THEME ARTICLE: SECURITY AND PRIVACY-PRESERVING EXECUTION ENVIRONMENTS

Persistent Memory Security Threats to Interprocess Isolation

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Persistent memory object (PMO) is a general system abstraction for holding persistent data in persistent main memory, managed by an operating system. A PMO programming model breaks interprocess isolation as it results in the sharing of persistent data between two processes as they alternatively access the same PMO. In this article, we discuss security implications of a PMO model. We demonstrate that the model enables one process to affect execution of another process, even without sharing a PMO over time. This allows an adversary to launch inter-PMO security attacks if two processes are linked via other unshared PMOs. We present formalization of inter-PMO attacks, their examples, and potential strategies to defend against them.

The release of a dual In-line memory modules (DIMM)-compatible Intel Optane PMem in 2018 enabled the incorporation of persistent memory (PM) into main memory. Although Intel recently discontinued Optane PMem, alternative products, such as Kioxia FL6[1] or Compute Express Link (CXL)-attached solid-state drives, are appearing. Compared to dynamic random-access memory (DRAM), PM provides higher density, better scaling prospect, nonvolatility, and lower static power consumption, while providing byte addressability and access latencies that are not much slower. Consequently, PM blurs the boundary of memory and storage.

When integrating it to computer system, one way to view PM is as persistent main memory used to host persistent data structures encapsulated in *objects* that are managed by the OS. These persistent memory objects (PMOs) were initially proposed in Yuanchao et al.[2] and used in recent works, e.g., in Yuanchao et al.[3] There are only a few studies addressing the security threats arising from PMO model, i.e., using PM as system objects hosting persistent data. For example, Yuanchao et al.[2] and Yuanchao et al.[3] look into reducing the exposure window of PMOs and PMO space layout randomization, however, they did not analyze which threats were possible and the situations under which the protection could be effective. A recent work[4] elaborates on the security threats stemming from the PMO model by showcasing *interprocess attacks* where one process (*payload*) successfully affects the execution of another process (*victim*) by overwriting the pointers of a PMO shared between them. Because of the long lifespan of a PMO, the attack does not require simultaneous PMO sharing; successive sharing over time (even across system boots) is sufficient.

The interprocess attack described in Mustafa et al.[4] still requires the payload and the victim to share a common PMO (simultaneously or successively over time). In this article, we demonstrate that an adversary can launch successful attacks on a victim even when they *do not share* a PMO, *whether simultaneously or over time*. We refer to this new attack as an *inter-PMO* attack. The attack only requires a connectivity path of PMOs between processes including the payload and the victim, and exploits the path to propagate corruption. By relaxing the requirement of a PMO needed to be shared in the interprocess attack,[4] the new attack significantly expands the capability of an adversary and warrants the need to protect all PMOs, irrespective of whether they are shared or not between the payload and the victim.

This article makes the following contributions. 1) We present inter-PMO attacks by defining them and analyzing the necessary requirements for them to occur, 2) present two examples of inter-PMO data-disclosure attacks, 3) present a step-by-step process to implement

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an example in a controlled environment, 4) evaluate the success rate of the implemented attack, and 5) discuss potential defense strategies.

BACKGROUND

PMO

A PMO is a general system abstraction for holding persistent data managed by an operating system (OS).[2] PMO data are not backed by files and may permanently reside in physical memory. The data in a PMO are held in regular data structures, hence, they may contain complex data types and pointers and are accessible directly with load-and-store instructions, unlike files.[1] The OS may provide file system-like namespace and permission settings to PMOs so that data in a PMO can be reusable across process lifetimes, and basic access control can be provided.

The key primitives for a PMO are *attach()*, *detach()*, and *psync()* system calls.[5] As a PMO already resides in physical memory and its data are already in data structure form, for a process to work on PMO data, it calls the *attach()* system call to map the PMO into its address space. Once attached, the process can access it with regular loads/stores, without involving the OS. *psync()* persists PMO updates in a crash-consistent way. *detach()* unmaps the PMO from the address space, making it inaccessible. After detachment, any load/store to the address region where the PMO used to map, result in protection faults.

