

SEVered: Subverting AMD's Virtual Machine Encryption

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ABSTRACT

AMD SEV is a hardware feature designed for the secure encryption of virtual machines. SEV aims to protect virtual machine memory not only from other malicious guests and physical attackers, but also from a possibly malicious hypervisor. This relieves cloud and virtual server customers from fully trusting their server providers and the hypervisors they are using. We present the design and implementation of SEVered, an attack from a malicious hypervisor capable of extracting the full contents of main memory in plaintext from SEV-encrypted virtual machines. SEVered neither requires physical access nor colluding virtual machines, but only relies on a remote communication service, such as a web server, running in the targeted virtual machine. We verify the effectiveness of SEVered on a recent AMD SEV-enabled server platform running different services, such as web or SSH servers, in encrypted virtual machines. With these examples, we demonstrate that SEVered reliably and efficiently extracts all memory contents even in scenarios where the targeted virtual machine is under high load.

CCS CONCEPTS

• Security and privacy → Virtualization and security;

KEYWORDS

AMD SEV, virtual machine encryption, page fault side channel, data extraction

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1 INTRODUCTION

As a common practice, cloud and virtual server customers conveniently run their services in Virtual Machines (VMs) remotely operated on the platforms of their server providers. The privileged Hypervisors (HVs) on these platforms ensure the logical separation of multiple VMs operating on the same hardware. Attackers have demonstrated that they are capable of circumventing this protection, achieving access to the memory of the VMs, e.g., with memory attacks via Coldboot [8] or Direct Memory Access (DMA) [3, 4, 6], or even gaining complete control of the HV [11, 14, 15]. However, the server provider running the HV poses the most obvious danger

to the VM's integrity and data confidentiality. Customers must rely on the trustworthiness of the providers and their HVs, since they can easily access all of the VMs' memory and identify sensitive data such as keys, passwords, or classified information.

To reduce the attack surface of virtualized systems towards malicious server providers, AMD introduced Secure Encrypted Virtualization (SEV) [2]. SEV is capable of transparently encrypting individual VMs using a Secure Processor (SP). The technology especially targets server systems and enables VMs to request encryption and receive proof about the encryption from the SP. The memory of each protected VM is encrypted within the SP based on an individual ephemeral key never leaving the SP. The implementation in hardware not only makes the systems resistant against memory attacks, but also prevents HVs from accessing sensitive VM data.

With SEVered, we demonstrate that it is nevertheless possible for a malicious HV to extract all memory of an SEV-encrypted VM in plaintext. We base SEVered on the observation that the page-wise encryption of main memory lacks integrity protection [2, 9, 10]. While the VM's Guest Virtual Address (GVA) to Guest Physical Address (GPA) translation is controlled by the VM itself and opaque to the HV, the HV remains responsible for the Second Level Address Translation (SLAT), meaning that it maintains the VM's GPA to Host Physical Address (HPA) mapping in main memory. This enables us to change the memory layout of the VM in the HV. We use this capability to trick a service in the VM, such as a web server, into returning arbitrary pages of the VM in plaintext upon the request of a resource from outside. We first identify the encrypted pages in memory corresponding to the resource, which the service returns as a response to a specific request. By repeatedly sending requests for the same resource to the service while re-mapping the identified memory pages, we extract all the VM's memory in plaintext. SEVered neither requires detailed knowledge of the target VM or service, nor a malicious process colluding from inside the VM. Our attack is also resistant to noise, i.e., concurrent activity in the target VM, and dynamically adapts to different noise levels.

2 ATTACK METHOD

Our target is an AMD SEV-enabled platform which runs an attacker-controlled HV and one or more VMs as shown in Figure 1. Our target VM's memory is fully encrypted by SEV. While being able to target multiple VMs at the same time, we describe our attack for a single VM. Inside the target VM, we assume presence of the following **components**:

Service. A process running inside the VM offering a *resource* via a publicly accessible remote connection. Common examples are HTTP, SSH, FTP or mail servers.

