PTAuth: Temporal Memory Safety via Robust Points-to Authentication

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Abstract
Temporal memory corruptions are commonly exploited software vulnerabilities that can lead to powerful attacks. Despite significant progress made by decades of research on mitigation techniques, existing countermeasures fall short due to either limited coverage or overly high overhead. Furthermore, they require external mechanisms (e.g., spatial memory safety) to protect their metadata. Otherwise, their protection can be bypassed or disabled.

To address these limitations, we present robust points-to authentication, a novel runtime scheme for detecting all kinds of temporal memory corruptions. We built a prototype system, called PTAuth, that realizes this scheme on ARM architectures. PTAuth contains a customized compiler for code analysis and instrumentation and a runtime library for performing the points-to authentication as a protected program runs. PTAuth leverages the Pointer Authentication Code (PAC) feature provided by the latest ARM CPUs, which serves as a simple hardware-based encryption primitive. PTAuth uses minimal in-memory metadata and protects its metadata without requiring spatial memory safety. We report our evaluation of PTAuth in terms of security, robustness and performance using 150 vulnerable programs from Juliet test suite and the SPEC CPU2006 benchmarks. PTAuth detects all temporal memory corruptions from all 3 categories, generates zero false alerts, and slows down program execution by 26.0% (this number was measured based on software-emulated PAC; it is expected to be lower on hardware with PAC support).

1 Introduction
Memory corruptions remain to be the most commonly exploited software vulnerabilities, despite the significant progress made by decades of research on mitigation techniques. Memory corruptions are caused by programming errors (or bugs) that break the type constraints of data in memory. They serve as the stepping stone for launching almost all types of software attacks, from simple stack smashing to heap spray and to more advanced return-oriented programming (ROP) and code reuse attacks. Generally, memory corruptions exist in two different forms: spatial or temporal. The former happens when data’s spatial boundary is breached. The latter is due to data being used out of its life span.

Temporal memory corruptions may seem less harmful than spatial corruptions. However, they are being increasingly exploited to bypass the state of the art defenses against spatial corruptions or control flow manipulations. Use-after-free (UAF) is the most common type of temporal memory corruption. To exploit a UAF, an attacker first plants crafted objects in place of expired/freed objects and then waits for the vulnerable program to access the planted objects, and in turn, unknowingly invoke code specified by the attacker. Double-free and invalid-free are two other types of temporal memory corruptions that can provide arbitrary write primitives for attackers.

To counter the powerful and stealthy attacks enabled by temporal memory corruptions, many mitigation or prevention techniques were proposed recently. One approach adopted by these works [31, 38, 52, 56, 59] aims to disable dangling pointers, without which UAF and its variants cannot occur. Though effective, these techniques are either too heavy for real-world deployment [38, 59] or limited in their scope of protection. For instance, DangNull [38] can only protect those pointers that reside on the heap. Techniques solely focusing on preventing dangling pointers, such as Oscar [31], are unable to prevent invalid-free vulnerabilities.

Another line of works on preventing temporal memory corruptions monitors every pointer dereference during runtime and ensures that the to-be-dereferenced pointer indeed points to the expected object (or type) [29, 41, 43]. These techniques are, in principle, more comprehensive than dangling pointer prevention. However, they tend to incur heavier runtime overhead.

Despite the approaches, the aforementioned techniques all require spatial memory safety to protect their in-memory metadata, whose integrity is critical for the runtime monitoring. This common requirement underlines two limitations of these
techniques. First, without external protection, they themselves are not robust against attacks or evasions. Second, requiring spatial safety can significantly increase the already high runtime overhead. Furthermore, many of the existing mitigations against temporal memory corruption, including [38, 56, 59], store a considerable amount of metadata in memory, increasing the memory footprint by as much as 2 times.

Motivated by the limitations of previous works (esp. limited coverage, the requirement of external protection, and high overhead), we present PTAuth, a novel system for dynamically detecting temporal memory corruptions in user-space programs. PTAuth follows the approach of runtime dereference checking. Unlike previous works, PTAuth has built-in protection of its in-memory metadata and thus obviates the need for external mechanisms to provide spatial memory safety. Moreover, PTAuth uses a checking scheme that minimizes metadata size and optimizes metadata placement for better compatibility and handling of data and pointer propagation.

Specifically, during the allocation of every heap object, PTAuth assigns a unique ID to the object and computes a cryptographic authentication code (AC) based on the object ID and the base address of the object. PTAuth stores the ID to the beginning of the object. It stores the AC to the unused bits of the pointer to the object. As a result, the pointer is “tied to” the object (or the pointee) at the particular location in memory. This points-to relationship can be verified during every pointer dereference by re-computing the AC. An AC mismatch indicates a temporal memory safety violation.

The in-memory metadata of PTAuth include AC for pointers and IDs for objects. Obviously, the robustness of the runtime checks hinges on the integrity of the metadata. PTAuth can detect corrupted or invalid metadata without requiring any form of spatial memory safety, thanks to the design of AC. By using a secret key for computing and verifying AC, PTAuth prevents attackers from forging or tampering with metadata. We prototyped PTAuth for the latest ARM architecture and employ PAC (pointer authentication code) [16], a hardware-based feature, to implement AC. PAC was originally designed for checking the integrity of protected pointers and has been enabled on the latest iOS devices [21]. We repurposed this hardware feature for performing secure encryption (i.e., calculating AC) and storing AC in unused bits of pointers.

The in-pointer storage of AC offers two benefits. First, storing AC does not consume additional memory space. Second, an AC is propagated automatically when the pointer is copied or moved, without requiring handling or tracking by PTAuth. An object ID is 8-byte long and is stored at the beginning of the object. The distributed placement of object IDs, as opposed to centralized storage, makes the runtime check faster. In summary, we made the following contributions:

- We designed a novel scheme for dynamically detecting temporal memory corruptions, which overcomes the limitations of previous works and achieves minimal metadata, full coverage, and built-in security against attacks and metadata tempering.
- We built a system for ARM platforms that utilizes PAC to implement the detection scheme in an efficient and secure way.
- We evaluated the prototype using standard benchmarks and compared it with the state-of-the-art temporal corruption detectors, confirming the advantages of our approach.

