If this optimization is enabled, an attacker may manipulate the cache contents to undermine SPAM security. To handle this issue, we propose two protection mechanisms. The first solution is to store the cache itself in a permuted fashion much like the rest of the application memory. In this case, the load time address of the cache will act as the base address. Alongside with the per-program key, a unique permutation is generated for the cache contents. Then, all cache accesses from the SPAM runtime are updated to use it directly with no additional latency. Alternatively, if available, functionality like Intel Memory Protection Keys (MPK) [59], [82] can be used to protect the cache. MPK provides a single, unprivileged instruction, wrpkru, that can change page access permissions by re-purposing four unused bits in the page table. First, the cache is placed in pages that have a particular protection key, forming the sensitive domain. Then, all cache accesses from the SPAM runtime are guarded with the wrpkru instruction so that no other loads/stores have access to the cache contents. For completeness, we evaluate MPK cache protection overheads on an Amazon Web Services (AWS) c5.large instance and find that it only incurs approximately a 2-3% overhead on average over having no protection.

**Architecture-dependent Optimization.** Inspired by Low-Fat [21], we use the Bit Field Extract BEXTR instruction to enhance performance. This  $\times 86\_64$  instruction extracts n contiguous bits from a given source. BEXTR allows us to save a few instructions when operating on permutations packed into integers. Instead of shifting and applying a mask to extract the necessary bits corresponding to a permutation (e.g., Block Offset bits in Figure 2), we replace this with a single instruction.

 $<sup>^5</sup>$ With BNDPRESERVE=1 & -fchkp-first-field-has-own-bounds

<sup>&</sup>lt;sup>6</sup>The main focus of the current prototype is security coverage. We leave investigating other performance optimizations to future work.

<sup>&</sup>lt;sup>7</sup>Our current prototype uses a default cache size of 2<sup>17</sup> entries. Each entry stores 64-bit address and 64-bit packed permutation, resulting in a total size of 2MB.

TABLE IV: Compiler Setup

Tool	Compiler	Compile Flags	Runtime Flags
ASAN	Clang 9	-fsanitize=address -asan-stack=0 -asan-globals=0 -fsanitize-recover=address -03 -flto=thin	print_legend=false print_full_thread_history=false halt_on_error=false detect_leaks=0
MPX	GCC 7.3.1	-fcheck-pointer-bounds -fchkp-narrow-bounds -fchkp-use-wrappers -02	CHKP_VERBOSE=0 CHKP_PRINT_SUMMARY=0
SPAM (This paper)	Clang 4.0.0	size-128func-scope-optcache -03 -fito=thin	

#### VII. EVALUATION

We evaluate SPAM across multiple dimensions. First, we compare the performance of SPAM against state-of-theart pre- and post-deployment memory safety solutions using SPEC2017. Second, we demonstrate SPAM's deployability by compiling and running three real-world applications. Third, we analyze Buf2Ptr's completeness by reporting its coverage for all benchmarks. Fourth, we evaluate SPAM's suitability for multi-threaded applications. Fifth, we measure the uniformity and efficiency of SPAM permutations to support our security claims.

Experimental Setup. We run our experiments on a baremetal Intel Skylake-based Xeon Gold 6126 processor running at 2.6GHz with RHEL Linux 7.5 (kernel 3.10). We compare SPAM against AddressSanitizer (ASAN) and Intel MPX, as representatives of pre- and post-deployment memory safety solutions, respectively.8 Each tool is run using its best recommended settings (See Table IV for a full list of compiler flags and environment variables). We run each tool such that it suppresses its warnings or errors so that benchmarks run to completion. Additionally, we disable any reporting to minimize the performance impact this functionality may have. For tools that provide coverage other than the heap, we only enable their respective heap support for a fair comparison with our current SPAM prototype. Given the difference in compiler versions and optimization levels that each tool supports, we normalize each against their respective baselines for proper comparison. To minimize variability, each benchmark is executed 5 times and the average of the execution times is reported; error bars represent the maximum and minimum values observed over the 5 runs.

## A. Performance Comparisons

We compare SPAM's performance against ASAN and Intel MPX by compiling and running a standard application benchmark suite, namely the C programs in SPEC2017 [8], using the three tools separately. Additional benchmarks (e.g., Olden [65] and PtrDist [4]) are evaluated in Appendix A. While analyzing the results, it is important to keep in mind

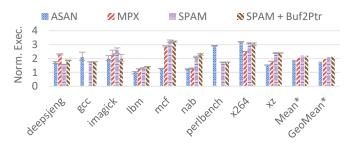


Fig. 7: Performance overheads of the C subset of SPEC2017 for different tools normalized to their corresponding baseline for heap memory protection.

the security coverage that each tool provides because they are not all the same.

**SPEC2017.** We specifically look at the C subset of benchmarks in SPEC CPU2017 [8]. Of the 9 C benchmarks, we found that perlbench and gcc are heavily reliant on undefined behavior, namely using out-of-bounds pointers in computations, storing them in memory, and returning them in-bounds again upon pointer dereferencing. The undefined behavior in perlbench and gcc makes them incompatible with SPAM and MPX. For the purposes of evaluating SPAM's performance, we run the two troublesome programs with an "in-order" permutation (i.e., all of the SPAM's instrumentation and runtime wrappers are used whereas the program data itself is written to memory with no shuffling) to closely model SPAM's impact. We omit perlbench and gcc from the computed averages in the figure. Benchmarks are run to completion using the test inputs and single threaded execution. For benchmarks with multiple inputs, the sum of the execution time of all inputs is used. The geometric mean of each tool is as follows: ASAN (1.77x), MPX (1.97x), SPAM  $(2.11x)^{10}$ , and SPAM + Buf2Ptr (2.13x). The main reason for the high overheads of certain SPEC2017 benchmarks, such as mcf and x264 is the excessive use of memcpy. Although our current prototype implements its own memcpy wrapper for performance, it is not as efficient as the standard library one with vectorization support. We leave the implementation of more efficient library wrappers for future work.

#### B. Real-world Case Studies

To demonstrate the capabilities of our current SPAM prototype, we use it to compile and run three real-world applications: the Nginx web server [78], the Duktape Javascript interpreter [81], and the WolfSSL cryptographic library [90].

**Nginx.** We use Nginx [78] (version 1.11.11), as a representative I/O bound benchmark. To simulate typical workload configurations, we have Nginx serve different sized files according to the page weight (i.e., the amount of data served) of modern websites according to the 2019 HTTP Archive Web Almanac report [38]. To generate the client load, we used the multithreaded Siege [28] benchmarking tool. We issued 500 requests with 50 concurrent connections for each page weight using the loopback interface to avoid network congestion issues. We

<sup>&</sup>lt;sup>8</sup>We exclude SoftboundCETS as it fails to run many of the benchmarks due to strictness and compatibility issues.

<sup>&</sup>lt;sup>9</sup>While our current prototype supports stack memory, there are still minor items that have yet to be completed to make it robust enough for all programs. Thus, we leave the evaluation of stack memory permutation for future work.

<sup>&</sup>lt;sup>10</sup>Enabling global memory permutation for SPAM incurs an additional 11% on top of the heap results bringing the geometric mean from 2.11x to 2.22x.

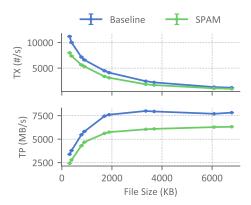


Fig. 8: Nginx performance overheads with SPAM for heap memory protection.

record the throughput (TP), and transfer rates (TX). The results in Figure 8 show that on average SPAM incurs a 1.3x overhead relative to the baseline. As file sizes become larger, the I/O starts to dominate and the performance impact of SPAM is as low as 1.24x; in contrast, for smaller files SPAM's performance impact increases to 1.4x. Enabling global memory permutation shows no measurable performance difference over the heap results. This is primarily due to the fact that the initial cost of permutation for globals (i.e., REGISTERGLOBAL) is amortized as the server is already loaded before it receives requests.

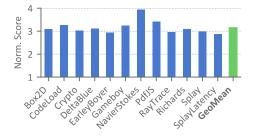


Fig. 9: Duktape performance overheads with SPAM for heap memory protection.

**Duktape.** We evaluate the Duktape [81] (version 2.5.0) Javascript interpreter with a default build configuration running the Octane 2 benchmark suite [29]<sup>11</sup>. We record the benchmark scores as reported by the Octane 2 suite and show the relative performance of SPAM compared to the baseline. The results in Figure 9 show an overhead with a geometric mean of approximately 3.15x. Similar to Nginx, enabling global memory permutation shows no measurable performance overheads for much the same reasons. The interpreter instance is already loaded by the time the Octane 2 benchmarks begin, thus amortizing the permutations associated with REGISTERGLOBAL.