Resource. Data in VM memory that is remotely readable through a *service*. A resource can spread over one or more memory

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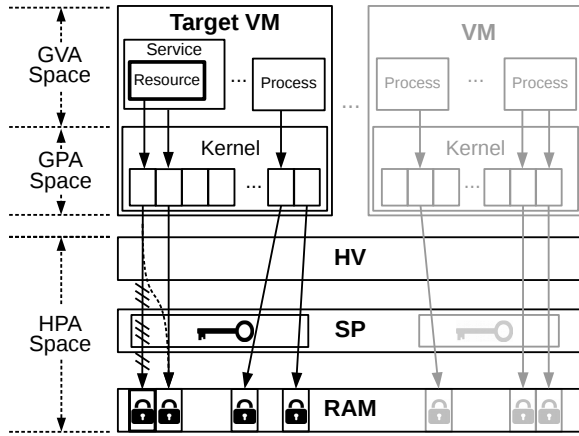


Figure 1: Overview on our memory extraction concept on a memory encryption platform with different VMs.

pages. A representative example in the context of a web server is a HTML page or a file offered for download. The suitability of a resource for SEVered depends on its *size* and *stickiness*, as discussed in Sections 2.3 and 2.4. We consider a resource to be *sticky* if it is probable that the resource remains present in guest-physical memory and is not relocated or evicted during our attack.

After identifying an appropriate service and resource in the target VM, the actual VM memory extraction is executed. The following two **phases** characterize our method:

- (1) **Resource Identification.** In this phase, we identify memory pages of the chosen resource in physical memory. As described before, the address translation in the VM is opaque to the HV due to SEV’s memory encryption. Therefore, several techniques have to be combined to reliably identify the GPAs belonging to the resource, as described in Section 2.1.
- (2) **Data Extraction.** In this phase, we extract plaintext from the encrypted VM by repeating requests while switching the mapping of the identified resource GPAs to HPAs in the HV as shown on the bottom of Figure 1. After completion, we restore the original state of the VM by mapping the resource pages to their original HPAs. This phase is described in Section 2.2.

2.1 Resource Identification

Despite the opaqueness of the VM’s guest memory mappings due to SEV’s encryption, the HV still controls the mapping from GPAs to actual physical pages, i.e., HPAs. We use this capability to establish a basic technique we call *page tracking* to gain information about the VM’s memory layout. During page tracking our HV registers each access to a GPA and the corresponding physical page by the targeted VM. We realize the page tracking by invalidating the Page Table Entries (PTEs) of the VM, i.e., by removing their *present* flags. As soon as a page is accessed, it triggers a page fault which we record before setting the present flag again. Hence, the page tracking triggers exactly *once* for each accessed page before tracking is restarted.

The goal of the resource identification phase is to identify the set of pages that store the service’s response, i.e., the target resource. We define the unknown set of resource pages as follows:

$$R = \{p : \text{Page } p \text{ contains (part of) the target resource}\}$$

The only information available to identify the target resource are the GPAs accessed by the VM as result of the described tracking process by the HV. When simply tracking a request to the target resource, the result contains a lot of pages that do not belong to the resource. With additional noise, e.g., concurrent activity caused by other clients accessing the VM, the tracking also records those accesses, making the result even fuzzier. To reliably identify our target resource in VMs with varying noise levels, we propose an iterative approach. The higher the noise, the more iterations can be conducted to converge to an approximation of R . We repeat the following steps $n \in \mathbb{N}$ times. The current iteration of our identification process is i with $1 \leq i \leq n$. We start each iteration i by requesting the resource via the target service and record all pages the VM accesses while fulfilling the request:

$$R_i = \{p : \text{Page } p \text{ accessed during request } i \text{ for target resource}\}$$

Since we request the resource ourselves, this gives us a sample set which is *guaranteed* to contain the resource pages:

$$R \subseteq R_i$$

R_i is typically large ($|R| \ll |R_i|$) since it includes not only the resource itself but also other pages of the service as well as memory pages of other processes and parts of the kernel. All concurrent activity during the recording must be considered as noise, as it directly increases $|R_i|$. We call this type of noise *R-noise*. Based on the observation that $R \subseteq R_i$, we can refine this set by intersecting all R_i recorded up to this point for which also holds $R \subseteq R^i$:

$$R^i = R^{i-1} \cap R_i \quad R^0 = R_1$$

R^i is updated on each iteration and contains only pages that are accessed for each access to the resource. After an appropriate number of iterations it should therefore only contain pages directly required for fulfilling the request to the target resource, filtering unrelated pages, such as pages from other processes.