2 Background

2.1 Exploiting Temporal Memory Bugs

Use-after-free: If a program reuses a pointer after the corresponding buffer had been freed, attackers may plant a crafted object in the same memory location, after the free and before the use, to trick the program into using the crafted object and consequently perform attacker-specified actions. According to recent reports [30, 38], UAF now counts for a majority of software attacks, especially on browsers, mostly because the deployed attack mitigations are unable to detect them. Moreover, most of the recent Android rooting and iOS jailbreaking exploits use UAF as a key part of their attack flows [13].

Double-free: Double-free is a special case of UAF, which occurs when a pointer is freed twice or more. This leads to undefined behaviors [8] and can be exploited to construct arbitrary memory write primitives, with which an attacker can corrupt sensitive information such as code pointers and execute arbitrary code.

Invalid-free: Invalid-free occurs when freeing a pointer that is not pointing to the beginning of an object or a heap object at all (i.e., freeing a pointer that was not returned by an allocator) [8, 43]. Similar to double-free, invalid-free may allow attackers to gain arbitrary memory overwrite abilities. The idea of House of Spirit [48] exploitation technique is partly based on exploiting invalid-free errors.

2.2 Pointer Authentication Code on ARMv8

Pointer Authentication Code, or PAC, is a new hardware feature available on ARMv8.3-A and later ARM Cortex-A architectures [10]. PAC is designed for checking the integrity of critical pointers. Compilers or programmers use the corresponding PAC instructions to (1) generate signatures for selected pointers, and (2) verify signatures before signed pointers are used. For instance, in a typical use case of PAC, compilers insert to programs the PAC instructions that, during runtime, sign each return address (i.e., a special code pointer) before saving it and check the signature before every function return. PAC is designed to detect unexpected or malicious
overwrites of pointers. It has been deployed and enabled on the latest iOS devices [21].

PAC generates pointer signatures, or authentication codes, using QARMA [25], a family of lightweight block ciphers. QARMA takes two 64-bit inputs (one pointer and one context value), encrypts the inputs with a 128-bit key, and outputs a 64-bit signature. A context value is chosen by the programmer or compiler for each pointer. A total of five keys can be set by the OS (i.e., code running at EL1) for encrypting/signing different kinds of pointers. Signatures are truncated and stored in the unused bits of signed pointers (i.e., depending on the virtual address space configuration, 11 to 31 bits in a 64-bit pointer could be unused).

Very recently, ARM announced ARMv8.6-A [23], which introduced some enhancements to PAC. In ARMv8.3, when a pointer authentication process fails, the top bits of the invalid pointer is changed to 0x20, which makes the pointer invalid to use. In contrast, in ARMv8.6, an exception is thrown when a pointer authentication fails, which prevents an attacker to brute-force the correct signature. Another improvement in ARMv8.6 is that a signature is XORed with the upper bits of the pointer, which help mitigate signature reuse attacks. At the time of writing this paper, neither the reference manual nor any hardware or simulator is publicly available for ARMv8.6-A. Our design and implementation of PTAuth are based on ARMv8.3.

Table 1 lists a subset of PAC instructions. Each instruction serves one purpose (signing or authentication), targets one type of pointers (code or data), and uses one of the five keys (i.e., two keys for each pointer type plus a generic key). Differentiating pointer types and having multiple keys help reduce the chance of pointer substitution or reuse attacks. The bottom two instructions in Table 1 are special. PACGA is not specific to pointer authentication and can be used as a data encryption instruction. It uses the generic key and outputs a 32-bit cipher to the upper half of a general-purpose register. XPAC removes the signature from a signed pointer. PAC enables fast and robust checking of pointer integrity. The signing and authentication are performed directly by the CPU without any software-level assistance. The keys are stored in the special CPU registers, which are accessible only to OS or EL1 code and not visible to user-level code.

We use PAC as a simple hardware-based primitive for efficiently and securely computing AC. The AC computation is based on our own scheme designed for detecting temporal memory corruptions. Our novel use of PAC is different from PAC’s intended usages and achieves a security goal that is orthogonal to, and broader than, the original purpose of PAC.

Table 1: PAC-related instructions.

| Instruction | Key Used | Pointer Type | Purpose       |
|-------------|----------|--------------|---------------|
| PACIAx      | Code.A   | Code         | Signing       |
| PACIBx      | Code.B   | Code         | Signing       |
| PACDAx      | Data.A   | Data         | Signing       |
| PACDBx      | Data.B   | Data         | Signing       |
| AUTIAx      | Code.A   | Code         | Authentication|
| AUTIBx      | Code.B   | Code         | Authentication|
| AUTDAx      | Data.A   | Data         | Authentication|
| AUTDBx      | Data.B   | Data         | Authentication|
| PACGA       | Generic  | Generic      | General       |
| XPAC        | -        | -            | Sig. stripping|

2.3 Fixed Virtual Platforms (FVP)

The ARMv8.3-A architecture (including PAC) was announced in late 2016 and is expected to enter mass production in 2020 to replace the current mainstream mobile architecture, namely ARMv8.0-A. At the time of writing, no development boards or commercially available SoC (Systems-on-Chip) use ARMv8.3-A. Apple’s latest iOS devices, using the A12 Bionic SoC, is based on ARMv8.3-A and supports PAC. However, the SoC and OS are proprietary and cannot be used for testing the prototype of PTAuth.

ARM offers so-called Fixed Virtual Platforms (FVP) for to-be-released architectures [20]. FVP is a full-system simulator that includes processors, memory, and peripherals. It is a functionally accurate model of the simulated hardware. FVP allows for the development and testing of drivers, software, and firmware prior to hardware availability. It is widely used in the industry.

Following this standard practice, we used the ARMv8.3-A FVP when building and evaluating our prototype system. Thanks to FVP’s functional accuracy, the evaluation results obtained on FVP are expected to be close to those obtained on actual hardware. We discuss more the implementation and evaluation in §5 and §6, respectively.

3 Design

3.1 System Overview

The goal of PTAuth is to dynamically detect temporal memory corruptions in the heap. The high-level idea is that, upon each pointer dereference (or pointer-based object access), temporal memory corruption can be detected by checking (1) whether the pointer is pointing to the original or intended object, and (2) whether the metadata or evidence proving the points-to relationship is genuine.