**WolfSSL.** We evaluate WolfSSL [90] (version 4.4.0), as it is a popular cryptographic library. We use the default build configuration and the included wolfCrypt Benchmarks with default parameters which measure symmetric algorithms, such

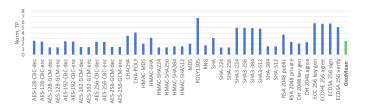


Fig. 10: WolfSSL performance overheads with SPAM for heap memory protection.

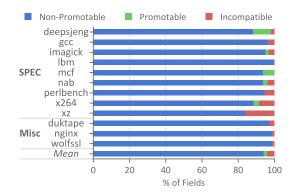


Fig. 11: Percentage of total struct fields covered by the Buf2Ptr transformation.

as AES and ChaCha20 and asymmetric algorithms, such as RSA and ECC in terms of throughput. The results in Figure 10 are normalized against a baseline execution and show an overhead with a geometric mean of 2.48x. Enabling global memory permutation increases the average overheads by an additional 16%.

#### C. Buf2Ptr Analysis

Coverage. We show the coverage of our current Buf2Ptr implementation in Figure 11. Coverage is reported in terms of the total number of fields in an application with each field belonging to one of three categories: (1) Non-promotable, means that Buf2Ptr is unnecessary as there are no array fields in an object (2) Promotable, means an array field which can be safely promoted and (3) Incompatible, means an array field that is currently considered unsafe to promote. The data shows that the majority of fields are considered to be non-promotable (94% on average). Defining structures with internal array fields is fairly uncommon among the benchmarks we sample (6% on average). As a result, the total number of promoted fields is quite low.

The fields that are considered to be incompatible can be grouped into two categories: (1) those that are fundamentally troublesome to the Buf2Ptr approach (see Listing 4 for detailed examples) and (2) artifacts of our current implementation. The ones that result from our current implementation artificially inflate our results for incompatible fields. The most noteworthy is the limited support for promoting fields wrapped in macros. As it stands, the current Clang rewriter API has limited support for macro rewriting. An alternative to this

<sup>&</sup>lt;sup>11</sup>Not all benchmarks are supported by Duktape.

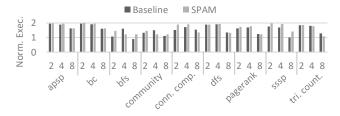


Fig. 12: SPAM's multi-threaded scalability for 2, 4, and 8 threads relative to the single threaded program.

current limitation is to expand macros before processing in the frontend, but this comes with its own drawbacks making it difficult to preserve the syntactic structure of the program. For our current implementation, we have chosen to forgo this route in favor of preserving the definition and use of macros and other formatting in the source code. This choice primarily affects the <code>imagick</code> and <code>x264</code> benchmarks which use a <code>CHECKED\_MALLOC</code> macro for all structs. In addition to macros, our current implementation has limited support for embedded struct declarations, variable length arrays and single statement variable declarations. These are straightforward extensions and are left for future work.

**Discussion.** The (SPAM + Buf2Ptr) column in Figure 7 shows the additional performance overheads of applying Buf2Ptr compared to SPAM alone. We notice that the performance overheads in Buf2Ptr are mainly due to (1) the one extra pointer access operation per each sub-object array and (2) the poor locality of sub-object arrays as they are allocated in different regions. The cost of the extra pointer operation can be easily amortized if there exist multiple successive accesses to the same sub-object array with different addresses. In this case, one possible optimization is to only compute the new base address of the sub-object once and allow all future accesses to use it. The locality issue highly depends on the application behavior. If the application tends to access all struct fields one after the other, locality and the processor's cache hit rate will be affected. If the application tends to access the same field from different objects, locality will not matter.

From a security perspective, the low number of promotable fields we have observed in the evaluated programs has a few interesting implications. First, it suggests that *intra-object overflows may account for a small portion of the attack surface in user-space programs*. However, it does not help us quantify the severity of intra-object overflow vulnerabilities. Second, with respect to Buf2Ptr, the low number of promotable fields means that the scope of incompatibilities is limited. Thus, one option to addressing the Buf2Ptr limitations discussed in Section IX may be done with minimal developer effort (e.g., annotations).

### D. Multi-Threaded Applications

State-of-the-art memory safety techniques (e.g., ASAN, Intel MPX) maintain explicit metadata for pointers and objects. This can result in false positives/negatives in multi-threaded programs if the metadata is not atomically updated in the same transaction as a program's atomic updates to its associated pointers or objects. The stateless nature of SPAM makes it well

suited for multi-threaded applications. To verify this hypothesis, we run the CRONO benchmark suite [2], a specialized multi-threaded suite of graph algorithms. Through successful instrumentation and execution of benchmark applications, it is shown that our proposed solution is thread-safe and is suitable for multicore systems. We perform a sweep of each benchmark using 2, 4, and 8 threads with each bar showing the normalized execution relative to the single threaded program. The baseline bars show how the performance scales for the default program with the SPAM bars representing the scaling for the hardened version. The results in Figure 12 show that the relative performance improvements of multi-threaded programs are unaffected by our stateless runtime as the bars for the baseline and SPAM are almost equivalent.

#### E. Permutation Analysis

Uniformity. As discussed in Section V, the uniformity of permutations is important as it reduces the success probability of an attacker. To evaluate the uniformity of permutations within our framework we conducted three experiments: (1) within (intra) allocation regions, (2) across (inter) regions, and (3) different alias numbers for the same address. The tests are designed to stress the permutation scheme. We use allocation regions of multiples of 128B for our LowFat allocator. For the intra region experiment (Figure 13(a)), we perform one million allocations of a given size, in this instance the smallest region (128B). For the inter region experiment (Figure 13(b)), we perform 100 allocations for 20 different LowFat regions (i.e., 2000 total allocations). For the aliasing experiment (Figure 13(c)), we perform 10,000 allocations using the same address (so that only alias number bits are different). For all experiments, we plot histograms with 10 bins. The values are normalized according to the expected value of each bin (e.g., the total number of allocations divided by total number of bins). As the data shows, the results in Figs. 13(a) and 13(b) are very close to ideal indicating that any permutation is equally likely of being generated. Figure 13(b) has slightly higher variability compared to Figure 13(a) simply due to the smaller number of allocations. Figure 13(c) shows slight modulo biasing as Fisher-Yates must bound the range of the values from the PRNG, as discussed in Section III-A. While it is theoretically possible to remove this bias, it involves the possibility of indefinitely polling the PRNG. We leave the exploration of alternative FPE shuffling schemes [37], [63] to future work.

TABLE V: Throughput of generating permutations for various PRNGs tested.

PRNG	Cycles			
AESRand	504			
xorshift64*	870			
xorshift128+	932			
rand	4652			

**Performance.** A cornerstone in our framework is the ability to generate truly random permutations. We tested a handful of pseudo-random number generators (PRNGs) available [53], [50], [79]. Table V shows the throughput of generating permutations for the various PRNGs ultimately leading to our choice of AESRand [79] as it was the most performant within



Fig. 13: The distribution of generated permutations (a) within the same allocation region (b) across different allocation regions and (c) for aliases of the same allocation.

our framework. This fact is critical in keeping performance overheads low as the PRNG lies within the critical path of our entire approach. AESRand is based on the Intel AES-NI instruction set extensions and 128-bit SIMD. It is known to pass two widely used statistical tests for PRNGs, namely Big Crush [48] and PractRand [20].

#### F. Summary

Unsurprisingly, our evaluation shows that SPAM suffers from high performance overheads. This is expected due to (1) the additional instrumentation instructions added for every load and store; and most importantly, (2) the software implementation of the permutation function. Both of these overheads can be mitigated with simple hardware support. For example, the getaddr primitive can be combined with a load or store in a single new instruction reducing code size and enhancing instruction cache utility. Additionally, the genperm primitive can be implemented with a hardware permutation network that reduces the current permutation latency from 504 cycles to be within 2 cycles [49], [71]. We leave the design space exploration of SPAM's hardware support for future work. Even without hardware support, the cohesive security of SPAM provides stronger guarantees than existing solutions at modest performance overheads (e.g., Nginx).

## VIII. DEPLOYMENT CONSIDERATIONS

SPAM requires a strict separation between application code and data (permuted domain) and external code and data (unpermuted domain). Otherwise, the loads and stores in the external code may inadvertently corrupt application memory as the external code (unless compiled with SPAM) is not instrumented to deal with permuted memory. In this section, we discuss different cases that affect the boundaries and how we handle them.