Next, we want to sample a set of page accesses which is *similar* to R_i but without accessing our target resource. Hence, we continue our iteration i by requesting an arbitrary *other resource*, for example, a different web page, from the same service. Again, we track and record all pages the VM accesses during the request:

$$X_i = \{p : \text{Page } p \text{ accessed during request } i \text{ for other resource}\}$$

X_i only contains target resource pages if another client accesses the resource while we record. Hence, pages that are part of X_i are *unlikely* to contain $p \in R$. Based on this, we define a set of *likely candidates* C_i for each iteration by subtracting those pages from R^i :

$$C_i = R^i \setminus X_i$$

This step filters all pages that are part of the service but not the resource itself. Because of the subtraction, while recording X_i we must only consider accesses to the target resource as noise. We call this *X-noise*. We define a multiset C^i , which provides the information *how often* a page was identified as candidate, to gather all candidates from all iterations. We denote the multiplicity of an element p in a

multiset A as $A(p)$. Based on this, we specify the union of a multiset as sum of multiplicities, i.e., $(A \cup B)(p) = A(p) + B(p)$, and the intersection as multiplication of multiplicities, i.e., $(A \cap B)(p) = A(p) \cdot B(p)$. With this we define C^i as:

$$C^i = (C^{i-1} \cup C_i) \cap R^i \quad C^0 = \emptyset$$

For candidates in C_i which are already present in C^{i-1} , the multiplicity increases in C^i . The intersection with R^i ensures that candidates from a previous iteration ($p \in C^{i-1}$) that can be excluded with the knowledge gained in the current iteration ($p \notin R^i$) are completely removed from C^i . We calculate the probability that a candidate page $p \in C^i$ is part of our target resource after iteration i based on how often it was a candidate:

$$P_i[p \in R] = \frac{C^i(p)}{|C^i|}$$

Note that if $|R| > 1$, the probability is distributed between all $p \in R$. Therefore, the probability is only interpreted in relation to the probability of other pages $p \in C^i$.

Finally, after n iterations, we calculate the probability $P_n[p \in R]$ for each $p \in C^n$ and build a list of candidate pages sorted by probability. By choosing n appropriately, our model is able to remove noise during both sampling phases (R- and X-noise), as shown in our evaluation in Section 3. With the resulting list, we start the extraction phase described in the next section.

Example. In order to clarify the resource identification mechanism, consider the following simplified example. During our first iteration ($i = 1$) we record R_1 and X_1 and calculate:

$$\begin{aligned} R_1 &= \{4, 8, 15, 16, 23, 42\} \\ R^1 &= R^0 \cap R_1 = R_1 \cap R_1 = \{4, 8, 15, 16, 23, 42\} \\ X_1 &= \{3, 8, 12, 15, 16, 23, 27\} \\ C_1 &= R^1 \setminus X_1 = \{4, 42\} \\ C^1 &= (C^0 \cup C_1) \cap R^1 = (\emptyset \cup \{4, 42\}) \cap R^1 = \{4, 42\} \end{aligned}$$

During our second iteration ($i = 2$) we record and calculate:

$$\begin{aligned} R_2 &= \{6, 8, 15, 16, 23, 42\} \\ R^2 &= R^1 \cap R_2 = \{8, 15, 16, 23, 42\} \\ X_2 &= \{2, 8, 12, 13, 15, 23\} \\ C_2 &= R^2 \setminus X_2 = \{16, 42\} \\ C^2 &= (C^1 \cup C_2) \cap R^2 = (\{4, 42\} \cup \{16, 42\}) \cap R^2 \\ &= \{4, 16, 42, 42\} \cap \{8, 15, 16, 23, 42\} = \{16, 42, 42\} \end{aligned}$$

Assuming $n = 2$, we now finished all iterations and calculate $P_2[p \in R]$ for the pages $p \in C^2$:

$$P_2[42 \in R] = \frac{C^2(42)}{|C^2|} = \frac{2}{3} \quad P_2[16 \in R] = \frac{C^2(16)}{|C^2|} = \frac{1}{3}$$

Hence, we start our extraction phase with the page list $[42, 16]$ ordered by probability.