Although the high-level idea is conceptually straightforward, how to realize it in an efficient and secure way is in fact challenging. What metadata are needed for establishing the points-to relationship? How are they computed and where are they stored? How can their integrity be verified? Answers to these design questions determine the efficiency and robustness of PTAuth. For instance, recording too much metadata leads to unnecessarily big memory footprint and redundant checks.
Storing metadata separately from objects and pointers may ease metadata protection but significantly increase the overhead for locating and accessing metadata. Storing metadata in-place allows for fast access, but pointer arithmetics may complicate locating metadata. Moreover, in-place metadata is hard to protect and can be easily corrupted.

Our points-to authentication scheme overcomes these challenges and the limitations of previous works. PTAuth randomly generates an ID for each heap object upon its allocation. It also computes a cryptographic authentication code (AC) based on the object ID and the base address of the object. The object ID, stored at the beginning of the object, and the AC, stored in the unused bits of the object’s pointer, together serve as the metadata to establish the verifiable points-to relationship between the object and its pointers. Furthermore, PTAuth can detect forged or corrupted metadata as long as the key for computing AC remains confidential and the AC computation can only be performed by PTAuth. We discuss the detailed design of the points-to authentication scheme in §3.4.

Our implementation of the points-to authentication scheme takes advantage of the PAC feature on ARM architectures. PTAuth uses PAC as a simple primitive, provided by hardware, for computing and checking AC and securing the key. We discuss in §3.5 the use of the PAC instructions and the compiler-based code instrumentation.

Figure 1 presents an overview of the PTAuth system. The application is instrumented by the PTAuth compiler. Points-to authentication and metadata integrity checks are inserted before the load and store operations. During runtime, the checks are performed by the PTAuth library using PAC instructions. PTAuth also installs a tiny OS patch for managing PAC encryption keys, which are only accessible from the kernel-space (or EL1) as enforced by the architecture.

3.2 Threat Model

We adopt a threat model common to user-space dynamic memory error checkers. We trust the OS and the underlying hardware (i.e., the TCB). It is technically possible to reduce or remove the trust on OS if a more privileged entity can protect the PAC key management routine (e.g., a hypervisor or EL2), which however is out of the scope for our current design. Our threat model also assumes that the basic defenses against code injection and modification are in place (e.g., DEP and read-only code). This assumption is realistic because such defenses are universally enabled on modern OSES. They are needed for protecting code instrumented by PTAuth (e.g., inline checks cannot be removed or uninstrumented code cannot be injected).

In contrast to previous work [38,43,52,56,59], we assume the possibility of arbitrary memory overwrite, which allows an attacker to corrupt the metadata of our system. Previous works on temporal safety that rely on metadata either assume there is no spatial violation in the program or spatial safety is enforced by external techniques to protect the metadata.

An attacker (in the user-level) is unable to generate a valid AC since she does not have access to the keys stored in the system registers in EL1. An attacker may attempt to perform AC reuse attacks. However, our threat model assumes that attackers cannot perform arbitrary memory read (i.e., leak valid AC and object ID in memory). This assumption is realistic in practice because leaking an AC and its corresponding object ID can be quite challenging because of ASLR and the rare nature of arbitrary memory read primitives. Based on previous research [34] and real-world attacks [9], attackers often do not have arbitrary memory read abilities when exploiting temporal memory errors. For example, WhatsApp double-free (CVE-2019-11932) and Internet Explorer use-after-free (CVE-2013-3893) vulnerabilities are exploited via memory overwrites. Arbitrary write allows attackers to bypass previous temporal safety protections. PTAuth remains robust even if such vulnerabilities exist.

3.3 Example Vulnerabilities

Before describing our points-to authentication scheme, we present three simple examples of temporal memory corruption below, which help explain why PAC can reliably detect them.

Use-after-free vulnerability: Figure 2 (a) is a typical example of UAF, where a pointer is used after its pointee has been freed. In this case, qtr, an alias of ptr, is used at Line 11 after ptr has been freed at Line 5. Although the programmer nullified the ptr at line 6, due to the aliasing, UAF still exists.

Double-free vulnerability: Figure 2 (b) shows a code snippet where a pointer can be freed twice, which may lead to undefined behaviors, including arbitrary memory writes.

Invalid-free vulnerability: Figure 2 (c) demonstrates a case where a pointer is freed while it is not pointing to the beginning of a buffer. This is a special type of temporal memory corruption [8, 43].

3.4 Points-to Authentication Scheme

Our authentication scheme applies to two types of data: objects and data pointers. Objects are dynamically allocated data on the heap. Data pointers reference the addresses of objects (we only consider pointers to heap objects in this paper). PTAuth verifies the identity of every object and the points-to relationship before it is accessed through a pointer. This verification relies on the AC (or authentication code) generated for the object and stored in its pointers.

The ID of an object is saved as inline metadata immediately before the object in memory (Figure 3). The ID establishes unique identities for objects and allows for binding pointers to their referenced objects (i.e., making the points-to relationship verifiable), which is essential for detecting temporal memory...
Figure 1: In our system, the application is instrumented by the LLVM pass of PTAuth. The points-to authentication is performed before the pointer load or store operations. A runtime library contains PAC instructions, is attached to the instrumented application to perform the security checks at runtime. The output of the system is a protected executable binary. At runtime, after an allocation, $AC$ is generated for the pointer. Before dereferencing a pointer, the $AC$ is authenticated to ensure that it is not a dangling pointer.

$$\text{int}^* \text{ptr} = (\text{int}^*) \text{malloc}(10);$$

$AC_a = \text{PACIA} (\text{Address}_a, \text{ID}_a)$

$\text{AUTIA} (\text{Address}_a, \text{ID}_a)$

Figure 2: Examples of double-free, use-after-free and invalid-free temporal memory corruptions, which are undetectable by pointer integrity approaches but detectable by PTAuth.

(a) Use-After-Free

(b) Double-free

(c) Invalid-Free

corruptions. Figure 3 (lower right) shows two objects in the heap with their metadata. The ID is a 64-bit random value generated at the allocation of the object. An $AC$ is 16-bit long and stored in the unused bits of a pointer (i.e., 48 effective bits in a pointer). Unlike the previous works such as DangerNull [38], which only protect pointers residing in the heap, PTAuth authenticates data pointers everywhere in memory, including heap, stack and global regions.

Next, we explain the definition and calculation of $AC$. We then discuss in §3.5 the runtime $AC$ generation and the checking mechanism.