Just like a file, a PMO may outlast a process' lifetime; it is conceivable that it will be attached and accessed by multiple processes at different times (or simultaneously read). Similarly, a single process may attach and access multiple PMOs simultaneously. When multiple processes alternatingly access a file, a process may make changes to the file that affect other processes. The same can occur to a PMO accessed by multiple processes. However, a PMO is mapped directly to the address space, hence, a change to PMO data by one process directly affects the address space of another process.

Security Implications of PM Versus Files

PMOs are expected to hold data structures, making them pointer rich. On the contrary, files are normally used to hold data (but can also be used to hold data structures, although less commonly). As a file contains no pointers, cross-process attacks are much harder to carry out. Pointers are attractive targets for attacks, which makes PM protection more important.

Also, data placed in a PMO-resident data structure are more tightly coupled with the execution flow of a process as they can be accessed with regular load/store instructions. Even nonpointer data in PMOs are more likely to be directly used to determine program control flow, making them attractive attack targets. In contrast, data from files are first deserialized and placed in data structures before being used in a process' execution flow.

Finally, unlike PMOs, file data are managed directly by the OS, any access (read/write) requires system calls, and the OS can perform security checks when serving the system calls. In contrast, PMO data can be manipulated directly by loads/stores transparent to the OS.

The combination of longevity, direct-byte addressability, and uncoordinated shared access distinguishes PMOs from both DRAM and traditional storage for memory protection in terms of vulnerability and consequences of security breaches as well as opportunities for novel solutions.

PREVIOUS WORK

Many prior studies have focused on the security vulnerabilities of PM fabric itself, rather than the PMO model. To address data remanence due to nonvolatility, PM encryption was proposed, e.g., in Pengfei et al.[6] and Pengfei et al.[7] The limited write endurance of PM may lead to early wear out if the attacker is allowed to write to them excessively. Hence, preventing redundant writes[8] and wear leveling are critical.

However, PM vulnerabilities go beyond just the fabric itself; hosting persistent data as in the PMO model, introduces new vulnerabilities while PM data are in active use. Memory exposure reduction and randomization[2] protects PMOs by reducing their exposure window (by attaching only when needed for access and detaching afterward) and hence, the attack surface. The authors proposed splitting the page table to accelerate attach and the PMO space layout randomization (PSLR), where the PMO is mapped to a different randomized location at each attach. Another work[3] focuses on mapping PMOs into separate domains to leverage domain protection such as Intel memory protection key. The intent was to restrict accesses to PMOs only to threads that access them. Both works[2,3] seek to make *unauthorized accesses* to PMOs difficult *for the process accessing the PMO*.

A recent work by Mustafa et al.[4] showed that a vulnerable (i.e., *payload*) process with PMO access can be used by an attacker to launch an attack on a different (i.e., *victim*) process that shares the same PMO successively over time. This article exposes that such a requirement is indeed unnecessary, i.e., that a security attack can be launched even when there is no shared PMO between the payload and victim.

THREAT MODEL

We consider a threat model where a process, referred to as victim, has no known memory safety vulnerabilities that can be exploited by adversary. Another process, referred to as *payload*, has memory safety vulnerabilities that the adversary can exploit. A third kind of process, referred to as *transmitter*, shares a PMO with the payload and a different one with the victim. Transmitters are not assumed to have memory safety vulnerabilities. An attack may start with the attacker exploiting some vulnerabilities in the payload, and transmit memory corruption over transmitters, to eventually affect the execution of the victim. This threat model is different from Mustafa et al.,[4] where a shared PMO is required between the payload and the victim.