2.2 Data Extraction

The resource identification resulted in a list of GPAs for the target VM which most probably contain the target resource. The data extraction phase uses this list and the ability of the HV to switch

mappings from GPAs to HPAs to extract arbitrary decrypted memory from our target VM.

First, we determine the number of pages r that are at least necessary to store the target resource. The sizes of the target resource S_r and a single page S_p are known, so that we can determine r as S_r/S_p . We then take the first r pages of the probability list and repeat the following two steps:

- (1) **Page Remapping.** We modify the Host Page Table (HPT) entries of the r pages so that their GPAs point to the memory pages we want to extract as depicted in Figure 1. After the modification we ensure that the corresponding Translation Lookaside Buffer (TLB) entries are flushed for the changes to take effect immediately.
- (2) **Data Request.** We request the target resource from our service. Since the underlying pages for the resource were remapped, the service unintentionally responds with data from the pages we chose to extract.

We repeat both steps remapping the resource GPAs to all memory regions of interest to extract them in plaintext.

If we receive the original resource for one or more of the r pages replaced in the first step, those pages do not belong to the target resource. In this case we continue the extraction with the next pages in the probability list or repeat the identification phase.

Concurrent accesses during the extraction phase can have different consequences. If the target resource itself is accessed by another client, the access returns wrong data to the client. If a different resource that *shares* a page with our target resource is accessed, the access returns wrong data and/or introduces malfunction in the target VM. All other accesses are unaffected. To exclude malfunctions, a target resource should be chosen which covers one or more complete pages, as discussed in the following sections.

2.3 Resource Size

The size of the resource determines whether all memory can be accessed and how many requests are required during the extraction phase. To access all areas of memory, the targeted resource must cover at least one entire page. The resource does *not* have to be page-aligned and can, for example, cover the second half of one page and the first half of another page. However, as explained before, such resources should be avoided because of possible malfunctions when concurrently accessed inside the VM.

Since all pages of the target resource can be remapped and used for extraction in every iteration of the data extraction phase, the larger the resource, the less iterations are required for extracting a certain amount of memory. In our experiments (see Section 3) we found that resources representing the content of a file in memory are especially convenient. They have the advantage that a sufficiently large file located in memory always covers at least one memory page and that no other data is located on the same page. This also guarantees that the page is always read starting without offset and no data is omitted at the beginning. However, the service only returns as many bytes as the actual size of the file.

2.4 Resource Stickiness

There are several factors that influence the degree of a resource's stickiness, some of which we discuss in the following:

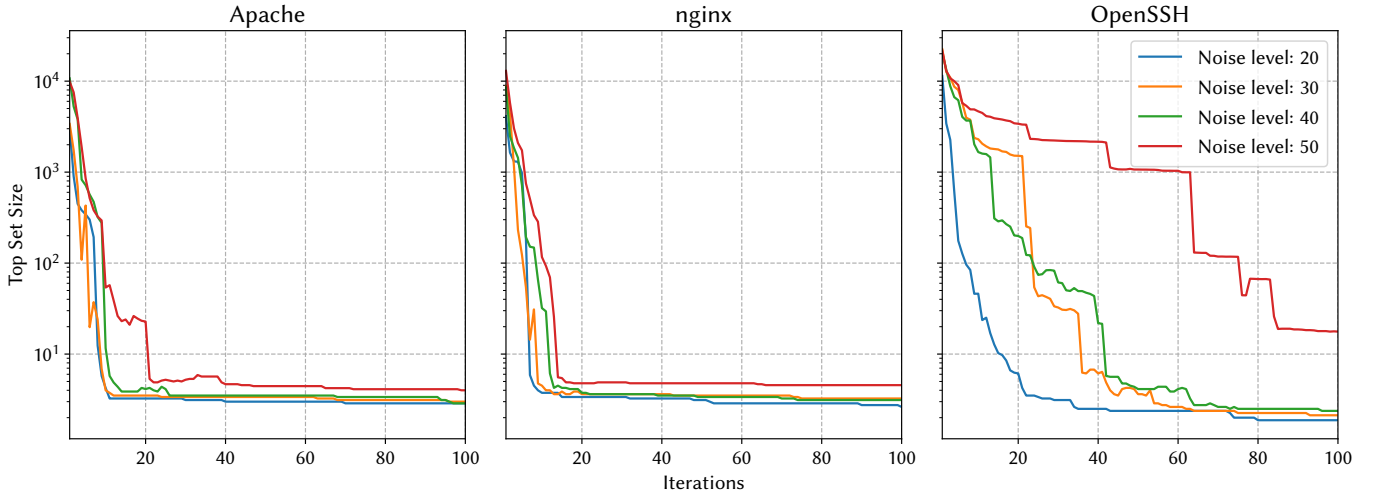


Figure 2: Measurements of top set size $|T|$ for increasing number of iterations and different noise levels.

Resource type. Resource memory pages can have different attributes. For example, they can be read-only or also writable. One important distinction is, if they are file-backed, i.e., are caching a part of a file in memory. When the system is low on memory, normal pages are swapped and file-backed pages are simply removed from memory. Depending on the configuration of the target system, e.g., via the swappiness file in Linux, file-backed pages are prioritized over non-file-backed pages when choosing a page for eviction. Optimally, a resource should be chosen based on its type matching the target VM’s configuration for maximum stickiness.

Process priority. When the target VM completely runs out of memory (including swap), it typically starts to kill processes. Optimally, a target service should be chosen that is unlikely to be killed when running out of memory.

VM memory pressure. As memory pressure in the VM decreases, the stickiness of all resources offered by all services in the increases and vice versa.

For a target VM running a typical Linux-based OS, we found in our evaluation that file resources cached in the Linux page cache provide high stickiness.

3 EVALUATION

We implemented our prototype on a system powered by an AMD EPYC 7251 processor with SEV fully enabled. Our system runs Debian Linux with the SEV-enabled kernel in version 4.13.0-rc1 and QEMU 2.9.50 as provided by AMD [1]. As malicious HV, we used Kernel-based Virtual Machine (KVM) and modified it to execute our attack. To realize our tracking mechanism, we extended the KVM infrastructure for guest write access tracking [7] to track all kinds of accesses. We furthermore extended KVM with functionality to alter memory mappings for the extraction phase. Both features can be controlled by the attacker in the host Linux running the target VM. In the following, we evaluate our prototype based on services commonly found in target VMs. We chose two web servers, Apache 2.4.25-3 and nginx 1.10.3-1, as well as an SSH server, OpenSSH

1:7.4p1-10. As target resource to be served by these services, we used a file of size 4 KB filling exactly one page in memory. We evaluate both phases of our attack separately.

3.1 Resource Identification

For our evaluation, the target page tp of our page-sized target resource is known. Based on this, we define a *top set* which we use to measure the performance of our identification mechanism:

$$T_i = \{p \in R^i : P_i[p \in R] \geq P_i[tp \in R]\}$$

The top set T_i contains all pages that our identification algorithm considers at least as likely to be the target page as the actual target page tp after i iterations. The smaller the set T , the better the identification. To ensure that the identification works in real world environments, we introduced four levels of noise into our target VM during our tests. A noise level of 20 refers to an environment where on the average 20 random accesses per second are made to our three services by arbitrary peers. Our noise model therefore generates both X-noise and R-noise (see Subsection 2.1). For each noise level and service, we conducted eight test runs with 100 iterations.

Figure 2 shows the average top set size $|T|$ for each service, noise level, and iteration. We use a logarithmic scale for the Y-axis, as the top set size quickly decreases after a few iterations. For Apache and nginx, the top set size quickly converges to about 3 to 4 candidates in average for all noise levels. The same holds for OpenSSH, where the top set size converges to about 2 to 3 candidates in average except for noise level 50 where 100 iterations were not sufficient to identify a small top set. The results show that the SEVered identification mechanism is able to handle noisy environments by dynamically increasing the number of iterations. Table 1 summarizes the number of iterations and absolute time required for every service and noise level until the top set converges to less than 5 candidates. Even in the highest noise level, the top set converges in less than 23 seconds and requires at most 22 iterations for the web servers.