Data Pointers: $AC$ essentially binds a data pointer to its pointee and makes the binding verifiable. $AC$ encodes: (1) the identity of the pointee object, and (2) the base address of the pointee. The ID and the base address together uniquely identify an object in time and space. This definition not only makes the points-to relationship easily verifiable, but also mitigates metadata reuse attacks. Figure 3 (bottom left) shows the computation of $AC$ using the PACIA instruction. PTAuth performs this computation when an object is allocated. When an object is deallocated or reaches the end of its life cycle, PTAuth simply invalidates its ID (setting it to zero). Upon each pointer dereference, PTAuth recomputes the $AC$ and compares it with the $AC$ stored in the pointer. A mismatch indicates a temporal memory safety violation. No temporal memory corruption can happen without failing the points-to authentication.

In our scheme, less memory is used for storing the metadata for both pointers and objects than most previous works. Furthermore, there is no assumption that the metadata cannot be tampered with. Last but not least, PTAuth can find the base address of an object reliably with the help of PAC. This is necessary for supporting pointer arithmetic operations, which may shift a pointer to the middle of its pointee, than thus, fail a naive authentication that simply takes the pointer value as the object base address. We discuss the details in §3.5.

The PAC instruction encrypts/signs the inputs (i.e., object
We do not consider or claim code pointer authentication as a way to thwart a broad range of attacks. PARTS [39] is a contribution to this work. For the rest of the paper, we focus on authenticating the points-to relationships between pointers and objects. Metadata of the object is allocated as an extra 8-byte memory during the allocation. The AC is stored in the unused bits, which is 16 bits.

ID and base address) using a data pointer keys (data.a or data.b) and saves the truncated ciphertext to the unused bits in the pointer. Therefore, unlike an object, PTAuth does not need to use extra space for storing AC for pointers. An AC is generated whenever a pointer takes a new value, which can happen at object allocation or when the pointer is re-assigned to another object (e.g., via the reference operator “\&”).

After a pointer becomes stale when its pointee is freed, any dereference of the dangling pointer will trigger an object ID mismatch, due to either the invalidated ID of the freed object, or a different ID of a new object allocated at the same location. Other temporal memory errors, such as double-free and invalid-free can be detected by PTAuth in the same way.

Code Pointers: Checking the integrity of code pointers is an intended use of PAC and is fairly straightforward. Unlike data pointers, we do not define our own AC for code pointers. PTAuth is fully compatible with the intended use of PAC for code pointers for preventing control flow hijacking attacks. They can be used together to thwart a broad range of attacks. We do not consider or claim code pointer authentication as a contribution to this work. For the rest of the paper, we focus on authenticating the points-to relationships while referring readers to the PAC documentation [12,16] and PARTS [39] for code pointer authentication.

3.5 Compiler-based Code Instrumentation & Runtime AC Checking

To apply the points-to authentication scheme to a given program, PTAuth takes the general approach of inline reference monitoring. Via a custom compilation pass added to LLVM [22], PTAuth instruments the program so that AC can be generated and checked at the right moments during program execution. The instrumentation is performed at the LLVM bitcode level, which is close to assembly code while retaining enough type and semantic information for our code analysis and instrumentation. The instrumentation sites are carefully selected to minimize the interception of program execution. Below we discuss in detail the code instrumentation needed for each type of operation on AC.

AC Generation: During runtime, PTAuth needs to generate AC for data pointers whenever a new points-to relationship is created. To this end, during compilation, PTAuth performs two types of instrumentation. First, it instruments all essential API for heap memory allocation, including malloc (the dynamic allocator for heap objects), calloc and realloc. PTAuth only works on user-space programs and we assume the ptmalloc allocator is used. This instrumentation allows PTAuth to intercept all memory allocations, where the object ID is generated and the AC for the pointer is computed as follows:

```
1 /* Computing AC for Data Pointer */
2 ID = RandomID() // 64-bit
3 AC = PACIA |B <BasePointer><ID>
```

Second, PTAuth instruments object deallocation sites, like free (heap object deallocation). At an object deallocation site, PTAuth simply sets the object ID to zero, which invalidates the object and thus prevents any further use of the object. Figure 3 (upper right) shows an example pointer and its AC. The base address and the ID of the pointee are used as the two inputs to the PACIA |B instruction to generate the AC:

AC Checking: PTAuth performs points-to authentication by checking the AC whenever a pointer-based data access happens (or a pointer reference occurs). During compilation, PTAuth instruments LLVM load and GetElementPtr instructions for pointers. For simplicity, we generally refer to both as load in our discussion.

PTAuth verifies the integrity of the pointer and authenticates the AC of the pointer value as follows:

```
1 /* Authenticating AC for Data Pointers */
2 ID = getID(Pointee) // Pointee is an object
3 AUTIA |B <BasePointer><ID>
```

Due to pointer arithmetics, a (legitimate) pointer may sometimes point to the middle, instead of the base, of its pointee. Therefore, during AC checking, PTAuth cannot simply use the value of the pointer as the base address of the to-be-accessed...
object. A naive solution to this problem is to use additional metadata for recording the object base address for each pointer. However, this not only increases space overhead but creates a more challenging problem of propagating the metadata as pointers are copied or moved.

PTAuth finds the base address of an object during runtime without requiring any additional metadata. For each AC checking, PTAuth, by default, uses the pointer value as the object base address. If the check fails, two possibilities arise. First, the pointer is valid but is pointing to the middle of its pointee (i.e., its value is not the base address, hence the mismatched AC). Second, the pointer is invalid and a temporal memory violation is about to happen. When encountering a failed AC check, PTAuth first assumes that the first possibility happened. It then starts a backward search from the current pointer location for the base of the object. This search terminates when (1) an AC match occurs (i.e., the correct Object ID and the base address are found), or (2) the search has exceeded the max distance or reached invalid memory, in which case a true temporal memory error is detected.

**Metadata propagation:** Thanks to our in-pointer storage of AC, when a pointer is copied or moved, the metadata of the pointer is automatically propagated without any special handling by PTAuth or any software. As for metadata for objects (i.e., IDs), they are not stored inside objects and thus are not automatically propagated during object duplication or movement. However, this is intended—object metadata should not be propagated when objects are copied or moved. This is because in our points-to authentication scheme, an object ID is assigned to and associated with the allocated buffer, rather than the data stored in that buffer. In contrast, previous works on temporal memory error detection, such as CETS [43], require special handling of metadata propagation at the cost of degraded runtime performance and limited data compatibility.