The goal of an adversary is to use the payload process to compromise the victim process. We assume that an adversary knows the addresses, data structures, and layout of the PMOs that are a part of the chain of transmitters but have no legit access to any of them. We assume that data structures in PMOs may contain buffers and pointers, and that the payload process code may have regular known vulnerabilities (e.g., buffer overflow, integer overflow, format string, and so on). We assume that a trusted system software, such as the OS, manages address space isolation between processes. PMOs are also managed by the OS, which applies permission checking while granting access to a PMO. This implies that access to a detached PMO is not permitted and results in segmentation fault. However, a process can read and write a legally attached PMO.

POINTER CLASSIFICATION

Based on the addressing mechanism, either absolute or relative pointers can be used to access PMOs and the data structures they hold. An absolute pointer contains the virtual address, e.g., in Mnemosyne.[9] An absolute pointer is fast to dereference because it relies on the traditional address translation mechanism. However, it makes PMO space layout randomization[2] costly; any time the PMO is mapped to a different virtual address region, pointers in the PMO must be rewritten accordingly. Finally, if multiple processes are allowed to simultaneously share a PMO, absolute pointers require the PMO to be mapped to the same virtual address range in all processes.

Alternatively, relative pointers can be used that combine a PMO ID and an offset in the format of `object:offset`. A relative pointer can use a regular 64-bit format, or a fat pointer format where a pointer is represented by multiple fields. To dereference a pointer, a translation table is looked up to translate the system-wide unique PMO ID to its base virtual address,[2] and then the offset is added to it. Unlike absolute pointers, relocating such PMOs is straightforward to perform. Note that the example attacks we present are valid, irrespective of pointer type.

ATTACK EXPOSITION

To sketch an inter-PMO attack, the necessary condition is that the attacker can use the vulnerabilities of a payload process to affect the execution of the victim process through a series of PMOs and transmitters. In this section, we define several terms and specify the necessary requirements for such attacks to succeed.

First, we define $S\_PMO(p)$ as the set of PMOs accessed by process p during its lifetime, and $S\_Proc(x)$ as a set of processes (SoPs) *sharing* a PMO x, with sharing defined as successively accessing a PMO during the PMO's lifetime. Note that the lifetime of p and x are different, with x's lifetime expected to be long. If there exists a PMO x that is shared by two different processes, P_i and P_j, we state that there is a *link* between them via x

$$\begin{aligned}&L(P_i, P_j, x) \Rightarrow\\ &\exists x \in S\_PMO(P_i) : P_j \in S\_Proc(x).\end{aligned} \tag{1}$$

Figure 1 shows an example of five processes shown in circles, sharing the five PMOs shown in rectangles in Figure 1(a), with their respective "S_PMO" and "S_Proc" shown Figure 1(b).

We define the *path* between two different processes, "P_i" and "P_l," as a set of links connecting them. Multiple paths might exist between two processes. For example, Figure 1(b) shows a path between "P_0" and "P_2"

$$Path(P_0, P_2) = \{L(P_0, P_2, a)\}$$

and two paths between processes "P_0" and "P_4"

$$\{L(P_0, P_1, a), (P_1, P_4, b)\}$$

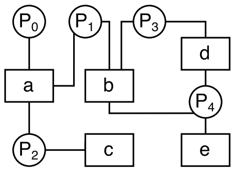
and

$$\{L(P_0, P_1, a), L(P_1, P_3, b), L(P_3, P_4, d)\}.$$

With $S\_PMO(p) \neq \emptyset$, there is always a path from a process p to itself.

PMO	S_Proc(PMO)	Proc	S_PMO(Proc)
a	$\{P_0, P_1, P_2\}$	P_0	{a}
b	$\{P_1, P_3, P_4\}$	P_1	{a, b}
c	$\{P_2\}$	P_2	{a, c}
d	$\{P_3, P_4\}$	P_3	{b, d}
e	$\{P_4\}$	P_4	{b, d, e}

(a)



(b)

FIGURE 1. (a) Example of S_PMO and S_Proc and (b) links between processes.