Externally Invoked Function Pointers. Instrumented code may be called externally via a function pointer. It is possible that the function is called from a non permuted domain. One example, is the comparison function pointer argument in qsort. This comparison function is typically defined by the application and thus will be instrumented. On the other hand, qsort itself is not instrumented as it belongs to external libraries. Depending on the logic of the external call that uses the function pointer we have the option of choosing to either (1) instrument the external library and all of its dependencies so that they are part of the permuted domain, or (2) create a variant of the function being pointed to by the function pointer and all of its dependencies that recursively unpermute the data upon load. Of the benchmarks we evaluate in Section VII, we

encountered this scenario with qsort in imagick, nab and x264 and handle them using the second option.

External Calls & Nested Memory. Depending on the API of the used external library, there may be instances in which pointers to permuted memory may be stored inside nested structures. SPAM handles these nested cases by relying on the type information of the function arguments to recursively unpermute and permute memory as necessary. The main limitation with the recursive approach is with self referencing structures (i.e., those with cycles). In this case, we support specifying a recursion limit for a given function. Alternatively, a suitable SPAM wrapper can be implemented to optimally handle the recursion depth necessary for a given function.

External Calls & Multi-threading. For multi-threaded programs, the semantics of the external call determine the instrumentation that our compiler emits. For external functions that only read permuted memory (e.g., memcpy), we emit a single copy unpermute primitive avoiding contention between other threads who may be trying to read the same memory while being unpermuted. If the external function tries to write to permuted memory, this is a race condition in the original code and should be resolved by the original developer using a synchronization primitive. In this case, SPAM emits the regular unpermute primitive.

Externally Allocated Memory. A number of functions in libc may return dynamically allocated memory, the majority of these are lumped under the *Dynamic Allocation Functions* [42] extension (e.g., strdup, getline, etc). While nothing is required for correctness to use these functions with SPAM, memory returned by them would be unpermuted. In order to protect memory in these situations, our prototype emits a permute primitive for memory returned by these functions.

#### IX. LIMITATIONS

In this section, we discuss the limitations of our current implementation and how we plan to address them in the future.

**Buf2Ptr.** Listing 4 shows the different types of legality constraints that apply to Buf2Ptr. For example, type erasure and type confusion result in the loss of the original type information due to implicit or explicit casting (e.g., Line 3 & 5). With the aid of alias analysis, it is possible to recover the original type in order to safely apply the transformation. A second legality requirement pertains to what we refer to as anonymous allocations (e.g., Line 8), or allocations in which the type is unknown. This pattern is common in applications with custom memory allocation wrappers that

```
1 struct Foo *f = malloc(sizeof(struct Foo));
2
3 // Type Erasure
4 void *type_erasure = (void *) f;
5 // Type Confusion
6 struct Bar *type_confusion = (struct Bar *)f;
7
8 // Anonymous Allocation
9 void *anon_alloc = malloc(10);
10 f = anon_alloc;
11 struct Foo *f2 = anon_alloc + sizeof(struct Foo);
12
13 // Struct Return-by-Value
14 struct Foo getCopy(struct Foo f);
```

Listing 4: Examples of code that cannot be legally transformed using our current Buf2Ptr prototype.

manually manage large memory chunks. In this situation, Buf2Ptr relies on the developer to provide type information for a safe promotion. Finally, while passing a structure by value is supported, returning it by value (e.g., Line 13) is not amiable, to promotion as it breaks the semantics of our transformation. We empirically evaluate how often these constraints prevent us from applying Buf2Ptr transformations and thus providing intra-object safety in Section VII-C.

**Inline Assembly.** With the current compiler infrastructure, SPAM is not able to properly instrument inline assembly code. However, in the future we anticipate that with the integration of a binary lifter [57], [92] we would be able to instrument IR generated from inline assembly.

Variadic Functions. Using functions with variable number of arguments is fully supported in our current prototype. That includes invoking variadic functions in instrumented code (e.g., printf and scanf). The only exception is invoking functions, which (1) are defined in uninstrumented code and (2) use va\_list as an argument (e.g., vsprintf). Those function invocations are not currently supported by our prototype. However, va\_list usage inside of instrumented code is fully supported. Support for passing va\_list externally is left for future work.

Additional Language Support. Our prototype currently supports C programs as evaluated in Section VII. Introducing support for other programming languages (e.g., C++) is straightforward as long as a clear separation between instrumented and uninstrumented code is established. This avoids unnecessary unpermute/permute overheads. In the case of C++, one way to add support would involve compiling the standard C++ library (e.g., libc++ or libstdc++) with SPAM so that data is unpermuted only at the system call interface.

### X. RELATED WORK

Table VI summarizes how SPAM compares to prior work. For each proposal, we specify its security guarantees, instrumentation level, and main limitations. We also highlight whether the proposal is available on commodity systems, has a precise failure model, supports multi-threading, and provides side-channel resiliency or not. Finally, we specify whether the proposal is used as a pre-deployment testing tool (i.e.,

Sanitizer) or a post-deployment mitigation.

**Software-based Memory Safety Techniques.** Many solutions have been proposed in academia and industry to tackle the memory unsafety problem of low level languages. We divide them into two categories: software and hardware.

Software only solutions can address a wide range of memory errors either pre-deployment (i.e., Sanitizers) or post-deployment (i.e., defenses). For instance, AddressSanitizer [70] uses shadow memory to detect out-of-bounds errors and uninitialized reads, respectively. However, it lacks the intra-object protection provided by Buf2Ptr. Additionally, while ASAN is great at finding memory corruption during testing, it cannot be used as a mitigation. An attacker who knows that ASAN is in use can simply move pointers past red zones. SPAM avoids such limitations by using finegrained per-instance memory permutation. On the other hand, EffectiveSAN [22], a sanitizer that is built on top of the LowFat allocator, can detect intra-object violations. However, EffectiveSAN does not detect use-after-free errors in which the freed object is reallocated to an object of the same type. This case is handled by SPAM as every allocation utilizes a random alias address, regardless of its type. Unlike SPAM, EffectiveSAN stores metadata separately, making it vulnerable to hardware memory violations, such as speculative execution and side-channels. Finally, CUP [9] uses per allocation metadata to provide spatial (inter) and temporal memory safety. This metadata is vulnerable to hardware memory corruption attacks and limits scalability of multi-threaded applications. While CUP instruments libc, compatibility with unprotected code is not supported by default as it poses significant performance overheads.

Software only solutions can also be used as post-deployment mitigations. For instance, SoftboundCETS [54], [55] provides intra-object protection with a modest performance overhead. Unlike SPAM, SoftboundCETS can not support multi-threaded applications, which highly limits its practicality. Another example is DFI [10], which utilizes points-to analysis to enforce data-flow integrity. While it is able to provide spatial safety it does not address temporal vulnerabilities. Moreover, DFI uses explicit metadata which limits its scalability for multithreaded applications.

Other software-based exploit mitigations, such as Isomeron [19] and Shuffler [89] focus on randomizing code layout. Randomizing the code layout serves as an effective means to make exploits (e.g., ROP, JIT-ROP, etc) more difficult with minimal performance overheads. However, these approaches do not directly provide protection against spatial/temporal memory safety vulnerabilities. Additionally, as they do not modify data, they provide no resiliency to side-channels. We categorize SPAM as a post-deployment mitigation that can reliably thwart attackers who abuse software/hardware memory vulnerabilities without using explicit metadata or inserting runtime checks.

Hardware-based Memory Safety Techniques. Hardware-assisted solutions are promising in terms of low runtime overheads. Industrial solutions include Intel MPX [58], which maintains objects bounds in hardware registers, Intel Control-flow Enforcement Technology (CET) [41], ARM pointer authentication (PAC) [51] and memory tagging (MTE) [3]. Un-

TABLE VI: Comparison with prior works.

