SEER: Practical Memory Virus Scanning as a Service *

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ABSTRACT

Virus Scanning-as-a-Service (VSaaS) has emerged as a popular security solution for virtual cloud environments. However, existing approaches fail to scan guest memory, which can contain an emerging class of Memory-only Malware. While several host-based memory scanners are available, they are computationally less practical for cloud environments. This paper proposes SEER as an architecture for enabling Memory VSaaS for virtualized environments. SEER leverages cloud resources and technologies to consolidate and aggregate virus scanning activities to efficiently detect malware residing in memory. Specifically, SEER combines fast memory snapshotting and computation deduplication to provide practical and efficient off-host memory virus scanning. We evaluate SEER and demonstrate up to an 87% reduction in data size that must be scanned and up to 72% savings in overall scan time, compared to naively applying file-based scanning approaches. Furthermore, SEER provides a 50% reduction in scan time when using a warm cache. In doing so, SEER provides a practical solution for cloud vendors to transparently and periodically scan virtual machine memory for malware.

1. INTRODUCTION

Virus Scanning-as-a-Service (VSaaS) has become a popular topic for research and industry [4, 9, 17, 20, 25]. However, existing solutions only scan secondary storage. As malware continues to mature, file-only virus scanning is insufficient. We have already seen several instances of "Memory-Only Malware" that evades detection by many popular virus scanners [19, 14, 15]. In fact, only 30% of the most popular host-based virus scanners support memory virus scanning [16], and the computational overhead of their signature matching techniques makes memory scanning an infrequent event.

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Memory-based VSaaS would provide benefit to both cloud clients and providers as Virtual Machines (VMs), like traditional hardware environments, require proper security measures to minimize threats and detect intrusions. However, designing a practical VM memory scanning service is non-trivial as (1) virus scanning is traditionally a CPU intensive task that can negatively impacts guest VM operations, (2) memory that changes during analysis can lead to false positives [2], (3) scanning multiple VMs concurrently can impact VM and host operations (i.e., "anti-virus storms") [23], and (4) file scanning optimizations are less effective for memory.

In this paper, we propose SEER as an architecture alternative to in-host memory scanning that enables efficient, transparent Memory VSaaS for virtualized cloud infrastructures. SEER "peers" into running VMs to efficiently identify malware in resident memory. SEER is built on DACSA, a decoupled architecture for cloud security analysis, to minimize guest and host performance [7]. DACSA enables fast memory snapshots and memory extraction. SEER processes snapshot data off-host to identify similar memory and duplicate scanning computation thus leading to a reduction in scan time. In doing so, SEER allows cloud providers to scan guest memory much more frequently and efficiently than naively applying existing file based scanning approaches.

Computation deduplication in SEER is achieved using a new algorithm that we call Prefix Based Scanning. Prefix Based Scanning is optimized by identifying partial data similarities across all memory segments to scan and normalizing similar data. For example, many Windows processes load *ieframe.dll* each containing small differences based on load address and runtime state. As a result, Prefix Based Scanning reduces the amount of computation to scan by only scanning identical prefixes once. Furthermore, our Prefix Based Scanning algorithm also identifies memory pages not present and virtually "fills in" similar memory from other processes per VM to increase virus scanner accuracy.

As a proof of concept to analyze the efficiency of SEER, we adapt the popular open source virus scanner ClamAV [10] to enable Memory VSaaS with Prefix Based Scanning. Our results show that SEER is practical and can be deployed by cloud vendors to find both existing file based malware and stealthy Memory-Only Malware in memory.

We make the following contributions:

- We propose a new architecture for efficient Memory VSaaS. SEER addresses a major gap present in existing Virus Scanning-as-a-Service solutions. We describe and overcome the challenges of memory scanning that prevent naive application of traditional file based scan-

ning techniques.

- We propose Prefix Based Scanning for efficiently scanning dynamic memory. Our proposed approach works to consolidate data thus reducing the amount of computation required to scan memory. The approach can be adopted by existing host based memory virus scanners to reduce scanning computation.
- We provide an experimental evaluation of SEER and show our design reduces the data size to be scanned up to 87% and the time to scan the data by up to 72%, compared to naive scanning approaches. We also demonstrate that SEER can correctly identify memory malware in infected machines.

The remainder of this paper proceeds as follows. Section 2 provides background on Memory-Only Malware and the challenges faced by memory scanning. Section 3 contains our design, implementation, assumptions and threat model. Section 4 evaluates SEER. Section 5 discusses deployment, security and privacy concerns, and limitations. Section 6 discusses related work. Section 7 concludes.

2. MOTIVATION AND BACKGROUND

2.1 Memory-Only Malware

Memory-Only Malware (**MoM**) identifies a class of stealthy malicious software that does not modify files on a target system. As such, MoM bypasses file-based detection techniques and the majority of popular virus scanners [16]. MoM trades persistence for stealth. While MoM will not survive system reboots, attackers are using new ways to gain persistence through "Watering Hole Attacks" [18].

MoM is not a new concept. The infamous Code Red Worm propagates only through memory [19]. More recently, security analysts have identified a Hydraq/McRAT variant that allows remote access to infected machines [15]. Finally, the popular MetaSploit framework provides an "out-of-the-box" MoM called Meterpreter [14].

Malware such as Zeus and Conficker also benefit from the lack of memory scanning. They only need to bypass virus scanning software once to gain a foothold. Once initial detection is bypassed, the malware uses code injection to infect benign active processes [12]. Injected code allows malware to stay resident in the running machine even when physical files are later found and removed. As a result, malware analysts recommend using memory dumps to discover and identify malware [12].

2.2 Scanning Memory

Memory scanning consists of analyzing virtual memory to find malware based on virus definitions. Previous work [9] has applied file-based scanners to physical memory. However, scanning physical memory will lead to incorrect results because virus definitions require correct context to match definitions. As a result, a memory based virus scanner must scan virtual memory to ensure correct context. For modern operating systems, each process has its own virtual memory.