To confirm that our noise model works as intended, we additionally analyzed the results regarding the noise they contain. X-noise is more critical than R-noise as it removes the target page from

Table 1: Number of iterations and time required until top set converges ($|T| \leq 5$) for different noise levels.

Noise Level	Apache	Nginx	OpenSSH
20	10 (7.4 s)	8 (5.56 s)	21 (38.85 s)
30	10 (7.5 s)	9 (6.62 s)	42 (85.47 s)
40	12 (9.7 s)	13 (13.2 s)	46 (111.09 s)
50	22 (23.0 s)	16 (17.84 s)	>100 (>5 min)

Table 2: X-noise probability and average recording size for different noise levels.

Noise Level	Apache	Nginx	OpenSSH
20	35% (8,220)	34% (8,355)	63% (18,960)
30	49% (10,860)	51% (10,360)	78% (21,475)
40	60% (13,040)	62% (12,430)	85% (23,015)
50	74% (15,950)	69% (15,970)	90% (24,990)

the candidate list of the iteration for which it happens. Table 2 shows the probability that X-noise occurs in an iteration for all noise levels. The table additionally shows the average size of X_i and R_i recordings. The results show that our noise model introduces significant X-noise in up to 90% of the X_i recordings and strongly increases the size of recordings.

Summarizing, our identification mechanism’s design enables quick resource identification and is robust against noise and thus applicable in real-world scenarios. Note that the resource requests can also be executed from several distributed clients to further hide the attack. Among the candidate pages in the top set, we *always* identified the last commonly accessed page to contain the target resource for all services. This observation is comprehensible, as all services must perform operations, such as opening a socket, before transmitting the requested content. Together with our converged top set, those observations allowed us in our test cases to *always* correctly identify our target resource’s single page making the attack very reliable to this point.

3.2 Data Extraction

With the knowledge about the location of the resource, we were able to reliably extract the entire memory of the target VM on our prototype implementation as described in Subsection 2.2. The resource was always sticky (Subsection 2.4) over the whole process. While preserving the VM’s stability at all times, the extraction of its entire 2 GB also worked under the noise model introduced for the identification phase. Table 3 summarizes the extraction speed with different services for our single-page resource. With OpenSSH, we experienced a higher response time reducing the extraction speed for this case. A single-paged resource represents a worst-case scenario, which can be significantly improved in practice when identifying a larger resource. This requires fewer requests to the target VM while receiving larger chunks of main memory.

Table 3: Extraction speed for different target services using a one page-sized resource.

Apache	Nginx	OpenSSH
79.4 KB/sec	79.4 KB/sec	41.6 KB/sec

3.3 Discussion

Our evaluation shows that SEVered is feasible in practice and that it can be used to extract the entire memory from a SEV-protected VM within reasonable time. The results specifically show that critical aspects, such as noise during the identification and the resource stickiness are managed well by SEVered.

Nevertheless, there are multiple possibilities for future work to further improve SEVered. For example, in various situations, a full memory dump is not required. An attacker could consider only extracting the private key of a web server. This key is likely to be found among the pages accessed during a request, as it would have to be accessed by the web server process in order to initiate an encrypted connection. With this knowledge, an attacker could limit the amount of pages possibly containing the TLS key to a fraction of the VM’s memory, drastically reducing the extraction time. A similar approach could be performed, for example, with password hashes or disk encryption keys a service accesses in the course of a request. An optimization to SEVered could be made by continuously analyzing the received data during the extraction phase. As soon as the targeted secret is found, the attacker could stop the extraction, decreasing the duration of the attack, increasing its stealthiness.