Proposal	Commodity Systems	Failure Model *	Deployment Stage	Instrumentation Level	Spatial Inter	Protection Intra	Temporal Protection	Multi-threaded Support ¶	Side-channels Resiliency §	Main Limitations
AddressSanitizer [70]	1	Precise	Pre	Source	/	XII	/	•	Θ	Detect subset of intra-object violations
EffectiveSAN [22]	/	Precise	Pre	Source	/	/	✓†	<b>-</b>	Θ	Metadata vulnerable to memory disclosure attacks
CUP [9]	1	Precise	Pre	Source	✓	Х	✓	0	0	Metadata vulnerable to memory disclosure attacks
SoftBoundCETS [54], [55]	1	Precise	Post	Source		/	/	0	0	No support for multithreading
DFI [10]	✓	Precise	Post	Source	1	<b>√</b> ‡	X	igorplus	Θ	Imprecise points-to analysis
Isomeron [19]	1	Imprecise	Post	Binary	Х	Х	Х	•	0	No data protection
Shuffler [89]	✓	Imprecise	Post	Binary	×	Х	X	•	0	No data protection
MPX [58], [95]	/	Precise	Post	Source	/	/	/	<b>-</b>	•	Dropped support in GCC/Linux
Intel CET [41]	X	Precise	Post	Source	х	×	X	•	Θ	No data protection
ARM PAC [62]	/	Precise	Post	Source	/	X	/	•	$\Theta$	Pointers-only protection
ARM MTE [3]	X	Precise	Post	Source	/	×	/	•	$\Theta$	Limited entropy (4-bits)
CHERI [86], [91]	X	Precise	Post	Source	/	×	/	•	igorplus	No support for intra-object protection
Califorms [68]	Х	Precise	Post	Source	1	✓	✓	•	$\odot$	No runtime randomization
PointGuard [16]	/	Imprecise	Post	Source	/	Х	Х	•	0	Pointers-only protection. Weak encryption (XOR)
Data Randomization [15], [6]	/	Imprecise	Post	Source	/	×	X	•	•	Same layout for all instances. Weak encryption (XOR)
SALADSPlus [12], [11]	/	Precise	Post	Source	/	/	X	$\Theta$	$\Theta$	Partial objects randomization
Shapeshifter [85]	/	Precise	Post	Source	/	/	X	$\odot$	$\odot$	Metadata vulnerable to memory disclosure attacks
POLaR [44]	/	Imprecise	Post	Source	/	/	X	$\odot$	$\odot$	Partial objects randomization
Smokestack [1]	/	Imprecise	Post	Source	/	х	х	igorplus	0	Stack-only protection
RA-malloc [43]	1	Imprecise	Post	Binary	1	X	X	•	Θ	Low randomization entropy (3-bits)
SPAM	/	Imprecise	Post	Source	/	/	1	•	•	Incomplete type information in Buf2Ptr

Solutions with imprecise failure models are suitable for post-deployment. Those with precise failure models are suitable for pre-deployment (i.e., testing).

• Supported (stateless); • Supported (requires synchronization on global metadata); • No support.

• Resilient to RowHammer, hardware side-channels, ColdBoot; • Resilient to some; • None.

Experimental support via -fsantize-address-field-padding

Does not detect errors where the free'd object is reallocated to an object of the same type.

Depends on points-to analysis.

fortunately, MPX introduces compilation complexities leading to low adoption in practice (GCC and Linux recently dropped its support [87], [80]). Intel CET only provides backward-edge protection with a shadow stack and a coarse-grained forward edge protection with ENDBRANCH instruction. ARM PAC's scope is limited, only protecting code pointers such as return addresses and function pointers. Using PAC to protect data pointers will come with a large performance overhead. While ARM MTE provides spatial and temporal memory safety it has a limited entropy of 1/16 compared to SPAM's 1/16!. Moreover, MTE does not provide intra-object spatial memory safety leaving it vulnerable to type-confusion attacks. On the contrary, SPAM's cohesive approach of permuting memory removes the need for concatenating incompatible defenses.

Academic proposals, such as CHERI [86], [91] and Califorms [68], come with their own limitations as well. For example, CHERI offers no intra-object protection. Califorms [68] avoids CHERI's limitations by randomizing the layout of structs at compile time, providing probabilistic intra-object protection. Unlike SPAM, Califorms' struct randomization is exactly the same for all instances of the same struct/class requiring that the binary remain secret. Moreover, CHERI [91] and Califorms [68] provide temporal memory safety by using quarantining (i.e., placing the freed memory chunks in a queue such that those chunk will not be returned again by malloc for some period of time). On the contrary, SPAM utilizes permutations, which allow memory chunks to be available to new allocations immediately after being freed, avoiding any additional performance penalty.

Data Randomization. Randomization stands as a last line of defense when full memory safety cannot be completely guaranteed. We divide data randomization techniques into two categories; static and dynamic.

Static techniques either randomize data structure layout at compile time [52], [76] or randomize the representation of data in memory via encryption [16], [6], [15]. The above techniques maintain the same layout for all instances of data structs, whereas SPAM changes the layout based on data location.

We distinguish SPAM from prior efforts on dynamic data randomization as follows. First, SALADSPlus [12], [11], Shapeshifter [85] and POLaR [44] do not randomize all program data-structures to reduce runtime overheads. The protected subset is either manually chosen [12], [11], [85], or based on data-flow analysis [44]. Second, the above solutions offer no protection for their runtime metadata. Unlike SPAM's strong threat model, POLaR [44] assumes that the attacker has no read/write capabilities before bypassing the defense itself. Third, while Smokestack [1] relies on secure PRNG to pick runtime permutations similar to SPAM, it generates the permutations offline and stores them in lookup table at program memory. The limited size of such table reduces Smokestack entropy compared to SPAM. Additionally, Smokestack's approach is highly tuned for stack protection and may not scale against heap vulnerabilities in its current state. Finally, RAmalloc [43] permutes heap allocations by randomizing the byte location of the starting address of pointers. As pointers are of 8-byte size, RA-malloc offers  $(\frac{1}{8})$  success probability for the attacker compared to  $(\frac{1}{16!})$  for SPAM.

Secure Allocators. Secure memory allocators provide probabilistic guarantees for spatial memory protection, temporal memory protection (e.g., FreeSentry [93] and Oscar [18]), or both (e.g., DieHard [5], DieHarder [56], FreeGuard [72], and GUARDER [73]). Although those solutions typically come with minimal performance overheads, they lack protection against intra-object memory violations. Additionally, they only randomize the starting location of the newly allocated object; making them vulnerable to hardware memory corruption attacks unlike SPAM that permutes the object-data itself.

#### XI. CONCLUSION

In this paper, we presented SPAM, a software defense that significantly improves the resilience of applications to software and hardware memory violations. SPAM's novel insight of permuting data based on its memory location permits perinstance dynamic permutation. Our proposed Buf2Ptr transformation allows SPAM to guarantee sub-object protection against data corruption attacks. We built an initial prototype to demonstrate SPAM using an LLVM compiler pass with an extension to to the compiler-rt runtime. We successfully compiled and ran a variety of applications with SPAM to show its deployability. SPAM + Buf2Ptr provides comprehensive security guarantees and has modest overheads for I/O bound workloads (e.g., 1.4x for Nginx). Moreover, SPAM efficiently scales with multi-threaded applications. Our security evaluation shows that SPAM provides strong probabilistic protection (where an attacker chance of success is as low as  $\frac{1}{16!} \approx 10^{-14}$ ) against a wide range of memory corruption attacks that have not been previously covered by a single mitigation.

Our experience developing SPAM shows that further optimizations would allow the security benefits of data permutation to extend to other parts of a system: (1) a SPAM instrumented OS can significantly harden the root of trust (2) a specialized SPAM allocator would allow us to provide finegrained memory safety to 32-bit systems without high runtime overheads (3) while we currently support C programs, with more engineering effort we can support C++ programs as well and (4) minimal hardware extensions can significantly reduce the overhead making SPAM applicable for a wide variety of workloads. We believe that cohesive solutions like SPAM are mandatory to stand against the daily influx of attacks.

### REFERENCES

- M. T. Aga and T. Austin, "Smokestack: Thwarting DOP attacks with runtime stack layout randomization," in *Proceedings of the 2019 IEEE/ACM International Symposium on Code Generation and Opti*mization, ser. CGO 2019, Washington, DC, USA, 2019, pp. 26–36.
- [2] M. Ahmad, F. Hijaz, Q. Shi, and O. Khan, "CRONO: A benchmark suite for multithreaded graph algorithms executing on futuristic multicores," in 2015 IEEE International Symposium on Workload Characterization, Atlanta, GA, USA, Oct 2015, pp. 44–55.
- [3] ARM, "Memory tagging extension: Enhancing memory safety through architecture," 2019. [Online]. Available: https://community.arm.com/developer/ip-products/processors/b/processors-ip-blog/posts/enhancing-memory-safety
- [4] T. Austin, "Pointer-intensive benchmark suite," Sept 1995. [Online]. Available: http://pages.cs.wisc.edu/~austin/ptr-dist.html
- [5] E. D. Berger and B. G. Zorn, "Diehard: Probabilistic memory safety for unsafe languages," in *Proceedings of the 27th ACM SIGPLAN Conference on Programming Language Design and Implementation*, ser. PLDI '06, Ottawa, Ontario, Canada, 2006, pp. 158–168.
- [6] S. Bhatkar and R. Sekar, "Data space randomization," in *Proceedings* of the 5th International Conference on Detection of Intrusions and Malware, and Vulnerability Assessment, ser. DIMVA '08. Paris, France: Springer-Verlag, 2008, pp. 1–22.
- [7] T. Bletsch, X. Jiang, V. W. Freeh, and Z. Liang, "Jump-oriented programming: A new class of code-reuse attack," in *Proceedings of the* 6th ACM Symposium on Information, Computer and Communications Security, ser. ASIACCS '11, Hong Kong, China, 2011, pp. 30–40.
- [8] J. Bucek, K.-D. Lange, and J. v. Kistowski, "SPEC CPU2017: Next-generation compute benchmark," in *Proceedings of the 2018 ACM/SPEC International Conference on Performance Engineering*, ser. ICPE '18, April 2018, pp. 41–42.