To find a path between two processes, P_i and P_l, we define SoPs initially with two members, P_i and P_l. We state that a path exists (PE) between two processes P_i and P_l if they are the same process, linked by a PMO x, or if there are distinct processes $P_j \notin SoP$ and $P_k \notin SoP$ such that P_i is linked to P_j via PMO y, P_k is linked to P_l via PMO z, and there exists a path between P_j and P_k.

$$\begin{aligned}
&PE(P_i, P_l, SoP) \Rightarrow \\
&(P_i = P_l) \vee L(P_i, P_l, x) \vee \\
&(\exists P_j \notin SoP \wedge P_k \notin SoP: \\
&(L(P_i, P_j, y) \wedge L(P_k, P_l, z) \\
&\wedge PE(P_j, P_k, SoP \bigcup \{P_j, P_k\}))).
\end{aligned} \tag{2}$$

Note that (2) is a recursive statement that resolves to *true* or *false*.

Conditions for a Successful Attack

If pointers within a PMO attached by a process are not corrupted, reads/writes on that PMO are performed at addresses as *intended* by the attaching process. However, if the pointers are corrupted, reads/writes can be diverted to *unintended* addresses within the same PMO or a different but attached PMO, depending on corruption. We denote $P_i \xrightarrow[x]{r/w} y$ to state that P_i's read/write to PMO x are diverted to PMO y. Furthermore, we denote $x \mapsto x'$ to indicate that PMO x becomes x' if it has data or pointers that have been corrupted.

An adversary can potentially launch a successful attack on a victim process V by controlling payload process PL if 1) a PE between PL and V [i.e., $PE(PL, V, \{PL, V\})$ is true], 2) a sequence of attach-detach sessions on PMOs by processes along the path successively follows the direction of links in the path, and 3) the PL is able to mislead processes along the path to perform *unintended* reads and writes, with PL-determined data, on PMOs of their respective links.

The first condition requires that at least one PE between the process PL and process V. If multiple PEs, the attacker has multiple options to attack V, with the shortest path potentially shortening the time to succeed. The second condition imposes order on the attach-detach sessions performed by processes. For example, consider "P_0" and "P_4" in Figure 1 as payload and victim processes, respectively. For the following path from "P_0" to "P_4":

$$\{L(P_0, P_1, a), L(P_1, P_3, b), L(P_3, P_4, d)\}$$

sequence of attach-detach sessions must be the same as the following for an attack to succeed:

$$1)\ P_0 \xrightarrow[a]{r/w} a \mapsto a' \quad 2)\ P_1 \xrightarrow[a']{r/w} b \mapsto b'$$

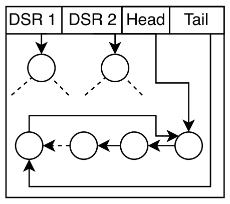
$$3)\ P_3 \xrightarrow[b']{r/w} d \mapsto d' \quad 4)\ P_4 \xrightarrow[d']{r/w} e \mapsto e'$$

where e is an unshared PMO of P_4. Note that we assume a process exclusively attaches PMOs in advance needed for both *intended* and *unintended* accesses. For example, for the second attach-detach session, P_1 attaches both a and b before reading/writing a.

The third condition requires that PL is able to mislead processes along the path to perform unintended writes, e.g., by diverting their control flow when they access a corrupted PMO.

EXAMPLE ATTACKS

This section sketches two example proof-of-concept attacks, with the first requiring transmitter control-flow hijacking while the second does not. The first example assumes that transmitter processes have memory vulnerabilities (e.g., buffer overflow) that can be exploited by an adversary. For both examples, consider SQLite,[10] a database engine that allows multiple processes to read the database simultaneously, but only one process can modify the database at any time. Suppose that SQLite is ported to PMOs for better performance, with each table represented by a persistent AVL tree. Figure 2(a) depicts a simple PMO that contains two B+ trees and a circular-linked list of free nodes. Two data structure root fields point to the root node of the trees, while the "Head" and "Tail" fields are pointers for the free list. Nodes are allocated/deallocated from/to the free list to perform insertion/deletion operation on trees. Figure 2(b) shows the library code to allocate a node from the free list. Suppose that the "DSRs" and "Head" and "Tail" fields are contiguously laid out at fixed offsets from the PMO base address. These fixed offsets allow a program to locate the free list and the data structure. We illustrate both data-disclosure attacks by using PMO-ported SQLite in Figure 3.