4 COUNTERMEASURES

SEVered depends on both the possibility to track the VM’s accesses to GPAs and the missing integrity protection. To prevent page faults from leaking information, Shinde et al. [13] proposed a method where processes create a deterministic sequence of page faults, independent from the input. However, this is not sufficient to hide the VM’s accesses to the critical resource from the HV. The best a VM can achieve is to generate additional page faults to complicate the resource identification phase. Additionally, integrity protection can hardly be achieved in software as the VM would require efficient and reliable software mechanisms to protect itself from modification of memory mappings and contents, e.g., by maintaining hashes in a safe location. Both mechanisms seem hard to realize to reliably protect an entire VM at all times, and would probably incur an intolerable performance overhead. We thus consider software-based countermeasures insufficient solutions against our attack. Therefore, a modification of AMD SEV seems inevitable to fully prevent SEVered. The best solution seems to be to provide a full-featured integrity and freshness protection of guest-pages additional to the encryption, as realized in Intel SGX. However, this likely comes with a high silicon cost to protect full VMs compared to SGX enclaves. A low-cost efficient solution could be to securely combine the hash of the page’s content with the guest-assigned GPA. This ensures that pages can not easily be swapped by changing the GPA to HPA mapping. Adding a nonce additionally ensures that an old page for the GPA cannot be replayed into the guest by a malicious HV.

Integration of such an approach into AMD SEV could effectively prevent remapping.

Note that the not yet available extension SEV Encrypted State (SEV-ES) does *not* protect against SEVered, since our attack does not require access to any VM state encrypted by SEV-ES.

5 RELATED WORK

While Payer [12] already pointed out the general problem of the SEV approach when it was announced, to the best of our knowledge, only one paper presenting an actual attack on SEV has been published at the time of writing. Hetzelt and Buhren [9] changed the program flow of an SSH service running in an SEV-encrypted VM. Using page remapping, they were able to gain unauthorized access to the service. This requires manual analysis of the SSH service to recognize page access patterns for different data flows. Our approach does neither require thorough analysis of a specific target service, nor to alter the program flow within the target VM. This eases the application of our method for different services and sustains the target VM's code integrity. Also, their method requires data being located at certain offsets within a page reducing the probability of a successful attack. In contrast, our results point out the particularly high success probability of SEVered even in realistic scenarios where the VM is under high load. Further, they also require a victim logging into his user account in order to be able to remap his session information to the attacker's session who logs in shortly after. In comparison, SEVered does not depend on any interaction from a victim, as we can perform all requests necessary for our attack ourselves remotely and at any time.

Buhren et al. [5] leveraged fault attacks on Secure Memory Encryption (SME) platforms, which SEV is built upon. They showed that it is possible to extract the private RSA key of a GnuPG user from encrypted memory. Their attacker model requires the attacker to have control over a process running on the target system and to have physical access to the system. They first used the process on the target system to perform cache timing attacks in order to identify relevant assets of a GnuPG process in memory. In the next step, they made use of DMA to inject faults into those assets, which caused GnuPG to create faulty signatures. They used these faulty signatures to calculate parts of an RSA key offline. Their very specific concept solely applies to SME platforms, but not to VMs on SEV environments and is difficult to execute on productive environments. Our approach makes it possible to extract the whole memory of a VM without physical access and without particular knowledge or control over processes on the target VM.

Additionally, in contrast to our prototype, both [9] and [5] did not realize the attack on real hardware, as only the AMD specifications for SEV and SME were public. The results of our work strongly indicate that [9] also works on real SEV platforms.

6 CONCLUSION

We presented the design and implementation of SEVered, an attack that reliably extracts the full plaintext memory of VMs encrypted with AMD SEV from a malicious HV. The only major requirement for our method is the presence of a service in the VM, which provides a resource to the outside. Such services are usually easy to find, since VMs are typically and widely used in server contexts

where they host web servers and other remotely accessible services. We demonstrated the feasibility of our approach by realizing a prototype on a recent AMD SEV-enabled platform. We evaluated the prototype with different services, namely the Apache and nginx web servers and an OpenSSH server. For every service, we considered various levels of concurrent accesses to evaluate SEVered under different, realistic load conditions. In all cases, we were able to efficiently identify the relevant resource of the target VM in memory by analyzing the VM's memory access patterns from the HV. With the gained knowledge we were able to use the malicious HV to remap the resource to other memory pages and to iteratively request all the VM's memory in reasonable time. As SEVered is independent of the specific service, our method can easily be adapted to a variety of different attack scenarios in practice. SEVered demonstrates that a malicious HV still remains able to extract sensitive data from its SEV-enabled guest VMs.

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