- [9] N. Burow, D. McKee, S. A. Carr, and M. Payer, "CUP: Comprehensive user-space protection for C/C++," in *Proceedings of the 2018 on Asia Conference on Computer and Communications Security*, ser. ASIACCS 18. New York, NY, USA: Association for Computing Machinery, 2018, p. 381392. [Online]. Available: https://doi.org/10.1145/3196494.3196540
- [10] M. Castro, M. Costa, and T. Harris, "Securing software by enforcing data-flow integrity," in 7th Symposium on Operating Systems Design and Implementation (OSDI '06), November 6-8, Seattle, WA, USA, B. N. Bershad and J. C. Mogul, Eds. USENIX Association, 2006, pp. 147–160. [Online]. Available: http://www.usenix.org/events/osdi06/tech/castro.html
- [11] P. Chen, Z. Hu, J. Xu, M. Zhu, and P. Liu, "Feedback control can make data structure layout randomization more cost-effective under zero-day attacks," *Cybersecurity*, vol. 1, no. 1, p. 3, Jun 2018.
- [12] P. Chen, J. Xu, Z. Lin, D. Xu, B. Mao, and P. Liu, "A practical approach for adaptive data structure layout randomization," in *Computer Security* – *ESORICS 2015*, G. Pernul, P. Y A Ryan, and E. Weippl, Eds. Cham: Springer International Publishing, 2015, pp. 69–89.
- [13] S. Chen, J. Xu, E. C. Sezer, P. Gauriar, and R. K. Iyer, "Non-control-data attacks are realistic threats," in *Proceedings of the 14th Conference on USENIX Security Symposium - Volume 14*, ser. SSYM'05. Baltimore, MD, USA: USENIX Association, 2005, pp. 12–12.
- [14] L. Cheng, H. Liljestrand, M. S. Ahmed, T. Nyman, T. Jaeger, N. Asokan, and D. Yao, "Exploitation techniques and defenses for data-oriented attacks," in *Proceedings of the 2019 IEEE Cybersecurity Development (SecDev)*, Tysons Corner, VA, USA, September 2019, pp. 114–128.
- [15] M. Costa, J.-P. Martin, and M. Castro, "Data randomization," Microsoft, Tech. Rep. MSR-TR-2008-120, September 2008. [Online]. Available: https://www.microsoft.com/en-us/research/publication/data-randomization/
- [16] C. Cowan, S. Beattie, J. Johansen, and P. Wagle, "Pointguard: Protecting pointers from buffer overflow vulnerabilities," in *Proceedings of the 12th Conference on USENIX Security Symposium Volume 12*, ser. SSYM03. Washington, DC, USA: USENIX Association, 2003, p. 7.
- [17] C. Curtsinger and E. D. Berger, "Stabilizer: Statistically sound performance evaluation," in *Proceedings of the Eighteenth International Conference on Architectural Support for Programming Languages* and Operating Systems, ser. ASPLOS 13. Houston, Texas, USA: Association for Computing Machinery, 2013, p. 219228. [Online]. Available: https://doi.org/10.1145/2451116.2451141
- [18] T. H. Dang, P. Maniatis, and D. Wagner, "Oscar: A practical page-permissions-based scheme for thwarting dangling pointers," in 26th USENIX Security Symposium (USENIX Security 17). Vancouver, BC: USENIX Association, Aug. 2017, pp. 815–832. [Online]. Available: https://www.usenix.org/conference/usenixsecurity17/technical-sessions/presentation/dang
- [19] L. Davi, C. Liebchen, A.-R. Sadeghi, K. Z. Snow, and F. Monrose, "Isomeron: Code randomization resilient to (Just-In-Time) return-oriented programming," in *Proceedings of the 2015 Network and Distributed System Security Symposium*, ser. NDSS '15, San Diego, CA, USA, February 2015.
- [20] C. Doty-Humphrey, "Practically random." [Online]. Available: http://pracrand.sourceforge.net/
- [21] G. J. Duck and R. H. C. Yap, "Heap bounds protection with low fat pointers," in *Proceedings of the 25th International Conference on Compiler Construction*, ser. CC '16. Barcelona, Spain: ACM, 2016, pp. 132–142. [Online]. Available: http://doi.acm.org/10.1145/2892208. 2892212
- [22] G. J. Duck and R. H. C. Yap, "EffectiveSan: type and memory error detection using dynamically typed C/C++," in PLDI '18: Proceedings of the 39th ACM SIGPLAN Conference on Programming Language Design and Implementation, 2018.
- [23] G. J. Duck and R. H. C. Yap, "An extended low fat allocator api and applications," 2018.
- [24] G. J. Duck, R. H. C. Yap, and L. Cavallaro, "Stack bounds protection with low fat pointers," in 24th Annual Network and Distributed System Security Symposium, NDSS 2017, San Diego, California, USA, February 26 - March 1, 2017. The Internet Society,

- 2017. [Online]. Available: https://www.ndss-symposium.org/ndss2017/ndss-2017-programme/stack-object-protection-low-fat-pointers/
- [25] R. Durstenfeld, "Algorithm 235: Random permutation," *Commun. ACM*, vol. 7, no. 7, p. 420, Jul. 1964. [Online]. Available: https://doi.org/10.1145/364520.364540
- [26] C. W. Enumeration, "CWE-134: Use of externally-controlled format string." [Online]. Available: https://cwe.mitre.org/data/definitions/134. html
- [27] S. R. A. Fisher and F. Yates, "Statistical tables for biological, agricultural and medical research," 1963. [Online]. Available: http://hdl.handle.net/2440/10701
- [28] J. Fulmer, "Siege," https://github.com/JoeDog/siege/, 2012.
- [29] Google, "Octane 2," https://github.com/chromium/octane, 2012.
- [30] GoogleProjectZero, "One perfect bug: Exploiting type confusion in flash," 2015. [Online]. Available: https://googleprojectzero.blogspot.com/2015/07/one-perfect-bug-exploiting-type\_20.html
- [31] GoogleProjectZero, "0day in the wild," 2019. [Online]. Available: https://googleprojectzero.blogspot.com/p/0day.html
- [32] L. Granboulan and T. Pornin, "Perfect block ciphers with small blocks," in Fast Software Encryption, 14th International Workshop, FSE 2007, Luxembourg, Luxembourg, March 26-28, 2007, Revised Selected Papers, ser. Lecture Notes in Computer Science, A. Biryukov, Ed., vol. 4593. Springer, 2007, pp. 452–465. [Online]. Available: https://doi.org/10.1007/978-3-540-74619-5\_28
- [33] D. Gruss, R. Spreitzer, and S. Mangard, "Cache template attacks: Automating attacks on inclusive last-level caches," in 24th USENIX Security Symposium (USENIX Security 15).