The virtual memory of a process (p) is a set of *memory segments* S_p. Each memory segment $s \in S_p$ represents an individual memory allocation managed by the operating system (OS) with size s_{size} bytes. Memory segments can contain stacks, heaps, or mapped files. Then $p_{size} = \Sigma s_{size},\ \forall s \in S_p$ represents the size of memory allocated for process p. Malware can potentially reside in any process memory segment, therefore **all** processes on the OS, represented as the set P, must be scanned. That is, $P_{size} = \Sigma p_{size},\ \forall p \in P$ bytes must be scanned.

A naive approach would be to scan all P_{size} bytes of memory. However, this faces the following challenges:

C1. Scanning is computationally intensive requiring significant CPU resources to match signatures. Scanning often disrupts critical operations during analysis. A large P_{size} can result in minutes of scanning and thus is not ideal for production environments.

C2. Memory modified during analysis can impact the correctness of scanner results, leading to false positives and negatives [2]. This occurs because scanners must copy, examine, and analyze memory that is constantly changing. As a result, false assumptions are made about the consistency of the data being analyzed.

C3. Multiple VMs scanned at the same time on a single host leads to "Anti-Virus Storms", which can affect non-scanning guests and host operations [23].

C4. Hashing is widely used by file-based virus scanners as an optimization to limit the amount of data to scan. Memory is often unique which limits the effectiveness of hashing memory segments to identify previously scanned data. We find that previous hashing techniques used for file-based scanning [20, 17] only reduces the memory segments to scan by ≈14% for a single VM.

3. SEER

Next we give an overview of the SEER architecture. We discuss the disparate components for enabling SEER and the workflow for scanning VMs. We then detail specific design decisions for Prefix Match Scanning.

3.1 Overview

The SEER architecture enables practical, VM transparent, efficient memory scanning for virtualized cloud infrastructures. SEER overcomes challenges (**C1-C4**) by shifting memory scanning to a third party in which (1) guest VM memory is extracted and only unique data is shipped off-host, (2) a scan scheduler pre-processes data to identify similarities in data to scan, and (3) a modified scanner uses pre-processed meta-data to identify viruses in an isolated environment. The VM and host only incurs a small cost for extracting and shipping data (**C1**,**C3**) and prevents malware or exploits that targets the scanning process [17].

Figure 1 illustrates the main components and flow of SEER. The cloud provider will request/schedule (1) VMs for scanning. The scan scheduler initiates a scan (2) by requesting the memory extractor to extract memory and then ship memory meta-data and unique page data for pre-processing. The scheduler (3) stores the data and builds a scan configuration based on data extracted. The scan scheduler then triggers a new scan (4) using the generated scan configuration and (5) results are relayed to the cloud provider. For our design discussion, we consider QEMU/KVM as the host and Windows as the guest VM operating system.

On the virtualization hosts, we leverage DACSA to support fast, non-intrusive VM memory snapshots and memory

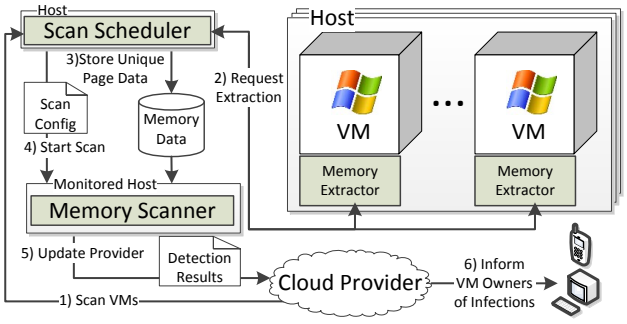


Figure 1: SEER Overview

extraction. DACSA creates a logical static copy of memory in milliseconds without copying data byte-by-byte [7]. This prevents consistency issues which can arise from analyzing memory that continues to change (**C2**). Memory segments to be scanned are extracted from the logical copy using pre-existing knowledge of the VM operating system similar to forensic techniques employed by Volatility [24]. Segment data meta-data is sent to the scheduler and instructs the extractor to send/store only unique page data. This prevents shipping large amounts of data over the network.

After the necessary page data is shipped, the scan scheduler beings pre-processing by reconstructing stored page data into memory segments for each VM. Each segment can be naively scanned with traditional virus scanners however the total size to scan (P_{size}) can be very large.

To address scanning large amounts of data, file based virus scanners use hashing to identify previously scanned data. Files hashed to known values do not need to be re-scanned. This technique is most beneficial on static data. Unfortunately, memory segments are often unique due to its dynamic nature making this simple optimization less effective.

We observe that while many memory segments are unique, many segments are similar to some other segments within a VM. For example, the Windows library *ieframe.dll* can be found mapped across many processes in a running system (e.g., Internet and Windows Explorer). Memory segments for *ieframe.dll* will share identical PE headers and code sections but will differ in their data sections. As a result, a naive scanner will simply identify both segments as unique.

Using simple hashing techniques to eliminate scanning duplicate data is not effective for memory. Furthermore, false positives can arise from scanning non-present or zeroed data due to coarse grained virus definitions. SEER employs four optimizations to address the above issues:

1. Only globally unique page data is sent off scanned VM hosts. This obviates shipping all snapshot memory and reduces the processing time to extract memory hence reducing impact to VMs, hosts, and network.
2. SEER matches identical prefixes across all memory segments. Matched prefix data determines where duplicate scanner computation occurs. SEER uses matched prefix data to scan identical prefixes only once. For example, two libraries extracted from memory will have duplicate header data but contain different runtime data. SEER will match the header as a prefix and only scan the header data once instead of multiple times.
3. Memory segments are normalized intra-VM to increase similarities between segments. Normalizing memory segments increases the lengths of matched prefixes. This results in less data being scanned.
4. The SEER scanner is provided meta-data and thus can avoid unnecessary computations by not processing non-present data.

The above optimizations allow SEER to efficiently scan unique data reducing the computation required to analyze the full set of memory segments (**C4**).

SEER leverages existing virus scanners for identifying and matching known malware signatures in memory. Thus, SEER's effectiveness at identifying malware is reliant on the adopted virus scanner's signature database and signature matching techniques. SEER does not look to improve matching of existing scanners but to provide a novel architecture for extending existing techniques to efficiently scan memory.