**Handling deallocation:** In contrast to pointer dereferencing, where a pointer can point to the middle of an object, for the deallocation procedure, the pointer should always point to the beginning of the object. Otherwise, invalid-free occurs, leading to undefined behaviors and temporal memory errors [8]. Based on this fact, PTAuth only performs one round of AC checking without the backward base address search. If the authentication fails at a deallocation site, it is either a double-free or an invalid-free error. If the authentication succeeds, PTAuth simply sets the object ID to zero (i.e., invalidation) and lets the program execution continue.

**Handling reallocation:** During reallocation, the base address of an object may or may not change depending on the size of the object and the layout of the memory. We handle reallocation by instrumenting realloc. If the base of an object has changed, the ID of the old object is nullified, a new ID is generated, and a new AC is computed for the new base pointer. In this case, the existing (stale) pointers to the old object are invalid and cannot be used anymore.

**External/uninstrumented Code:** During compilation time, PTAuth treats as a blackbox externally linked code or code that cannot be instrumented. This design enables backward and external compatibility. PTAuth instruments the entries to such blackboxes so that immediately before an object or pointer flows into a blackbox (e.g., as an argument to an external function call such as memcpy), PTAuth authenticates the pointer and then strips off its AC, which can be done efficiently using the XPAC instruction. Conversely, when a pointer returns from a blackbox, PTAuth generates the AC for it, whose subsequent uses are subject to checks.

### 3.6 Optimizations

**Unnecessary Checks:** We optimize the instrumentation strategy by avoiding insertions of unnecessary checks during compilation. The optimization is inspired by the fact that, for any valid pointer, UAF and other temporal memory violations cannot happen through the pointer until it is being freed or later. Therefore, it is not necessary to perform points-to authentication on any use of a pointer that can only take place before the pointer is freed. Obviously, detecting all such pointer uses in a program is an intractable problem [37, 49], which requires perfect alias analysis. However, we can solve this problem within the scope of a function by performing conservative intra-procedural analysis. By tracking a pointer’s def-use chain inside a function, we can identify a set of use sites where the pointer and its aliases have not been free or propagated out of the function. PTAuth can safely ignore these use sites during instrumentation i.e., no runtime check is needed. Figure 4 demonstrates an example of how redundant checks are removed by optimization. In this example, all checks on req up to Line 13 are unnecessary and are omitted by PTAuth. We also extend this optimization to the implementation level. Some frequently used glibc functions such as printf and strcpy never free pointers passed to them as parameters. Therefore, we whitelist such functions and allow the intra-procedural discovery of safe pointer uses to continue beyond such functions.

**Global objects:** Performing temporal checks on pointers to global objects is also unnecessary because such objects are never deallocated. PTAuth detects those address taken global objects that can be determined statically during the compile-time and remove the checks for them.

### 3.7 Design Comparison

In Table 2, we compare PTAuth with closely related works in terms of the use/check, management, and protection of the metadata. PTAuth uses inline metadata, which makes the access fast because no heavy lookup is needed. Thanks to the inline metadata, the memory overhead of PTAuth is low and there is no complex handling needed for pointer arithmetics.
4 Security Analysis

An attacker may attempt to evade PTAuth with the goal of causing temporal memory corruption without being detected. We analyze the possible attacks permitted by our threat model and explain how the design of PTAuth prevents them. Since PTAuth performs load-time authentication and our threat model assumes attackers capable of arbitrarily writing to data memory (e.g., by exploiting certain vulnerabilities), the attacker essentially needs to somehow generate the correct AC for the data pointer that she writes before the data is used by the target program or checked by PTAuth. We note that code inject or modification is not allowed under our threat model thanks to DEP and the read-only code region. We identify the following ways that attackers may try to forge the AC:

**Directly generating AC:** One intuitive evasion of PTAuth is to generate the AC for the attacker-supplied data, either offline or dynamically. Offline AC generation does not work because the set of keys used for calculating AC is dynamically generated for each program execution or process and is not static. Alternatively, the attacker may try to directly generate AC on the fly while the target program is running. This is impossible either because the PAC keys are stored in the special CPU register and not accessible from the user space, even if the attacker has the arbitrary memory read capability. Moreover, the attacker cannot inject code and thus cannot directly calculate AC using injected PAC instructions. Also, brute-force is not applicable in this context because one wrong guess can lead to a crash of the process.

**Reuse PAC instructions:** The attacker’s next possible move could be to reuse the existing PAC instructions already loaded in the memory (e.g., those used by PTAuth) for calculating AC on injected data. However, our system can easily get merged with the standard use of PAC for protecting code pointers as well. Therefore, code reuse attacks are prevented thanks to the code pointer integrity check by PAC (i.e., any corrupted return addresses or call/jump targets trigger authentication failures and are detected before the program control flow is hijacked).

**ID spray:** Another possible attack vector is spraying the ID into the object to misguide the dangling pointers that are pointing to the middle of object. The design of PTAuth considers this attack. Since the AC is bound to the beginning address of an object, even if the correct ID is found in the middle of object, authentication will be failed.

5 System Implementation

We built a prototype for the PTAuth system, including (i) a customized compiler for instrumenting and building PTAuth-enabled programs, (ii) a runtime library, linked to instrumented programs, for performing dynamic AC generation and authentication, and (iii) a set of bootloader and Linux patches necessary for configuring the CPU and enabling the PAC feature [15, 18]. All the system components are implemented in C/C++ with a small set of inline assemblies that directly use the PAC instructions. The PTAuth LLVM pass is approximately 2K lines of C++ code and the runtime library is 1K lines of C code. The current implementation supports C programs. It is based on ptmalloc memory allocator from glibc. All of the main APIs of the memory allocator such as malloc, calloc, realloc and free are supported in the current implementation.

**Customized Compiler:**

Our compiler is based on LLVM 6.0, which already has basic assembler and disassembler support for PAC on ARMv8.3-A. We built the code analysis and instrumentation logic (§3.5) into an LLVM transform pass. It operates on the LLVM bitcode IR. At each instrumentation site, such as pointer load and store, it inserts a call, based on the type of the instrumented instruction, to the PTAuth runtime library.