  Washington, D.C.: USENIX Association, Aug. 2015, pp. 897–912. [Online]. Available: https://www.usenix.org/conference/usenixsecurity15/technical-sessions/presentation/gruss
- [34] M. Hähnel, W. Cui, and M. Peinado, "High-resolution side channels for untrusted operating systems," in 2017 USENIX Annual Technical Conference (USENIX ATC 17). Santa Clara, CA: USENIX Association, Jul. 2017, pp. 299–312. [Online]. Available: https://www.usenix.org/ conference/atc17/technical-sessions/presentation/hahnel
- [35] J. A. Halderman, S. D. Schoen, N. Heninger, W. Clarkson, W. Paul, J. A. Calandrino, A. J. Feldman, J. Appelbaum, and E. W. Felten, "Lest we remember: cold-boot attacks on encryption keys," *Communications of the ACM*, vol. 52, no. 5, pp. 91–98, 2009.
- [36] M. Hedayati, S. Gravani, E. Johnson, J. Criswell, M. L. Scott, K. Shen, and M. Marty, "Hodor: Intra-process isolation for high-throughput data plane libraries," in 2019 USENIX Annual Technical Conference (USENIX ATC 19). Renton, WA: USENIX Association, Jul. 2019, pp. 489–504. [Online]. Available: https://www.usenix.org/conference/atc19/presentation/hedayati-hodor
- [37] V. T. Hoang, B. Morris, and P. Rogaway, "An enciphering scheme based on a card shuffle," in Advances in Cryptology CRYPTO 2012 32nd Annual Cryptology Conference, Santa Barbara, CA, USA, August 19-23, 2012. Proceedings, ser. Lecture Notes in Computer Science, R. Safavi-Naini and R. Canetti, Eds., vol. 7417. Springer, 2012, pp. 1–13. [Online]. Available: https://doi.org/10.1007/978-3-642-32009-5\_1
- [38] HTTP, "The 2019 Web Almanac: Http archive's annual state of the web report," https://almanac.httparchive.org/en/2019/, 2019.
- [39] H. Hu, S. Shinde, S. Adrian, Z. L. Chua, P. Saxena, and Z. Liang, "Data-oriented programming: On the expressiveness of non-control data attacks," in 2016 IEEE Symposium on Security and Privacy (SP), San Jose, CA, USA, May 2016, pp. 969–986.
- [40] R. Hundt, S. Mannarswamy, and D. Chakrabarti, "Practical structure layout optimization and advice," in *Proceedings of the International Symposium on Code Generation and Optimization*, ser. CGO 06. USA: IEEE Computer Society, 2006, p. 233244. [Online]. Available: https://doi.org/10.1109/CGO.2006.29
- [41] Intel, "Intel control-flow enforcement technology preview," 2017. [Online]. Available: https://software.intel.com/sites/default/files/managed/4d/2a/control-flow-enforcement-technology-preview.pdf
- [42] ISO, "Information technology Programming languages, their environments and system software interfaces Extensions to the C library Part 2: Dynamic Allocation Functions," International Organization for Standardization, Geneva, CH, Standard, Dec. 2010.

- [43] D. Jang, J. Kim, H. Lee, M. Park, Y. Jung, M. Kim, and B. B. Kang, "On the analysis of byte-granularity heap randomization," *IEEE Transactions* on Dependable and Secure Computing, pp. 1–1, 2019.
- [44] J. Kim, D. Jang, Y. Jeong, and B. B. Kang, "POLaR: Per-allocation object layout randomization," in *Proceedings of the 2019 IEEE/IFIP International Conference on Dependable Systems and Networks*, ser. DSN 2019, Portland, Oregon, USA, June 2019.
- [45] Y. Kim, R. Daly, J. Kim, C. Fallin, J. H. Lee, D. Lee, C. Wilkerson, K. Lai, and O. Mutlu, "Flipping bits in memory without accessing them: An experimental study of dram disturbance errors," in *Proceeding of the 41st Annual International Symposium on Computer Architecuture*, ser. ISCA 14. IEEE Press, 2014, p. 361372.
- [46] D. E. Knuth, The Art of Computer Programming, Volume 2 (3rd Ed.): Seminumerical Algorithms. USA: Addison-Wesley Longman Publishing Co., Inc., 1997.
- [47] P. Kocher, D. Genkin, D. Gruss, W. Haas, M. Hamburg, M. Lipp, S. Mangard, T. Prescher, M. Schwarz, and Y. Yarom, "Spectre attacks: Exploiting speculative execution," in 40th IEEE Symposium on Security and Privacy (S&P'19), May 2019.
- [48] P. L'Ecuyer and R. Simard, "TestU01: A C library for empirical testing of random number generators," ACM Transactions on Mathematical Software (TOMS), vol. 33, no. 4, pp. 1–40, 2007.
- [49] R. B. Lee, Zhijie Shi, and Xiiao Yang, "Efficient permutation instructions for fast software cryptography," *IEEE Micro*, vol. 21, no. 6, pp. 56–69, Nov 2001.
- [50] G. Library, "ISO C random number functions." [Online]. Available: https://www.gnu.org/software/libc/manual/html\_node/ ISO-Random.html#ISO-Random
- [51] H. Liljestrand, T. Nyman, K. Wang, C. C. Perez, J.-E. Ekberg, and N. Asokan, "PAC it up: Towards pointer integrity using ARM pointer authentication," in 28th USENIX Security Symposium (USENIX Security 19). Santa Clara, CA: USENIX Association, Aug. 2019, pp. 177–194. [Online]. Available: https://www.usenix.org/conference/usenixsecurity19/presentation/liljestrand
- [52] Z. Lin, R. D. Riley, and D. Xu, "Polymorphing software by randomizing data structure layout," in *Detection of Intrusions and Malware, and Vulnerability Assessment*, U. Flegel and D. Bruschi, Eds. Springer Berlin Heidelberg, 2009, pp. 107–126.
- [53] G. Marsaglia, "Xorshift RNGs," Journal of Statistical Software, Articles, vol. 8, no. 14, pp. 1–6, 2003. [Online]. Available: https://www.jstatsoft.org/v008/i14
- [54] S. Nagarakatte, J. Zhao, M. M. Martin, and S. Zdancewic, "SoftBound: Highly compatible and complete spatial memory safety for C," in *Proceedings of the 30th ACM SIGPLAN Conference* on *Programming Language Design and Implementation*, ser. PLDI '09. Dublin, Ireland: ACM, 2009, pp. 245–258. [Online]. Available: http://doi.acm.org/10.1145/1542476.1542504
- [55] S. Nagarakatte, J. Zhao, M. M. Martin, and S. Zdancewic, "CETS: Compiler enforced temporal safety for C," in *Proceedings of the 2010 International Symposium on Memory Management*, ser. ISMM '10. Toronto, Ontario, Canada: ACM, 2010, pp. 31–40. [Online]. Available: http://doi.acm.org/10.1145/1806651.1806657
- [56] G. Novark and E. D. Berger, "Dieharder: Securing the heap," in *Proceedings of the 17th ACM Conference on Computer and Communications Security*, ser. CCS 10. Chicago, Illinois, USA: Association for Computing Machinery, 2010, p. 573584. [Online]. Available: https://doi.org/10.1145/1866307.1866371
- [57] T. of Bits, "Mcsema," 2014. [Online]. Available: https://github.com/ lifting-bits/mcsema
- [58] O. Oleksenko, D. Kuvaiskii, P. Bhatotia, P. Felber, and C. Fetzer, "Intel mpx explained: A cross-layer analysis of the intel mpx system stack," Proceedings of the ACM on Measurement and Analysis of Computing Systems, vol. 2, no. 2, p. 28, 2018.
- [59] S. Park, S. Lee, W. Xu, H. Moon, and T. Kim, "libmpk: Software abstraction for intel memory protection keys (intel MPK)," in 2019 USENIX Annual Technical Conference (USENIX ATC 19). Renton, WA: USENIX Association, Jul. 2019, pp. 241–254. [Online]. Available: https://www.usenix.org/conference/atc19/presentation/park-soyeon
- [60] J. Pewny, P. Koppe, and T. Holz, "STEROIDS for DOPed applications: A compiler for automated data-oriented programming," in 2019 IEEE