Assumptions and Threat Model: We assume that an attacker has full control over the guest VM. However, attackers wish to remain stealthy and avoid detection thus avoiding behaviors which raise suspicion such as attacks on availability or resource exhaustion.

3.2 VM Host Memory Segment Extraction

Next we discuss the process of memory extraction and segment data shipping off VM host machines. Memory extraction is built on DACSA to limit the impact to host and guest environments. We add discussion on shipping memory segments not previously discussed in DACSA [7].

3.2.1 *DACSA: Fast Snapshots and Extraction*

DACSA is a decoupled architecture for virtual machine memory analysis. DACSA introduced a reliable fast memory snapshot technique using Copy-On-Write to create a *logical copy* of Virtual Machine memory allowing memory to become a data source for analysis. Memory forensic techniques are then applied to extract security relevant information. DACSA showed to have minimal impact on host and guest operations during the snapshot and memory extraction process. Due to space constrains we limit the discussion on fast snapshotting and memory extraction. We encourage the reader to read previous work on DACSA [7].

3.2.2 *Carving Segments from the Logical Copy*

Memory segments[1] are carved from the logical copy based on the VM guest OS semantics. For Windows, memory segments are obtained from walking each process's Virtual Address Descriptor (VAD) tree structure [5]. The VAD tree is a binary tree where each node represents an allocated memory space by the process and thus a single memory segment. Each VAD tree node contains a starting and ending virtual address specific to the process. We extract memory segment data using these addresses and the process's page-tables.

3.2.3 *Shipping Memory Segment Data*

Each segment is processed during segment extraction page-by-page using the VAD starting and end address. A hash of each page is generated to determine if the page data needs to be sent to the schedule. First, the hash is looked up locally. If not found, the hash is added to a batch of hashes to send to the scheduler. Once the batch is sent, the schedule checks each page in a global hashtable and returns which pages are

[1]We use "memory segment" to refer to the carved unit of memory, which does not correspond to an x86 segment.

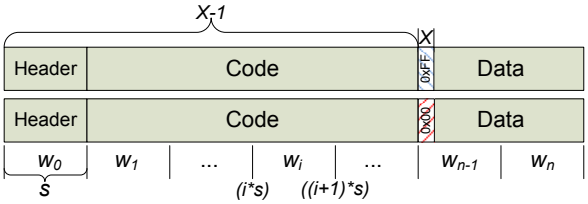


Figure 2: Two binaries that differ at byte X have an identical $X-1$ bytes prefix. Binaries are split into windows size s. Hashes of window w_{n-1} identifies the difference.

needed for scanning. If the page hash value has been stored before, meta-data for the hash is stored with the hash identifying the VM, segment, and offset. The scheduler then uses the hash to reconstruct the segment for pre-processing and scanning. This process is similar to VM memory deduplication techniques [8].

3.3 Segment Similarity Detection Off-Host

For segments that are similar but not identical, we observe the scanner may unnecessarily duplicate scanning effort. For example, Figure 2 depicts two identical binaries that contain only a single byte difference at index X. A traditional naive scanner will identify each segment as unique and scan each segment separately from low bytes to high. We observe that after each scan instance has processed the first $(X-1)$ bytes in the example, the scanner signature matching states will be equal as the prefix $(X-1)$ bytes are identical for both binaries. Thus, the scanner will have duplicated matching computation for this prefix.

Prefix information provided to the scanner allows a single unique prefix to be scanned only once across similar segments. This is beneficial for binaries used across many processes and machines as most will be unique but share some identical header and code sections.

3.3.1 Prefix Matching

SEER needs to quickly identify common prefixes across all segments. While byte-by-byte comparison provides very fine-grained matching, it comes at a large cost. We are only concerned with identifying identical prefixes which are aligned to the beginning of memory segments.

To quickly identify differences in data, previous techniques such as fuzzy hashing [11] and rolling hashes [22] have been proposed. Unfortunately, these techniques do not lend themselves to finding the longest prefix in pseudo-random data. Specifically, the effectiveness of these approaches relies on finding a suitable *trigger*. Instead, we choose a more straightforward approach which uses a rolling window to approximate the longest prefix.

Figure 2 provides a reference for partial segment hashes, which we discuss next. After segment extraction, each segment is divided into $n+1$ non-overlapping parts of data using meta-data to reconstruct segments. We refer to this data as window w. The i^{th} window, w_i, represents bytes from $(i*s)$ to $((i+1)*s)-1$ where s is the window size. Each w_i is hashed by the scheduler in order from $i=0$ to $i=n$. Window hashes, window offsets $(i*s)$ and size (to handle boundary cases) can then be compared across segments beginning from low to high index. If two hashes at an index do not match, the index identifies the longest prefix for a pair.

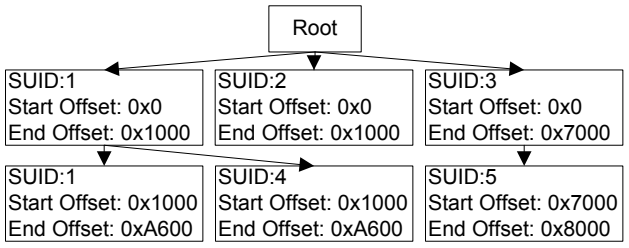
Encoding Prefix Information: SEER needs to quickly determine the longest prefixes across all segments and store relevant information for scanning. We achieve this through a combination of hash tables and building a rooted directed tree (e.g., as in Figure 3). The rooted directed tree naturally represents prefixes by encoding information in each node. As the tree is walked from the root towards children, data for segments can be processed and read in linear fashion.