(a)

```
void* allocNode(){
lastNode=*Tail;
firstNode=*Head;
lastNode->fd=
     firstNode->fd;
*Head=firstNode->
     fd;
return firstNode;}
```

(b)

FIGURE 2. (a) PMO layout and (b) library code to allocate a node from the free list.

Data-Disclosure Attack by Hijacking Transmitter Processes

Let us assume that the source (Src) fields of PMO_0, PMO_1, PMO_2, and PMO_3 point to B+ trees representing `CS_faculty`, `Phys_faculty`, `Maths_faculty`, and `Bio_faculty` tables, respectively. The destination (Dst) fields of PMO_0, PMO_1, PMO_2, and PMO_3 points to B+ trees representing `CS_profs`, `Phys_profs`, `Maths_profs`, and `Bio_profs` tables, respectively. PMO_3 is private to victim P_3, and we expect that payload process P_0 cannot read data from PMO_3. Note that the following PE between the payload and victim.

$$\{(P_0, P_1, PMO_0), (P_1, P_2, PMO_1)\\ (P_2, P3, PMO_2)\}.$$

We demonstrate that payload can read from PMO_3 even though it is private to the victim and there is no shared PMO between the two processes.

The attack relies on following sequence of attach-detach sessions:

$$1)\ P_0 \xrightarrow[PMO_0]{r/w} PMO_0 \mapsto PMO_0'$$

$$2)\ P_1 \xrightarrow[PMO_0']{r/w} PMO_1 \mapsto PMO_1'$$

$$3)\ P_2 \xrightarrow[PMO_1']{r/w} PMO_2 \mapsto PMO_2'$$

$$4)\ P_3 \xrightarrow[PMO_2']{r/w} PMO_3 \mapsto PMO_3'$$

Note that the first attach-detach session performs *intended* reads/writes on PMO_0 while others perform *unintended* reads/writes on PMO_1, PMO_2, and PMO_3.

Consider that each process independently executes a query on an attached PMO to extract records from its faculty table (i.e., a source B+ tree) with the designation of professor and insert them into the professor table (i.e., a destination B+ tree). To launch the attack, an adversary first discovers function pointers fp_i in the volatile memory portion of P_i's address space and injects code blocks M_i, shown in Algorithm 1, in the heap region of P_i, where $i = 1, 2$. Note that Δ is address displacement between a free-list node and its fd field.

Algorithm 1. Pseudocode of M_i for $i = 1, 2$.

```
Require: addr($M_{i+1}$), addr($fp_{i+1}$), $\Delta$
1:  attach ($PMO_{i-1}$); attach($PMO_i$);
2:  *($PMO_{i-1}$.DSR_Src)
        =*($PMO_i$.DSR_Dst);
3:  firstNode=*($PMO_i$.Head);
4:  firstNode->$fd$=&($M_{i+1}$);
5:  *($PMO_i$.Tail)=&($fp_{i+1}$)$-\Delta$;
6:  psync($PMO_{i-1}$); psync($PMO_i$);
7:  detach($PMO_{i-1}$); detach($PMO_i$);
```

In the first attach-detach session, the adversary uses payload process "P_0" to attach "PMO_0," overwrites the forward pointer fd of the first node of its free list such that it points to M_1 and also overwrites the "Tail" field to point to the location of $fp_1 - \Delta^2$ (shown by the orange arrows in Figure 3). Finally, the adversary psyncs "PMO_0," detaches it, and waits.