- European Symposium on Security and Privacy (EuroS&P), Stockholm, Sweden, June 2019.
- [61] B. Powers, D. Tench, E. D. Berger, and A. McGregor, "Mesh: Compacting memory management for c/c++ applications," in Proceedings of the 40th ACM SIGPLAN Conference on Programming Language Design and Implementation, ser. PLDI 2019. Phoenix, AZ, USA: Association for Computing Machinery, 2019, p. 333346. [Online]. Available: https://doi.org/10.1145/3314221.3314582
- [62] I. Qualcomm Technologies, "Pointer authentication on ARMv8.3," 2017. [Online]. Available: https://www.qualcomm.com/media/ documents/files/whitepaper-pointer-authentication-on-armv8-3.pdf
- [63] T. Ristenpart and S. Yilek, "The mix-and-cut shuffle: Small-domain encryption secure against N queries," in Advances in Cryptology CRYPTO 2013 33rd Annual Cryptology Conference, Santa Barbara, CA, USA, August 18-22, 2013. Proceedings, Part I, ser. Lecture Notes in Computer Science, R. Canetti and J. A. Garay, Eds., vol. 8042. Springer, 2013, pp. 392–409. [Online]. Available: https://doi.org/10.1007/978-3-642-40041-4\_22
- [64] P. Rogaway, "A synopsis of format-preserving encryption," 2010.
- [65] A. Rogers, M. C. Carlisle, J. H. Reppy, and L. J. Hendren, "Supporting dynamic data structures on distributed-memory machines," ACM Trans. Program. Lang. Syst., vol. 17, no. 2, p. 233263, Mar. 1995.
- [66] P. Roy and X. Liu, "Structslim: A lightweight profiler to guide structure splitting," in *Proceedings of the 2016 International Symposium on Code Generation and Optimization*, ser. CGO 16. New York, NY, USA: Association for Computing Machinery, 2016, p. 3646. [Online]. Available: https://doi.org/10.1145/2854038.2854053
- [67] J. H. Saltzer and M. D. Schroeder, "The protection of information in computer systems," *Proceedings of the IEEE*, vol. 63, no. 9, pp. 1278– 1308, Sep. 1975.
- [68] H. Sasaki, M. A. Arroyo, M. T. I. Ziad, K. Bhat, K. Sinha, and S. Sethumadhavan, "Practical byte-granular memory blacklisting using Califorms," in *Proceedings of the 52nd Annual IEEE/ACM International Symposium on Microarchitecture*, ser. MICRO 52. Columbus, OH, USA: Association for Computing Machinery, 2019, p. 558571. [Online]. Available: https://doi.org/10.1145/3352460.3358299
- [69] F. Schuster, T. Tendyck, C. Liebchen, L. Davi, A.-R. Sadeghi, and T. Holz, "Counterfeit object-oriented programming: On the difficulty of preventing code reuse attacks in C++ applications," in *Proceedings* of the 2015 IEEE Symposium on Security and Privacy, ser. SP '15, Oakland, CA, USA, 2015, pp. 745–762.
- [70] K. Serebryany, D. Bruening, A. Potapenko, and D. Vyukov, "AddressSanitizer: a fast address sanity checker," in USENIX ATC '12: Proceedings of the 2012 USENIX Annual Technical Conference, 2012.
- [71] Z. Shi, X. Yang, and R. B. Lee, "Arbitrary bit permutations in one or two cycles," in *Proceedings IEEE International Conference* on Application-Specific Systems, Architectures, and Processors. ASAP 2003, The Hague, Netherlands, June 2003, pp. 237–247.
- [72] S. Silvestro, H. Liu, C. Crosser, Z. Lin, and T. Liu, "FreeGuard: A faster secure heap allocator," in *Proceedings of the 2017 ACM SIGSAC Conference on Computer and Communications Security*, ser. CCS '17. Dallas, Texas, USA: ACM, 2017, pp. 2389–2403. [Online]. Available: http://doi.acm.org/10.1145/3133956.3133957
- [73] S. Silvestro, H. Liu, T. Liu, Z. Lin, and T. Liu, "Guarder: A tunable secure allocator," in 27th USENIX Security Symposium (USENIX Security 18). Baltimore, MD, USA: USENIX Association, 2018, pp. 117–133.
- [74] K. Z. Snow, F. Monrose, L. Davi, A. Dmitrienko, C. Liebchen, and A.-R. Sadeghi, "Just-in-time code reuse: On the effectiveness of finegrained address space layout randomization," in 2013 IEEE Symposium on Security and Privacy, Berkeley, CA, USA, May 2013, pp. 574–588.
- [75] A. Sotirov, "Heap feng shui in javascript," BlackHat, 2007.
- [76] D. M. Stanley, D. Xu, and E. H. Spafford, "Improved kernel security through memory layout randomization," in 2013 IEEE 32nd International Performance Computing and Communications Conference (IPCCC), San Diego, CA, USA, Dec 2013, pp. 1–10.
- [77] R. Strackx, Y. Younan, P. Philippaerts, F. Piessens, S. Lachmund, and T. Walter, "Breaking the memory secrecy assumption," in *Proceedings of the Second European Workshop on System Security*, ser. EUROSEC 09. Nuremburg, Germany: Association for Computing Machinery,

- 2009, p. 18. [Online]. Available: https://doi.org/10.1145/1519144. 1519145
- [78] I. Sysoev, "Nginx," http://nginx.org/en/, 2004.
- [79] P. D. Tiglao, "Aesrand," 2018. [Online]. Available: https://github.com/ dragontamer/AESRand
- Torvalds, "mpx-for-linus [80] L. removal." Available from Linux Kernel Source Tree. 2020. [Online]. Availhttps://git.kernel.org/pub/scm/linux/kernel/git/torvalds/linux.git/ commit/?id=ccaaaf6fe5a5e1fffca5cca0f3fc4ec84d7ae752
- [81] S. Vaarala, "Duktape," https://github.com/svaarala/duktape, 2013.
- [82] A. Vahldiek-Oberwagner, E. Elnikety, N. O. Duarte, M. Sammler, P. Druschel, and D. Garg, "ERIM: Secure, efficient in-process isolation with protection keys (MPK)," in 28th USENIX Security Symposium (USENIX Security 19). Santa Clara, CA: USENIX Association, Aug. 2019, pp. 1221–1238. [Online]. Available: https://www.usenix.org/conference/usenixsecurity19/presentation/vahldiek-oberwagner
- [83] V. van der Veen, D. Andriesse, M. Stamatogiannakis, X. Chen, H. Bos, and C. Giuffrdia, "The dynamics of innocent flesh on the bone: Code reuse ten years later," in *Proceedings of the 2017 ACM SIGSAC Conference on Computer and Communications Security*, ser. CCS '17, Dallas, Texas, USA, 2017, pp. 1675–1689.
- [84] W. Wang, G. Chen, X. Pan, Y. Zhang, X. Wang, V. Bindschaedler, H. Tang, and C. A. Gunter, "Leaky cauldron on the dark land: Understanding memory side-channel hazards in sgx," in *Proceedings of the 2017 ACM SIGSAC Conference on Computer and Communications Security*, ser. CCS 17. Dallas, Texas, USA: Association for Computing Machinery, 2017, p. 24212434. [Online]. Available: https://doi.org/10.1145/3133956.3134038
- [85] Y. Wang, Q. Li, Z. Chen, P. Zhang, and G. Zhang, "Shapeshifter: Intelligence-driven data plane randomization resilient to data-oriented programming attacks," *Computers & Security*, vol. 89, 2020. [Online]. Available: https://doi.org/10.1016/j.cose.2019.101679
- [86] R. N. M. Watson, J. Woodruff, P. G. Neumann, S. W. Moore, J. Anderson, D. Chisnall, N. H. Dave, B. Davis, K. Gudka, B. Laurie, S. J. Murdoch, R. M. Norton, M. Roe, S. D. Son, and M. Vadera, "CHERI: A hybrid capability-system architecture for scalable software compartmentalization," in 2015 IEEE Symposium on Security and Privacy, San Jose, CA, USA, May 2015, pp. 20–37.
- [87] G. Wiki, "Intel memory protection extensions (intel mpx) support in the gcc compiler," 2018. [Online]. Available: https://gcc.gnu.org/wiki/ Intel%20MPX%20support%20in%20the%20GCC%20compiler
- [88] J. Wilander, N. Nikiforakis, Y. Younan, M. Kamkar, and W. Joosen, "RIPE: Runtime intrusion prevention evaluator," in *Proceedings of the* 27th Annual Computer Security Applications Conference, ser. ACSAC '11, Orlando, Florida, USA, 2011, pp. 41–50.
- [89] D. Williams-King, G. Gobieski, K. Williams-King, J. P. Blake, X. Yuan, P. Colp, M. Zheng, V. P. Kemerlis, J. Yang, and W. Aiello, "Shuffler: Fast and deployable continuous code re-randomization," in *Proceedings of the 12th USENIX Symposium on Operating Systems Design and Implementation*, ser. OSDI 16. Savannah, GA, USA: USENIX Association, 2016, pp. 367–382.
- [90] WolfSSL, "wolfssl," https://github.com/wolfSSL/wolfssl, 2006.
- [91] H. Xia, J. Woodruff, S. Ainsworth, N. W. Filardo, M. Roe, A. Richardson, P. Rugg, P. G. Neumann, S. W. Moore, R. N. M. Watson, and et al., "Cherivoke: Characterising pointer revocation using cheri capabilities for temporal memory safety," in *Proceedings of the 52nd Annual IEEE/ACM International Symposium on Microarchitecture*, ser. MICRO 52. Columbus, OH, USA: Association for Computing Machinery, 2019, p. 545557. [Online]. Available: https://doi.org/10. 1145/3352460.3358288
- [92] S. B. Yadavalli and A. Smith, "Raising binaries to llvm ir with mctoll (wip paper)," in *Proceedings of the 20th ACM SIGPLAN/SIGBED International Conference on Languages, Compilers, and Tools for Embedded Systems*, ser. LCTES 2019. New York, NY, USA: Association for Computing Machinery, 2019, p. 213218. [Online]. Available: https://doi.org/10.1145/3316482.3326354
- [93] Y. Younan, "FreeSentry: Protecting against use-after-free vulnerabilities due to dangling pointers," in *Proceedings of the 2015 Network and Distributed System Security (NDSS) Symposium*, San Diego, CA, USA, February 2015.