Algorithm 1: Algorithm for updating scheduler.

```
   foreach S ∈ Segments do
1      node = root
       foreach w ∈ Windows do
2          if node.SUID = S.SUID
3              node.window = w
4          if w.index >= node.index + node.size
5              if hash(w) ∈ node.children
                   node = node.children(hash(w))
6                  AssociateWindow(node, S.SUID,w)
               else
                   node =NewNode(node, S.SUID, w)
7          else
8              if node.hashes[w.index] = hash(w)
9                  AssociateWindow(node, S.SUID,w)
               else
10                 split node at w.index
                   create two children
                   node = new child for w
```

Prefix information is encoded in the tree nodes. Each node represents a unique prefix and maintains several pieces of information used for scanning and segment association. Specifically, nodes contain (1) associated segment ids ($SUIDs$) which track matched segments, (2) a range to explicitly define where the matched prefix starts and ends for the associated $SUIDs$, and (3) a hash table for looking up child nodes. To track hashes and data for each node, window hashes are stored for each index represented by the node. These hashes are used to later build and retrieve the data stored from segment extraction.

Algorithm 1 depicts how the tree is built using memory segments and windows. As windows are processed by the scheduler, the tree is walked and updated. For processing new segments, the walking begins at the root node (**line 1**). If the received hash's index does not fall in the current node's explicit range (**line 4**) then the hash value is not represented by the current node as a previous prefix has been defined for the hash's index. As a result, the current node's child hash table is searched for an association (**line 5**). A new node is added if no child node with the hash and corresponding index is found (**line 7**). If the hash matches a child, the hash is associated with the matched child node (**line 6**). During association, the SUID is added to the node's list of SUIDs with common prefix and matched indexes. If the hash's index falls in the current node's explicit range (**line 8**), the node's stored hash for index is compared (**line 9**). If identical, the associated SUID is updated for the node (**line 10**). Otherwise, a new prefix is identified and the current node is split at the window index creating two child nodes (**line 11**). To quickly add new unique prefixes, each node stores the first SUID used to create the node. If the SUID for the window hash is the same as the node's first SUID (**line 2**), the node only needs to update the current node with the window hash and index information (**line 3**). Such



SUID	VM	Address	Size	PID
1	1	0x112000	0xA600	872
2	1	0x60000	0x1000	872
3	1	0x1e000	0x7000	872
4	1	0x482000	0xA600	1788
5	1	0xff0000	0x8000	1788

Figure 3: Scan tree representing 5 memory segments.

is the case when the root node contains no children.

Figure 3 depicts a prefix matched tree with five unique memory segments. Segments with SUID 1 and 4 represent a mapped binary. We see that the longest prefix for 1 and 4 is found at offset 0x1000. Thus, the scanner would only need to scan the first 0x1000 bytes of SUID 1 and 4 one time instead of twice. SUID 2 represents a unique segment as reflected by a node with no children. SUID 3 and 5 represent a data file for browser history. We see that the longest prefix is found at offset 0x7000 when SUID 3 ends. SUID 5 is added as a child of SUID 3 as SUID 5 has an extra 0x1000 bytes in the segment. In this case, the scanner would only scan the first 0x7000 bytes of SUID 3 once. The total savings dictated by the tree is 0x8000 bytes.

3.3.2 *Binary Normalization*

Binaries mapped across processes often provide opportunities to match large prefixes, as per our *ieframe.dll* example. This property allows additional opportunities to deduplicate scanning work. We found that binaries have a semi-consistent structure in which static headers and code resides at the beginning. While nothing prevents code sections from being located at the end of binaries, this pattern is default for common compilers. This attribute of binaries ensures prefixes match at least header and code sections for segments with the same backing file on disk.

Unfortunately, we found that beginning memory is not always identical due to how the underlying OS manages memory for mapped files. For example, a page may be marked not present in a process's page table but mapped in another. As a result, we use a technique for normalizing binaries to extend the length of matched prefixes.

Filling Non-Present Pages: OS memory management units employ on-demand paging to reduce the memory footprint of processes and improve performance. Only processes accessing the page has its pagetable updated to include the new physical page mapping. As a result, pagetables between processes are not synchronized for common shared binaries.

The lack of inter-process pagetable synchronization impacts prefix matching for memory segments. For example, consider two processes that both use the *ieframe.dll*. The third page of *ieframe.dll* is accessed by process P_1 but not P_2. As a result, the third page for P_1 will be marked present while the same page for P_2 is non-present and the corresponding window hashes (w_2) will not match. The longest prefix for P_1 and P_2 will be the index of w_2.

SEER conservatively normalizes memory segments by filling in non-present pages with pages found present in other segments that are mapped to the same binary file. During memory extraction, segments are grouped by binary headers, corresponding load addresses, and size. In Windows, binary files loaded from the same file on disk will all be placed at the same address in memory by the default loader.

Once grouped, each segment's data is walked to identify present pages and indexes. If a page is present, the status is checked to see if a previous data page has been stored for that index. If previously stored, a hash of the data is compared to ensure equality. In some cases, present data at a page index may not be equal and conflict across segments in the group. This occurs if a page has been modified by a process, for example, when modifying data or malicious code manipulation. In this case, we conservatively mark the page status for the page index as *unknown* and do not use the page to fill non-present pages for groups of binaries. Page filling occurs with regards to given VM.

3.4 Prefix Matched Scanning

After all memory segments have been processed, the scheduler contains a tree of nodes representing unique prefixes covering all segments. Each node in the tree contains information used by the scanner to scan the unique prefix.

To scan all segments, each node must be processed and data represented by the node scanned. We process each node by walking the tree in a Depth First Search manner. As the scanner requests data to scan, node attributes are used to determine which data to provide. A node boundary is reached when the scanner asks for data at an offset greater than the current node's end address. As a result, the scanner takes actions to walk each child.

Each child node to be processed requires the same scan state as the parent. Thus, the scan state must be saved or duplicated so each child can have its own copy to continue scanning correctly. To facilitate coping scan state, the scanner forks execution for each child node. The last child does not fork, but only assigns the last child node for processing.

Ignoring Non-Present Memory: Windows of segments found to be non-present can be skipped by the scanner as they provide no information for matching. This provides two benefits: (1) it increases scanning efficiency and (2) it reduces the possibility of false positives occurring that match for non-present regions. When a non-present window is to be scanned, the scanner simply updates the index to be read to the next present page thus preserving scanner context.