**Runtime Library:** The runtime AC checking logic is built into a dynamically linkable library. It exposes the call gates for the instrumented code to invoke the AC generation and authentication routines. These routines calculate or check AC for different scenarios, as described in §3.4 and §3.5. The library does not maintain any data internally thanks to the in-place storage of AC and the OS-managed PAC keys. Therefore, no data inside the library needs to be protected or verified. However, we do enable code pointer integrity checking using PAC when compiling the library, which ensures that no control flow hijacking can occur during the execution of the library.
OS and bootloader patches: By default, PAC instructions (except for PACGA and XPAC) are disabled by CPU. To use all PAC instructions and the corresponding key slots, the OS needs to set to 1 the EnIA, EnIB, EnDA, EnDB fields in the SCTLR_EL1 register. The OS also needs to generate and maintain the PAC keys for each process. Only the OS (or code running at EL1) can perform these tasks. We implemented these tasks via a small patch to Linux. We also used a customized bootloader [18], which enables the PAC feature during system boot by setting SCR_EL3.APK and SCR_EL3.API to 1. We built the customized bootloader and the patched Linux into a system image, which was then installed on the ARMv8.3-A FVP. As discussed in §2.3, FVP is the functional-accurate whole-system simulator for ARM architectures, which emulates processors, memory, and peripherals. We used this prototype and environment for evaluating PTAuth.

6 Evaluation

In this section, we evaluate the prototype of PTAuth in terms of security, runtime overhead and memory overhead. The security experiments were conducted on the FVP simulator. The performance experiments were performed on a Raspberry Pi 4 with ARMv8-A Cortex A53 processor (1.5GHz) and 4GB memory, running Gentoo 64-bit Linux (v4.19). We explain this experiment setup in §6.1.

Our experiments aim to show: (i) whether PTAuth detects temporal memory corruptions such as after-free, double-free and invalid-free; (ii) how much performance overhead PTAuth incurs during runtime; (iii) how much memory overhead PTAuth incurs during runtime. We used Juliet test suite [27] and four real CVE for security experiments. To evaluate the runtime and space overhead, we used SPEC CPU2006 benchmarks.

6.1 Experiment Setup and Methodology

At the time of writing this paper, no publicly available development board supports ARMv8.3 instructions. Although Apple’s A12 Bionic SoC supports PAC instructions, it is proprietary and we were not able to instrument and run the benchmarks on top of that. In fact, PAC on iPhone is currently reserved for the OS and not officially supported in apps yet. The latest version of Xcode (the compilation toolchain for iOS apps) still does not build app executables (*.ipa) that target the ARM64e architecture (required for using PAC instructions).

We performed the security-oriented experiments on the FVP simulator that supports PAC. However, we were not able to run the performance benchmarks (e.g., SPEC CPU2006) on FVP. Due to their heavy workloads, they often crash or halt the simulator. Therefore, we conducted the performance evaluation on a Raspberry Pi 4 (ARMv8-A Cortex A53), which is much more powerful than FVP but does not have hardware support for PAC. We emulated as software functions the three PAC instructions used by PTAuth, namely PACIA, AUTIA, and XPAC. The syntax of these functions, including output and input is the same as the original PAC instructions. However, we did not implement the cryptographic algorithms such as QARMA in the emulated PAC instructions. Clearly, software implementation of QARMA would be much slower than hardware implementation. This could prevent us from getting an accurate estimate of the performance overhead. Instead, we used xor, or, and, shift, load and store operations in the software implementation to simulate the encryption and AC computation, whose runtime overhead should be comparable to PAC’s hardware-based encryption. Figure 5 demonstrates the implementation of PACIA instruction as a function.
Figure 6: When the PACENABLED flag is enabled during the compile-time, actual PAC instructions are generated for the final binary. Otherwise, software implementation of the corresponding instructions is invoked. This implementation helps to test the design on an SoC that does not support the ARMv8.3 instruction set.

| Vulnerability          | CWE | # of Prog. | PTAUTH | PAC / PARTS [39] |
|------------------------|-----|------------|--------|------------------|
| Double-Free            | 415 | 50         | ●      | ○                |
| Use-After-Free         | 416 | 50         | ●      | ○                |
| Invalid-Free           | 761 | 50         | ●      | ○                |

Table 3: Selection of 150 vulnerable programs from the Juliet Test Suite and detection results.

emulated PAC or hardware-based PAC instructions. Figure 6 shows an example of the software emulation for PACIA instruction. The security experiments were conducted using the FVP with our system image, which uses the patched bootloader and OS.

6.2 Security Evaluation

Temporal memory corruption detection: Our security test set contains 150 C programs selected from the NIST Juliet test suite [27]. We chose the Juliet Suite for two reasons. First, it is one of the largest test suites that contains both vulnerable and non-vulnerable versions of programs. The vulnerable programs, covering common types of temporal memory corruptions, are ideal for our security evaluation. The non-vulnerable/patched counterparts are useful for our compatibility testing. Second, unlike the generic CPU benchmarks, the test programs in Juliet are not too big or computationally demanding, which is preferred for our security evaluation because the FVP is a whole-system simulator and runs much slower than real hardware. We tried running larger and heavier benchmarks on FVP but they often crash or halt the simulator. In contrast, the Juliet programs run smoothly on FVP.

Our selection of the 150 Juliet tests covers double-free, use-after-free and invalid-free bugs. The first two columns of Table 3 show their CWE (Common Weakness Enumeration) IDs and the number of selected tests for each vulnerability category. When running with PTAuth enabled, the vulnerable programs all terminated immediately before the bug is triggered. The result shows that PTAuth achieved a 100% detection accuracy without missing a single case in any vulnerability category. This experiment also shows that the standard use of pointer authentication is not helpful in detecting temporal violations. As it can be seen in Table 3, none of the vulnerabilities can be detected by PAC or PARTS [39], which are based on simple pointer value authentication. We also ran the non-vulnerable version of the test programs with PTAuth enabled. All programs finished properly without any crash or halt. This result shows that PTAuth does not cause any false alerts nor break the normal functioning of non-vulnerable programs.

Case study of real-world vulnerabilities: In order to evaluate the effectiveness of our system on real-world vulnerabilities, we selected four recent CVEs and used them to test PTAuth. As shown in Table 4, our experiments demonstrate that these CVEs cannot be exploited in PTAuth. For instance, in CVE-2019-5481, an attacker sends a large crafted request to Curl, which realloc() fails to handle. On the exit path, the pointer is freed. At the cleaning phase, the pointer is freed one more time. Since these two steps are far from each other, a programmer can easily miss that. However, when PTAuth is enabled, the ID of the object has changed, and thus, the pointer cannot be authenticated anymore and double-free is detected.