- [94] C. Yu, P. Roy, Y. Bai, H. Yang, and X. Liu, "LWPTool: A lightweight profiler to guide data layout optimization," *IEEE Transactions on Parallel and Distributed Systems*, vol. 29, no. 11, pp. 2489–2502, Nov 2018
- [95] T. Zhang, D. Lee, and C. Jung, "Bogo: Buy spatial memory safety, get temporal memory safety (almost) free," in *Proceedings of the Twenty-Fourth International Conference on Architectural Support for Programming Languages and Operating Systems*, ser. ASPLOS 19. New York, NY, USA: Association for Computing Machinery, 2019, p. 631644. [Online]. Available: https://doi.org/10.1145/3297858.3304017

## APPENDIX A ADDITIONAL EVALUATION

This appendix provides more information about our Nginx configuration and additional performance results for SPAM.

## A. Configuration

**Nginx.** In Listing 5, we show the configuration file used for both the baseline and SPAM enabled Nginx instances used during evaluation. Here benchmark\_html is a directory that contains the files of different sizes that are served. The different sized files are generated using python -c "print('X' \*\${FS})" > \${FS}.html where \${FS} is the file size. Additionally, we disable non-essential features as shown in Listing 6 to narrow the scope of testing to just file serving.

```
worker_processes 1;
2
    error_log logs/error.log debug;
3
5
    events [
      worker_connections 1024;
   http {
      include
                    mime.types;
10
11
      default_type application/octet-stream;
12
      root benchmark_html;
13
      sendfile
                       on;
      tcp_nopush on;
      keepalive timeout 65;
15
16
      server (
17
                      8776;
        listen
18
        server_name localhost;
19
20
21
        location / {
          index index.html;
22
23
        error_page
                      500 502 503 504 /50x.html;
25
        location = /50x.html {
26
               docs/html;
27
          root
28
29
30 }
```

Listing 5: The Nginx web server configuration used in our performance evaluation.

#### B. Additional Results

**Olden.** We further evaluate SPAM on a pointer and allocation intensive benchmark suite, Olden [65]. We use the big test input as specified by llvm-test-suite. Figure 14 shows the geometric mean of each tool: ASAN (2.02x), MPX (3.65x),

```
user: $ auto/configure \
         --without-pcre \
         --without-http_rewrite_module \
         --without-http-cache
          --without-http_gzip_module \
         --without-http_proxy_module \
7
          --without-http_limit_conn_module \
          --without-http_limit_req_module \
8
          --without-http_browser_module
          --without-http_charset_module
10
          --without-http_ssi_module
11
12
          --without-http_userid_module
          --without-http_access_module \
13
14
          --without-http_auth_basic_module \
          --without-http_geo_module
15
          --without-http_map_module \
16
17
          --without-http_split_clients_module \
          --without-http_referer_module
18
19
          --without-http_rewrite_module
20
          --without-http_fastcgi_module
          --without-http_uwsgi_module
21
          --without-http_scgi_module
          --without-http_memcached_module
23
24
          --without-http_empty_gif_module
25
          --without-http_upstream_hash_module \
          --without-http_upstream_ip_hash_module
26
          --without-http_upstream_least_conn_module \
          --without-http_upstream_keepalive_module \
28
          --without-http_upstream_zone_module
```

Listing 6: The Nginx build configuration parameters.

SPAM (3.25x) and SPAM + Buf2Ptr (3.31x). An interesting outlier for MPX is em3d whose singly-linked list data structure stresses the bounds checking mechanism.

**PtrDist.** We evaluate SPAM performance compared to ASAN and Intel MPX using the Pointer-Intensive Benchmark Suite [4], or PtrDist, which is a collection of applications specifically designed to test pointer-intensive operations. Figure 15 shows the evaluation results using the input set, as specified by the llvm-test-suite.

### C. SPAM Overheads Breakdown

Figure 16 shows the performance overheads for SPAM's instrumentation and memory allocator without permuting program data for SPEC2017. The overheads are relative to the uninstrumented baseline using the default system malloc. Instrumentation (which includes the allocator overhead) on average accounts for 58%. There is further room for improvement by using more accurate alias analysis, and writing tighter code for optimized case specific functions allowing for more inlining opportunities. As we can see, padding allocations to be multiples of 128 bytes adds an average allocator overhead of 20% for SPEC. While this allows permutations to be computed more efficiently, it is worth noting that there may be room for future performance gains by aligning to a smaller size.

## APPENDIX B LIBRARY WRAPPERS

To avoid paying the performance penalty of unpermuting and permuting memory when making external library calls, we implement SPAM optimized wrappers for memory intensive functions. This allows us to directly operate on permuted memory. The most important of these functions are primarily

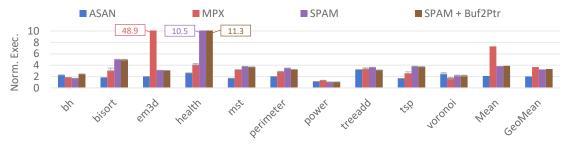


Fig. 14: Olden performance for different tools normalized to their corresponding baseline for heap memory protection.

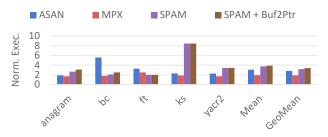


Fig. 15: PtrDist Performance.

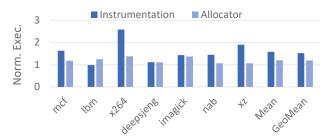


Fig. 16: SPAM overhead for SPEC2017.

found in the C standard library's string.h section (e.g., memcpy, memmove, memset, strcpy, etc). Table VII lists the libc wrappers we implemented to support the programs used in Section VII.

## APPENDIX C SYSTEM-LEVEL APPLICABILITY

While our current implementation explores SPAM's applicability within the application domain, we expand on how SPAM integrates in the context of an entire system.

OS Interface. Only user-land applications are currently supported by our prototype. As a result, data needs to be unpermuted before making any system-call (e.g., write). Similarly, we permute the data directly after system calls that write to program memory (e.g., read). The above data serialization adds additional runtime overheads and allows an attacker with access to an OS vulnerability to corrupt the data while it is unpermuted. One possible solution is to instrument OS APIs with SPAM so that no serialization is needed. We leave this for future work.

**Non** 64-bit Architectures. Non 64-bit systems (e.g., 32-bit processors) are widely used in Internet-of-Things and Cyber

## TABLE VII: SPAM Wrapper List



Physical Systems, not to mention a large body of legacy systems. Thus, it is important to consider the applicability of SPAM to this class of devices. While our current implementation is not suited for these systems due to our choice of LowFat allocator and use-after-free protection, this does not preclude SPAM from supporting 32-bit architectures. To do so, we propose leveraging the flexibility to use a traditional allocator (e.g., dlmalloc) while ensuring that no two C structs are of the same size. The latter condition is to guarantee use-after-free protection in the absence of the alias bits. As SPAM permutes structs based on base address and size, having unique struct sizes guarantees unique permutations even if the base address is the same.

## APPENDIX D SPAM RUNTIME APIS

We list the C API for the functionality described in Section IV.

**Get Allocation Base Address.** SPAM needs a way to retrieve the base address of an allocation from an arbitrary pointer in order to then compute the correct permutation. How this

metadata is retrieved varies depending on the underlying allocator used to implement SPAM. Our current prototype relies on the LowFat allocator [21] which is able to retrieve this information implicitly in constant time by partitioning the memory space into aligned fixed sized regions. It is important to note that broader SPAM technique is not bound to a specific allocator.

**Get Allocation Size.** In addition to the base address above, the runtime also needs a mechanism to determine the bounds, or size, of an allocation. Given the base address the underlying allocator must be able to return this information. In our current implementation using LowFat, this information is implicitly derived from the base address itself.

```
void *GetPermPtr(void *Ptr, uint64_t Perm) (4)

void *Unpermute(void *Ptr)

void *Permute(void *Ptr) (5)

void RegisterGlobal(void *Ptr) (6)

void *RegisterStack(void *Ptr) (7)
```