Scanner Specific Considerations: Scanning with prefix matching assumes that memory is scanned in a linear fashion. This ensures all matching efforts for the previous prefix has been complete prior to forking. Thus the scanner should not peek at data ahead beyond the current window. Reading data in non-linear fashion will result in walking child nodes prior to matching efforts thus preventing savings from scanner effort deduplication.

3.5 Implementation

We prototype SEER using QEMU [1] v0.13.0 with KVM

Table 1: Average Impact on Throughput (MB/s) and Response Time (Resp. Time) of SEER on both the VM being scanned (i.e., snapshot and shipped) and other VMs on the same host.

VM Impact	MB/s	Resp. Time	Snapshot Time	Data Shipped
Scanned	8.02%	9.14%	4.90 sec	153.4 MB
Non-Scanned	0.70%	0.76%	4.48 sec	140.4 MB

virtualization software as the host. Our host is Ubuntu 12.04 64-bit and VM environments are Windows 7 SP1 64-bit.

The memory extractor and scheduler are configured to allow both storing complete memory segments to network storage or sending only unique data windows as discussed in Section 3.2.3. For our evaluation, we save complete memory segments to allow for better support for evaluating different configurations.

SEER requires minor modifications to virus scanner software to enable best efficiency and accuracy. Thus, we adapted ClamAV, a popular open source virus scanner, to the SEER architecture with minimal modifications by hooking I/O requests through a shared library. For example, read requests for scanned memory segments are intercepted and return specific data based on the current node. If a read request crosses a scan tree node boundary, the process can immediately fork and return the appropriate values for each read. ClamAV virus definitions for PE/COFF binaries support context aware definitions. For example, virus definitions can target specific sections for binaries. The sections found in binary disk files reside at different locations in memory as sections are often page aligned while sections on disk are block aligned. Thus we modify how ClamAV interprets PE/COFF files so that sections are aligned correctly with memory. In total, we only modified 9 lines of ClamAV code to enable memory virus scanning with SEER.

4. EMPIRICAL EVALUATION

We evaluated SEER on an IBM System X server with a Xeon E5450 Quad-Core CPU with 32GB RAM. The server hosts Window 7 SP1 64-bit VMs configured with 1GB RAM and 1 VCPU with QEMU/KVM as the host. An IBM System X server with an AMD Quad-Core Opteron 2384 and 32GB RAM was used for scheduling scans, storing, and scanning data. A third IBM System X server with an AMD Quad-Core Opteron 2384 and 16GB RAM was used to benchmark the host with VMs. These machines are interconnected via two 10Gbps switches, one managing public network and one for management network.

We investigated the impact of SEER's components across the scanning process. First, we performed benchmarks on host and guest VMs to investigate the impact of fast snapshotting and shipping memory. Next, we investigated at SEER's impact on matching efforts and total scan times under varying conditions, configurations, and caching. Finally, we evaluated SEER's ability to find malware in memory and discuss false positives.

4.1 SEER Impact on Guest VMs

The guest VM is momentarily paused to create the logical copy for carving and shipping. We measured the average time a VM is paused at 0.2112 seconds with a standard deviation of 0.07359 seconds.

We measured the impact of VM snapshotting and data shipping (i.e. phase 1) for VMs being scanned and co-located VMs that are not scanned. We used SpecWeb'2009 [21] to simulate a webserver under load to measure the reduction in throughput (MB/s) and response time for a single guest VM (i.e. VM under test). The VM under test was configured with IIS, ASP.Net, and the SpecWeb banking application. SpecWeb was configured to simulate 200 simultaneous users making at least one request every second. The benchmark was run under three conditions: 1) no VMs on the host in phase 1, 2) the VM under test in phase 1, 3) the VM under test is co-located with VM in phase 1. Table 1 contains the results. A VM can expect an 8.02% reduction in throughput and a 9.14% reduction in response time during the 4.9 second phase 1. A co-located VM not scanned can expect a 0.7% reduction in throughput and 0.76% in response time during phase 1. We note here that the average amount of data shipped was 153.4 MB and 140.4 MB for these configurations however this number is highly dependent on the processes and services running. The average time to snapshot and ship the data was less than 5 seconds under load. The majority of time was spent shipping data.

4.2 Scanned Data and Scan Times

We investigated SEER under the following configurations: Naive, Prefix Matched with Normalization (**PMN**), and Prefix Matched Normalization ignoring Non-Present data (**PMNP**). Naive refers to an unmodified ClamAV using full segment hashes to identify previously scanned segments. PMN provides the potential savings of adopting our techniques for host based memory scanners. PMNP shows the most efficient configuration for scanning memory that can be both present and non-present data.

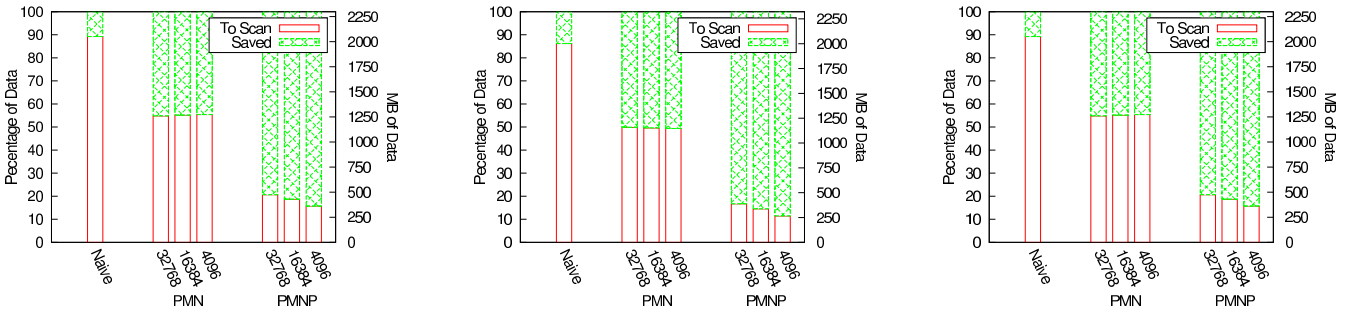
PMN and PMNP configurations were tested with different windows sizes to investigate window size impact on efficiency. For the smallest window, we used 4KB. This naturally maps to present/non-present page data. We also used different multiples of 4KB aligned windows. The Naive configuration does not have a window size but hashes the entire memory segment to identify duplicates.