In the second attach-detach session, "P_1" attaches "PMO_0" and "PMO_1" and allocates a node from the free list of "PMO_0." The "`allocNode()`" library function in Figure 2 removes the first node from the list. Line 2 of the code gets "`lastNode`" by dereferencing "`Tail`." As "`Tail`" was overwritten by the adversary, "`lastNode`" points to $fp_1 - \Delta$. The left side of the assignment statement in line 4, "`lastNode->fd`," points to a location pointed to by "`lastNode`" plus the address displacement between `lastNode` and its `fd` field, i.e., $(fp - \Delta) + \Delta = fp$. As "`firstNode->fd`" was set by the adversary to point to M_1, line 4 makes "fp" point to M_1. Finally, when the function pointer is used by the P_1, M_1 is executed. The execution of M_1 (see Algorithm 1) redirects $PMO_0.Src$ to the root node of destination Adelson-Velsky and Landis (AVL) tree of "PMO_1," as shown by the red arrow in Figure 3. M_1 also overwrites "PMO_1's" "Tail" field and the fd pointer of the first node in the free list, shown by orange arrows. Finally, M_1 psyncs "PMO_0" and "PMO_1" and detaches them.

In the same way, the third attach-detach session by P_2 redirects $PMO_1.Src$ to the root node of destination B+ tree of PMO_2 and overwrites the free-list pointers of PMO_2, while the fourth attach-detach session by P_3

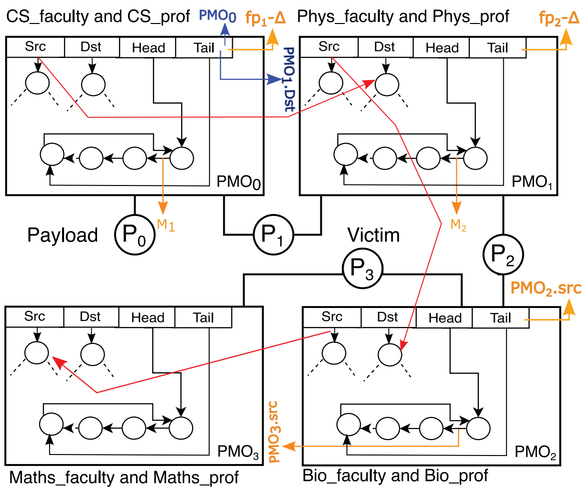


FIGURE 3. Setup for data-disclosure attack. No PMOs are shared between the payload and the victim. Src: source; Dst: destination.

redirects $PMO_2.Src$ to the root node of source B+ tree of PMO_3.

Now consider following the sequence of query execution. P_3 attaches PMO_2 and PMO_3, executing a query on the "Bio_faculty" table. As $PMO_2.Src$ was redirected, the query extracts records from the "Maths_faculty" table (i.e., PMO_3) of the victim and inserts them into the "Bio_prof" table. Afterward, P_3 psyncs and detaches both PMOs. Next, P_2 attaches PMO_1 and PMO_2, executes a query on the "Phys_faculty" table, which actually extracts records from the "Bio_prof" table and inserts them into the "Phys_prof" table (as $PMO_1.Src$ was redirected), including those records that were copied over from the "Maths_faculty" table. P_2 then psyncs and detaches both PMOs. Next, P_1 attaches PMO_0 and PMO_1, executes a query on the "CS_faculty" table, which actually extracts records from the "Phys_prof" table and inserts them into the "CS_prof" table (as $PMO_0.DSR\_Src$ was redirected). Finally, when P_1 psyncs and detaches PMO_0, process P_0 can attach PMO_0 to read records of the "Maths_prof" inserted into "CS_prof." The attack demonstrates that private data of the victim is disclosed to the attacker by payload process even when they do not share a PMO.

Data-Disclosure Attack Without Hijacking Transmitter Processes

The attack presented in the previous the section not only assumes memory vulnerabilities for transmitter processes, it also requires an adversary to find the address of function pointers in the volatile memory portion of the processes' address space. The attack may not succeed if either a function pointer is not found for any one of P_1 or P_2, or if the address of the function pointers or injected code blocks M_i changes (e.g., due to the relaunching of a process) anytime between address discovery and invocation of function pointers by processes. Furthermore, execution of code blocks injected into the heap region of a process is possible only if data execution prevention (DEP) is not supported on the platform. Otherwise, control flow of processes cannot be hijacked.