In CVE-2019-7317, a pointer is passed as an argument to a function. Since the type of function is not known at compile time, it is difficult to track if the pointer is freed in the destination function or not. The previous techniques that rely on inter-procedural analysis might miss this bug. However, our optimization safely assumes that the destination function may free the pointer. Therefore, optimization is stopped at this point. As it can be seen in Figure 7, at Line 5, that png_image_free_function function can be called indirectly and arg pointer (an alias of image) is freed there. At Line 7, the image pointer is used, causing UAF. In PTAuth, all the aliases of a pointer contain AC and cannot be authenticated when the pointee object has been freed and its ID invalidated.

Robustness evaluation: We created a small set of programs that contain both temporal and spatial memory corruptions to evaluate the robustness of PTAuth. This scenario is analogous to the real-world attacks where an attacker can exploit arbitrary memory write and temporal memory corruptions. We selected 30 programs from Juliet test suite in 3 different categories. Then, we injected memory overwrite vulnerabilities

```
1  #if PACENABLED
2  asm {  
3    "mov %x0,%0\n"
4   :
5    :="r" (ptr);}
6  asm{  
7    "pacia %x0, %x1\n"
8    :="r" (ptr)
9    :="r" (id));
10  #else
11  ptr = _pacia(ptr,id);
12  #endif
```
such as buffer-overflow to them, which allow an attacker to overwrite the metadata of objects and pointers. This primitive is enough to bypass previous protections such as CETS that simply compare the plain ID of the key and object. However, it cannot bypass PTAuth because attackers cannot generate valid AC without the secret PAC key. As expected, we triggered those vulnerabilities and PTAuth was able detect and prevent them.

6.3 Performance Evaluation

Runtime overhead: As stated earlier, we could not run the heavy benchmarks on the FVP simulator. Therefore, we replaced the PAC instructions with the software emulated functions and conducted the performance experiments on the real hardware.

We selected SPEC CPU2006 benchmarks for our performance evaluation. These benchmarks are appropriate for testing PTAuth since they are memory- and CPU-intensive. Figure 8 shows the runtime overhead, which varies across different benchmarks. This variation is due to the fact that in some benchmarks the numbers of data pointers and objects are more than those in the other benchmarks. For instance, although mcf is a fairly small program, it contains many data pointers. This means that more checks are required to protect this application.

We compared PTAuth with the closely related works, including CRCCount [52], DangSan [56], and CETS [43]. These prior techniques are either based on pointer invalidation or object (lock) invalidation. In our comparison, we skipped DangNull [38] because DangSan outperforms it. Since the source code of CRCCount is not available, we used the reported number from the paper for comparison. The current prototypes of DangSan and CETS are not compatible with ARM architecture. Our comparison is based on the reported numbers. We note that CETS was evaluated on only seven benchmarks from SPEC CPU2006, as shown in Figure 8.

We used nine C benchmarks that are both compatible with our current implementations and have been used in previous works. The geometric mean overhead of PTAuth on all benchmarks is 26.0%. The number for CRCCount is around 5.0% and 1.0% for DangSan. CETS did not provide runtime overhead for two benchmarks but for the provided ones the geometric mean overhead is 10.0%. We should note that the main overhead of our current implementation is that the actual PAC instructions are not used and we instead used the emulated functions due to the unavailability of hardware. We believe when using the actual PAC instructions, the overhead of our system should be much lower than the current results.

PTAuth does not rely on external mechanisms (such as bound checkers) to protect the metadata, whereas the previous works do and, in turn, incur additional runtime overhead. In order to show the impact of protecting the metadata of DangSan, CRCCount and CETS, we added the reported runtime overhead of SoftBound [42] to the overhead of DangSan, CRCCount and CETS. Figure 10 shows the impact of using SoftBound along with the three techniques. It also shows the overhead of PTAuth, which is much lower, thanks to PTAuth’s ability to protect its metadata by itself.

Memory overhead: The only source of memory overhead in our design is the extra 8-byte memory allocated for storing each object ID. Since the metadata for the pointers is stored in the unused bits of the pointer, therefore, no extra memory is needed to store AC. Furthermore, the memory overhead in our system is removed thanks to the following optimization. Based on our observation, the ptmalloc allocator in the glibc of Linux appends extra paddings when the object size is not 32-byte aligned. For instance, if an object with the size of 16 bytes is allocated, it is padded to 32 bytes. Thus, when the size of the allocation is not aligned to 32 bytes and at least 8 bytes padding is available, the extra padding bytes are used for storing the object ID, without requiring additional memory space.

To evaluate the overall memory overhead, we measured

```c
#include <stdio.h>

int main() {
    int result = 0;
    if (result != 0) {
        // calling png_image_free_function()
        indirect
        result = function(arg);
    }
    return result;
}
```
the maximum resident set size (RSS) of SPEC CPU2006 benchmarks. This metric was used by other works as well. Then we could have a fair comparison. RSS is the amount of space held by a process in physical memory. We collected the peak amount of memory for each process as maximum RSS. Figure 9 illustrates the memory overhead caused by PTAuth on each benchmark. The geometric mean is about 0.002%. This number is 1.0% for CRCount and 15.0% for the DangSan. CETS did not report any memory overhead. To have a fair comparison, we used the maximum RSS numbers, as reported in CRCount paper. However, we believe that mean RSS would be a more precise metric to evaluate the memory overhead of such systems. The main reason is that the memory overhead for these systems heavily depends on the number of objects, pointers and the metadata. Maximum RSS does not necessarily reflect the number of pointers and objects in the memory. For instance, the memory overhead for that part of the code that allocates many small objects is higher than that part which allocates a few large objects. Therefore, More objects and pointers generate more overhead. However, based on maximum RSS, the large objects play more important roles in measuring the overhead. Therefore, we measured the overhead of our system based on mean RSS as well, which is approximately 1.0%.

7 Discussion and Limitation

In this section, we elaborate on the limitation of our design and implementation.

Multi-threading: The current prototype does not support multi-threaded applications. This is mainly because of updating the metadata and freeing the pointers. This task should be performed atomically. When a pointer is freed, the operation of free and updating ID of the object should be performed consecutively. Otherwise, in a race condition situation, use-after-free or double-free might take place.