We configure scanning to be performed serially on a single processor under all above configurations. While prefix based scanning is naturally parallelizable, we use a single processor to avoid unfairly biasing in favor of SEER.

To investigate potential savings under different working conditions, we scanned VMs under three different operating environments: (1) idle machine after booting to login, (2) a loaded webserver running IIS and MySQL with 100 simulated simultaneous clients navigating a PHPBB web application, and (3) VMs running a set of the following unique GUI applications: IDA Pro, Chrome, Internet Explorer 64-bit, Notepad, Windows Update, IIS Administrator, WampServer Installer, OllyDBG, Process Monitor, and Visual Studio Express 2010. All workloads are run on the same VM image. Workload (2) looks to investigate the potential impact of a high number of reads and writes but similar number of processes as workload (1) without loading into the Windows desktop. Workload (3) pertains to loading the desktop environment to investigate the impact of unique processes on the amount to scan and scan times. To remove non-deterministic nature of memory, carving and scanning were done on static snapshots of memory for each operating

Table 2: Average cost of snapshotting and shipping VM memory for remote scan.

	1 VM				10 VMs			
	Cold		Cached		Cold		Cached	
Type of VM	Time	Shipped	Time	Shipped	Time	Shipped	Time	Shipped
Login	6.62 Sec	223.8 MB	6.07 Sec	46.39 MB	5.89 Sec	140.0 MB	5.47 Sec	37.63 MB
Webserver	7.26 Sec	325.1 MB	5.85 Sec	76.24 MB	6.42 Sec	155.4 MB	5.29 Sec	36.56 MB
Profiled	8.73 Sec	382.0 MB	8.23 Sec	137.2 MB	7.79 Sec	239.9 MB	7.39 Sec	111.67 MB



(a) Boot to login (b) Loaded IIS webserver (c) Unique GUI applications

Figure 4: Percent Data savings and to scan for a single VM. X-axis is window size.

environment. We took 10 snapshots for each workload type and incremental snapshots for all 10 at 5 minute intervals.

We detail the data savings and total scan times for scanning both a single machine and across multiple machines. Using multiple machines looks at potential savings of matching prefixes across machines. During scanning, memory segment data is read off the disk and provided to the scanner for analysis. Table 2 shows the average cost for snapshots and data shipping of each operating environments for both a single VM snapshot (i.e. 1 VM) and all 10 VM snapshots.

Data Saved/Scanned: Figure 4 shows the amount of data scanned and saved for a single VM instance across workloads. The x-axis shows the windows sizes in bytes. We see that naive hashing can save 12-14% of data from being scanned across all workloads. For PMN, we see the window sizes have little effect on the amount of data scanned with a savings of 40-45%. PMNP shows the greatest savings of 80-90%. Window sizes have a small impact on PMNP at 5% impact as a result of the smaller windows being able to identify more non-present regions. The differences between Figures 4(a) and 4(b) show that a busier machine does not impact Prefix Matching performance. In fact, we saw that a busy machine had an additional savings of ≈5%. For Figure 4(c), we see that more data needs to be scanned as more libraries and processes are loaded and run. This will affect the total time to scan a VM.

Figure 5 shows the percentage of data scanned for each VM workload as more VMs are added to be scanned. As a result, the tree encodes prefixes across multiple VMs allowing the potential prefix matching between VMs. We remove the variable window size and set it to 4KB across each scan as the previous figure indicates windows sizes have little impact on percent data to scan or save.

For the idle machine at login and the loaded webserver, the graph shows additional savings by adding VMs to scan at ≈20% and ≈60% for Naive and PMN. PMNP has little additional savings by adding VMs to scan.

For the unique GUI based tests, we see no additional savings across VMs. This is a result of different libraries and processes being loaded for different applications. This indicates that adding VMs to scan only provides benefit when the VMs being scanned are running similar applications.

Total Scanning Time: SEER adds processing time overhead which needs to be accounted when evaluating the performance of scanning. The overhead of SEER can be found from building the scan tree and forking the scanner thousands of times. To investigate the impact of this overhead, we scan the memory segments for all of the above configurations to investigate the wall time savings of using SEER.

Figure 7 depicts the per VM total scan times across different configurations. Each graph breaks down the costs for pre-processing (i.e., prefix matching and storage), forking scanner processes, and scanning. Across graphs we can see that the window size impacts total scan times by increasing pre-processing overhead. For PMN configurations, a 4KB window adds 1.5-2 minutes of scan time compared to a window size of 32KB. For PMNP, a 4KB window still adds additional overhead, but this is mitigated by savings during scanning. Overall, PMNP reduces the total scan time by 62-72% compared to Naive for a single VM. In line with our data saving results, Figures 7(a) and 7(b) show little difference in total scan time under different workloads. Figure 7(c) has a larger total scan time due to the difference in the amount of data scanned.

Figure 6 depicts the scan times across multiple VMs for a window size of 32KB as it provided the most scan time savings for a single VM as per the previous graph. The data shows that by adding more VMs, the total savings of PMN becomes ≈46% more efficient then Naive for the same workload. On the other hand, PMNP has little extra savings by adding additional VMs at 73.5% total scan time savings over Naive for the same workload.

The overhead associated with "Pre-Process" phase is independent of the virus scanner complexity. Thus, the results discussed above represent the computational and time savings when adapting a virus scanner containing the same complexity as ClamAV. If a more complex scanner is adapted, the savings is expected to be greater than the results above.

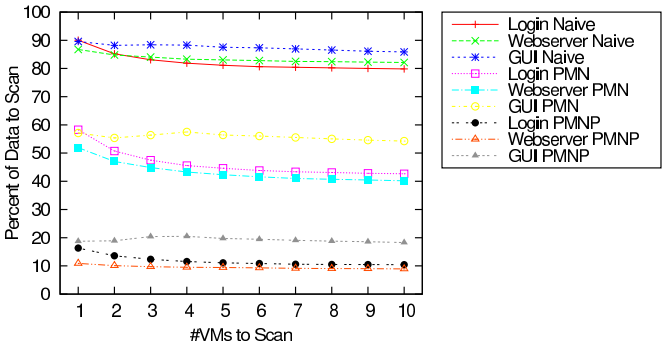


Figure 5: Percent Data to scan as VMs are scanned together. Windows size fixed to 4KB.