We observe that the aforementioned attack can be launched even without hijacking P_1 and P_2. In such a case, neither address discovery for function pointers nor code injection is needed, although attack steps become more convoluted but not impossible. As an example, "Payload P_0" can attach "PMO_0" and overwrite its "Tail" field with the address of "PMO_0," and the "Head" field with the address of "$PMO_1.Dst$," represented by the blue arrows in Figure 3. Assuming that the adversary knows the address of "PMO_1" and its layout, the address of "$PMO_1.Dst$" is calculated as $address(PMO_1) + Size(Src)$. Finally, "$P_0$" psyncs "$PMO_0$" and detaches it. When "P_1" attaches both "PMO_0" and "PMO_1" and allocates a node from the free list of "PMO_0," the "allocNode()" library function in Figure 2 dereferences "Tail" (line 2) to get "lastNode." As "Tail" was overwritten, "lastNode" actually points to "$PMO_0.Src$." Line 3 of "allocNode()" dereferences "Head" to get "firstNode." As "Head" was overwritten, "firstNode" points to the root node of destination B+ tree of "PMO_1." With an address displacement of zero between a node and its fd field, line 4 of "allocNode()" redirects "$PMO_0.Src$" to the root node of destination B+ tree of "PMO_1," as shown by the red arrows in Figure 3, achieving the same effect as in the first example attack.

EXECUTION OF CODE BLOCKS INJECTED INTO THE HEAP REGION OF A PROCESS IS POSSIBLE ONLY IF DATA EXECUTION PREVENTION (DEP) IS NOT SUPPORTED ON THE PLATFORM.

In the same way, "Payload" can perform the remaining two pointers' redirections, shown in Figure 3, by carefully overwriting "PMO_0," provided that the attach-detach sessions are performed in the desired sequence by other processes along the path between "P_0" and "P_3." (The details of these pointer redirections are not shown in the figure due to limited space.) Once all the pointer redirections are materialized, "Payload" can read private data of the victim in the same way as shown in the previous section.

ATTACK PROTOTYPING

We implemented a proof-of-concept inter-PMO attack, as illustrated in Figure 3. We implemented it on a Greenspan PMO system,[5] which was built on Linux 5.14.18 to support PMO creation and management. We built a simple, persistent database modeled after SQLite, consisting of the eight tables in Figure 3, i.e., two tables per PMO, representing one of four departments [i.e., CS (computer science), physics, bio (biology), and maths)]. Our implementation of processes "P_1," "P_2," and "P_3" executes queries to find records of professors from the *faculty_table* and inserts them into the *prof_table* of the respective departments. "P_0" repeatedly reads all records from the *prof_table* of the CS department. All processes other than "P_3" (i.e., *victim*) have buffer-overflow vulnerability.

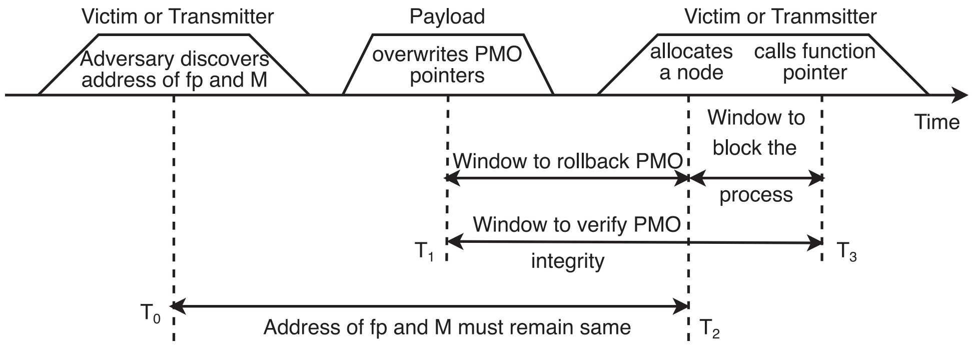


FIGURE 4. Steps to alter control flow of a process.