Stack use-after-free: Although temporal issues often happen in the heap due to the dynamic memory allocation, stack use-after-free is also possible when the address of an object in the stack is stored in a global pointer. Since allocation and deallocation steps in stack are different from heap, they require special care. For instance, by intra-procedural analysis, the allocated objects in the stack frame that are address taken should be identified. Then an extra 8-byte memory needs to be allocated before the address taken object. This extra memory is used as metadata and should be allocated in the prologue phase of stack creation. For the pointers, no special consideration is needed because the metadata is stored in the unused bits. In the end, in the epilogue phase, all the metadata of objects should be invalidated. Since deallocation of stack frame is caused by return operations, double-free bugs are not applicable to stack. PTAuth current design and implementation does not detect stack use-after-free.

PAC instructions: In the current implementation, we have used both PAC instructions and the software emulated implementation of the instructions. We used the FVP simulator to run the PAC instruction. However, FVP is not a performance aware simulator. It does not model cycle timing and all the instructions are executed in one processor clock cycle [19]. We also observed that large benchmarks halt the FVP which prevented us from running performance experiments on it. Since A12 Soc is proprietary and there is no public SoC available to test the implementation, the reported runtime overhead is anticipated to be different in real hardware. In other words, the actual PAC instructions are expected to be faster than the software emulated instructions.

We leave these limitations for future work when the real hardware is available.
8 Related work

Safe C: Memory corruption bugs are highly diverse and commonly targeted by software attacks [55]. Prior work introduced memory safety to the C language via a safe type system [33, 36, 44, 54]. These safe languages are immune to temporal vulnerabilities. However, they either impose a significant amount of memory and runtime overhead or they are not applicable to protect legacy C/C++ codes. For instance, Cyclone [36] is a safe dialect of C which is not applicable to protect legacy codes. It is no longer supported but several ideas of Cyclone have been implemented in Rust [2, 6]. CCured needs some annotations by the programmer. It also uses fat pointers to store metadata which breaks the application binary interface (ABI).

Safe memory allocator: These systems prevent allocated objects from ending up at the same address of freed objects [24, 26, 46, 53]. For instance, DieHard [26] and DieHarder [46] randomize the locations of allocated objects in the heap and consequently provides probabilistic temporal memory safety (i.e., making object reuse or replacement difficult). Partition-Alloc [5] and Internet Explorer isolated heap [7] allocators prevent memory reuse by allocating objects of different types or sizes in separate buckets. Although these schemes have low runtime overhead, it has been shown that they can be bypassed on targeted attacks [11, 35]. Moreover, they suffer from a huge memory overhead caused by memory fragmentation.

Memory error detectors: Memory error detectors [28, 45, 50] are widely used among developers. However, due to the high overhead, they are only suitable for debugging or non-production use. AddressSanitizer [50] is a memory error detector that creates shadow memory and red zones around objects. It detects out-of-bounds accesses in heap, stack, and global objects, as well as use-after-free bugs. However, it provides a probabilistic detection system for use-after-free bugs which is susceptible to bypass [57].

Pointer invalidation: Another line of work focused on pointer invalidation. DangNull [38], DangSan [56], FreeSentry [59] and pSweeper [40] explicitly invalidate all the pointers to an object when the lifetime of the object is finished. CRCount [52] uses a reference counting approach for counting the number of pointers to an object. When there is no pointer to an object, then it is freed. In this approach, the pointers are invalidated implicitly during the runtime of the program. This approach suffers from memory leak issue since some pointers are never invalidated. Consequently, the objects will reside in memory for a long time. In general, pointer invalidation systems need to keep a huge amount of metadata in the memory to track the relationship between pointers and objects. Inevitably, those metadata are prone to corruption.

Pointer dereference validation: Some other approaches similar to our design, detect and prevent temporal corruption bugs by pointer dereference validation [29, 43, 58]. CETS [43] provides temporal safety by assigning a unique identifier to each object and its pointers. The main challenge in this scheme is that extra metadata for the pointers should be stored in the memory. Also, a unique identifier should be assigned to each object and its pointers. Since these metadata are stored disjointly, obtaining these information efficiently during the runtime is challenging. In order to tackle this problem, in our design, we proposed an inline metadata scheme for both pointers and objects. However, inline metadata is prone to corruption by linear overflow. To address this problem, we used PAC to guarantee the integrity of the metadata before using them. To sum up, our approach reduces the high look-up table costs for loading the metadata and provides integrity of the metadata in a unified design.

Hardware-assisted schemes: Similar to PTAuth, there are some approaches that take advantage of hardware to provide temporal safety. Oscar [31], which is the following work of [32], is a page permission-based scheme to prevent temporal memory safety violations in the heap. Basically, Oscar improves the original idea of allocating each object in a separate page (similar to PageHeap and Electric Fence [3, 4]) to prevent UAF vulnerabilities.

Another line of work relies on hardware to provide spatial and temporal protections. Hardware-assisted AddressSanitizer (HWASAN) [14, 51] is the following work of AddressSanitizer. HWASAN uses address tagging feature [1] to implement a memory safety tool, similar to AddressSanitizer. Memory Tagging Extension (MTE) [17] has been introduced in ARMv8.5 for providing spatial and temporal safety. However, the hardware is not available yet. Intel MPX [47] was introduced by Intel to provide spatial safety. However, due to the high-overhead, it was discontinued by the maintainers.

9 Conclusion

We presented a resilient and efficient points-to authentication scheme called PTAuth, for detecting temporal memory corruptions. By defining the authentication codes (AC) for pointers, our scheme allows for convenient and simultaneous checking of metadata integrity and identities when they are being accessed. The unified verification of the two properties (integrity and identity) enables the unified detection of all kinds of temporal memory corruptions in the heap. PTAuth uses PAC on ARMv8.3-A as a basic encryption/signing primitive during AC calculation, which is fast and secure thanks to the hardware-level support. PTAuth contains: (i) a customized compiler for instrumenting programs with necessary inline checks, (ii) a runtime library for AC generation and authentication, and (iii) a set of OS patches for PAC-related CPU configuration. Our evaluation using 150 vulnerable programs shows that PTAuth detects the temporal memory corruptions from all 3 categories, and incur overhead comparable to previous memory error detectors.
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