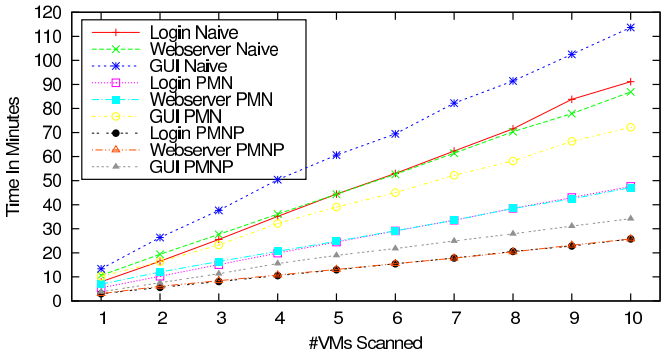
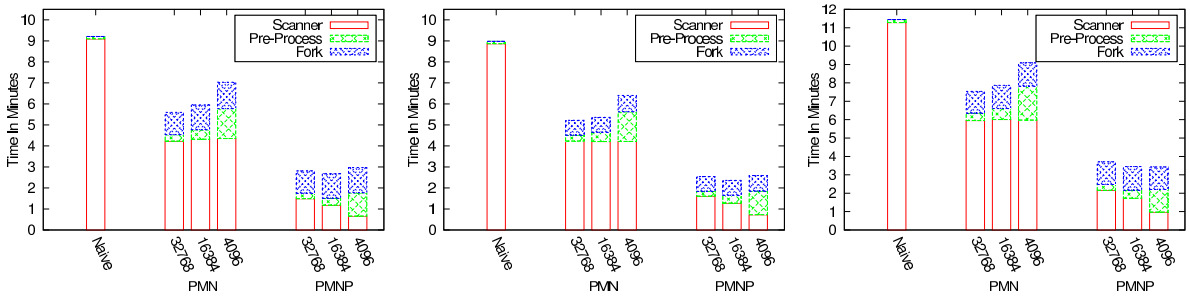


Figure 6: Total scan time across multiple VMs. Window sized fixed at 32KB.



(a) Boot to login (b) Loaded IIS webserver (c) Unique GUI applications

Figure 7: Total scan time for single VM under different loads and configurations.

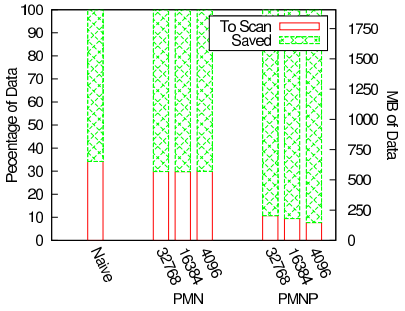


Figure 8: Percent data savings and to scan for warm cache Boot to login VM. X-axis is window size.

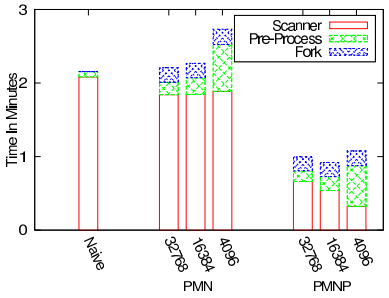


Figure 9: Total scan time for Boot to login VM with a warm cache.

Caching: After a VM has been scanned, hashes and status information of the scanned memory segments can be cached to prevent re-scanning identical segments in the future. We looked at the effectiveness caching segment hashes for future scans. Figure 8 and Figure 9 depict the benefits of warm caching for the "Boot to Login" configuration. Figure 8 shows a reduced percent data savings between Naive and PMN with a difference of 5-10% while PMNP and Naive have a savings difference of about 25-35%. Figure 9 shows the scan times for PMN and Naive were equal due to the overhead of pre-processing and forking. However, we still see a ≈50% reduction in scan times for PMNP at a window size of 32KB. We found similar results for both the loaded IIS server and GUI application configurations.

Write Working Set: During the Pre-Process phase in Figures 7 and 9, the QEMU process copy remains resident in memory and the guest VM continues to run. During this time, Copy-On-Write in the host is managing the Write Working Set, set of memory pages which have changed since forking. If the Write Working Set becomes too large, host memory can become depleted due to the dynamic nature of memory. We observed that our Write Working Set changes at rate of 100-300 MB per minute for the first minute. Given, the snapshot and shipping time is typically 4-10 seconds, the Write Working Set is not a concern.

4.3 Malware Identification/False Positives

SEER's effectiveness at identifying malware in memory is dependent on the adapted virus scanner's signatures. However, we still wish to verify the SEER correctly extracts memory segments that map to existing virus signatures for memory only malware and file based malware and investigate false positives using existing signatures.

To investigate ClamAV's ability to extract segments to find malware using existing signatures, we compromised one VM with the file based malware Cerberus RAT and another VM with the Memory-Only Malware Meterpreter. Both malware were configured to infect *explorer.exe*. SEER successfully found both malware running in the memory of the

Table 3: Malware samples from malc0de.com by type identified by SEER.

Malware Types	# Samples
Trojan.Adload	2
Trojan.NSIS.Agent	7
NSIS.Clicker.Agent	1
W32.AdInstall	1
Trojan.IRC.Zapchast	1
WIN.Trojan.DarkKomet	1
Trojan.Adload	1
Adware.Cpush	1
Trojan.Spy	2
Total	17

explorer.exe process showing that SEER can be used to identify both file-based malware and Memory-Only-Malware. We then collected 652 samples of malware from malc0de.com [13]. The samples were scanned with an unmodified ClamAV and 60 samples were identified as Malware. 17 samples were successfully run in a guest VM. SEER was able to correctly identify all 17 samples of malware from memory. Table 3 shows the malware types scanned identified by ClamAV.