We implemented *step 1* of the attack, i.e., stitching the path (shown by the red arrows in Figure 3), by exploiting buffer-overflow vulnerability to inject shell code for M_1 and M_2 on the stack of "P_1" and "P_2," respectively. Note that this step can be completed in other ways (without code injection), e.g., by return-to-libc or return-oriented programming. In *step 2*, "P_0" (i.e., "Payload") repeatedly runs the query to read records from the *prof_table* of the CS department until it finds a record of a professor from the maths department (i.e., private "PMO_3" of the victim), indicating a successful attack.

THE ATTACK FAILS FOR LOWER TIME BUDGETS AS THE EXECUTION OF QUERIES BY P_1, P_2, AND P_3, AND THE PROPAGATION OF RESULTS TO PMO_0 TAKE AT LEAST 0.75 s.

Evaluation

We consider an attack successful when P_0 can obtain a record of a maths professor. We define *time budget* as the duration within which an attack is attempted, and *success rate* as the number of successful attacks divided by the total number of attack attempts for a given time budget. We observe that the success rate is one for time budgets greater than or equal to 0.75 s, and zero otherwise. This shows that 0.75 s is the minimum time for the example attack to succeed. The attack fails for lower time budgets as the execution of queries by P_1, P_2, and P_3, and the propagation of results to PMO_0 take at least 0.75 s. In a more realistic setting, with larger tables and processes also performing nondatabase accesses, the attack may take longer time to succeed.

POSSIBLE DEFENSE APPROACHES

Inter-PMO attacks based on hijacking of transmitter processes can be successful only if addresses of function pointers (fp_i) and injected code blocks (M_i) are not changed between two successive runs of the relevant process, i.e., P_1, P_2, or P_3. If PMO PSLR is enabled, the addresses of fp_i and M_i will be randomized on subsequent runs, and hence, the attack will fail to change the execution flow of transmitter processes and the victim. Furthermore, with M_i as the code blocks injected by an adversary in heap regions of processes, the attack can only be successful if DEP is not supported or enabled.

However, DEP does not protect against all kind of attacks. For instance, our example of inter-PMO attack *without hijacking* transmitter processes can succeed in the presence of DEP because it does not rely on code injection. On the other hand, it can also fail if PSLR is enabled as the address range at which PMOs are mapped in the address space of a process if it is randomized on the next attach call. However, some attack frameworks can breach PSLR or DEP defense schemes,[11] therefore, additional protection is needed to detect and foil inter-PMO attacks.

Figure 4 shows the timeline of the steps performed by "Payload" to alter the control flow of a process, as in the data-disclosure attack of Figure 3. The figure shows opportunities for detecting and foiling the attack.

First, the address of fp and M must remain the same between T_0 and T_2 for altering control flow of the target process. If the addresses change, the attack will corrupt PMO but not result in control-flow hijacking. Second, the window of time between T_1 and T_3 is the window of opportunity to detect the attack by verifying the integrity of the data structures in the PMO. In other words, the integrity check must be performed before T_3 because the control flow gets altered by that time. The integrity of data structure(s) can be checked by performing topology verification and data-structure-specific invariant checks. Third, in the window of time between T_1 and T_2, if a PMO-integrity problem is detected and a noncorrupted previous version exists, the PMO can be restored and an attack foiled. But, between T_2 and T_3, to foil the attack, the target process must be blocked/terminated.

CONCLUSION

In this article, we showed that multiple processes may access persistent data in an uncoordinated way under the PMO programming model. This allows a process to affect the execution of other processes even when they do not share a PMO. This makes PMOs a new tool for launching security attacks. We presented a formalization of such attacks, demonstrated and evaluated example attacks, and provided a discussion of possible defense approaches. The article made the case for increased memory safety protection when PM is used.

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