To investigate false positives, we recorded all segments identified as malware by our modified ClamAV across each benign scan configuration. This set represents the false positives. We found all observed false positives can be categorized into two types. First, ClamAV marked host based virus scanner definitions as malicious. Specifically, ClamAV identified Windows Defender virus definitions loaded into memory as malware. On disk these definitions files are obfuscated thus do not trigger false positives. This problem can be addressed by white listing host scanner processes in memory. The second false positive type occurs from overly-broad ClamAV signatures which use MD5 hashes of zeroed data as virus definitions. We found 154 out of 2,056,340 MD5 signatures matched only zeroed data. These signatures should not be used for memory scanning. Upon removing these signatures from the definitions database and whitelisting scanner processes, no false positives were triggered.

5. DISCUSSION

Deploying SEER: SEER shows the best performance using PMNP configuration with a window size at 32 KB. The performance of PMNP is highly dependent on memory segments containing non-present data. If adapting Prefix Matched scanning for a host based memory scanner, non-present information is not encountered and thus performance would be comparable to PMN.

Security and Privacy Concerns: Memory contains the entire running state of a machine and thus contains very sensitive information such as encryption keys, browser data, etc. SEER extracts memory segments such that finding sensitive data may be easier for malicious parties. For example, a malicious party can quickly identify the webserver process which is known to contain stored SSL certificates. Thus, care must be taken when storing memory segments prior to scanning and properly removing benign data after analysis.

Virus scanners themselves have been known to be a target for attack [17]. Since SEER accesses sensitive data across potentially many VMs, care should be taken to ensure compromise of the SEER scanner itself is mitigated and identifiable. The simplest solution would be to isolate the scanner to a monitored machine and network.

Alternative Operating System Support: Our current implementation of SEER only supports Windows environments. However, SEER can support other operating systems by porting memory carving techniques for guest operating systems. We believe this to be a straightforward porting effort for well-known operating system structures. For example, Linux have structures called virtual memory areas that map directly to memory segments. For unknown operating systems, VMI techniques can be used to identify internal process structures and virtual memory [6].

Limitations: Currently, SEER does not attempt to extract paged-out memory from VM page-files or swap partitions. While it is technically feasible to extract paged-out memory from disk files, the overhead associated with extraction can have a significant negative impact on both host and guest VM operations. As a result, malware can attempt to avoid scanning by hiding in paged-out regions of memory which can cause false negatives. However, we argue that hiding malware in swap is non-trivial as (1) malware must use a deterministic mechanism to force the operating system to page out malicious content, (2) the deterministic mechanism must be in memory thus providing an indicator for hiding, and (3) scanning of memory cannot be bypassed.

SEER relies on memory forensic techniques to find and walk kernel data structures to extract memory segments. These techniques are commonly used by memory forensic tools [24] and popular Virtual Machine Introspection (VMI) solutions [6, 9]. However, walking kernel data structure is potentially vulnerable to Direct Kernel Object Manipulation (DKOM) attacks [3]. Unfortunately, identifying and preventing all DKOM attacks remains an open problem.

SEER provides detection of memory compromise but not protection. Thus, SEER cannot prevent infection of well-known malware or exploits. While security products often protect against infection by hooking file operations, exploitation commonly uses memory only techniques. As a result, security products can be disabled without notification once an exploit has code execution.

Finally, there is concern that attackers can allocate large memory segments by simple virtual memory allocation. SEER mitigates this potential impact by providing page status to the scanner to bypass non-present memory. To force SEER to scan data, the attacker must fill allocated memory with random data thus requiring the scheduler to store unique data. However, this process would deplete system resources exposing malicious activity.

Using Existing Virus Scanner Signatures: We show in our evaluation that existing signatures for file based scanning can be used to identify malware in memory. This obviates creating all new signatures to adapt to memory scanning. However, the effectiveness for matching viruses is dependent on the correctness and precision of signatures. Furthermore, signature based scanning has known limitations and thus SEER suffers from the same limitations.

6. RELATED WORK

Jiang et al. [9] provided virus scanning for individual virtual machines by scanning files on running Virtual Hard Drive (VHD) and physical memory from the hypervisor. Unfortunately, scanning from the hypervisor can impact host and VM performance. Also, scanner vulnerabilities can lead

to complete system compromise putting other VMs on the host at risk [17]. SEER instead performs scanning off host in an isolated environment while scanning virtual memory to correctly match virus definitions.

Wei et al. [25] presented scanning offline logical VHDs stored in a customized deduplicated image library. The authors were able to show a reduction in virus scanning efforts by only scanning unique files once across all logical VHDs. Similarly, Soules et al. [20] discussed how to efficiently schedule virus scanning for an enterprise network by scanning unique files only once. These approaches rely on the static nature of files on disk to reduce scanning efforts. However, SEER instead focuses on efficiently scanning dynamic memory for live running virtual machines.

Oberheide et al. presented CloudAV which describes how to increase the effectiveness of file virus scanning by using multiple pieces of scanning software [17]. Services such as VirusTotal, Jotti, and NoVirusThanks provide multi-scanner virus scanning similar to CloudAV without an end client. CloudAV and similar tools rely on data files being similar across machines and thus only unique files need to be scanned. However, the authors do not discuss how to handle dynamic data. SEER instead provides a new technique to increase scanning efficiency of memory.

Trend Micro recently released a VMWare appliance called "Deep Security" capable of agentless virus scanning of virtual machine files using a central virtual appliance for VMWare [4]. Unfortunately, Deep Security only supports file based scanning and relies on the static nature of files to enable scalability. In contrast, SEER tackles the hard problem of enabling virus scanning of highly dynamic data.

7. CONCLUSION

In this work we proposed SEER, an architecture for enabling Memory Virus Scanning-as-a-Service for virtualized environments. SEER overcomes several challenges of memory scanning by transparently and efficiently scanning memory outside of the context of the analyzed VM. SEER quickly and correctly acquires virtual machine memory and we show in the empirical evaluation our technique has minimal impact on VM operations and hosting environments. We propose a new approach for scanning memory by normalizing memory, matching similar prefixes across memory, and then scanning based on prefix data. Our results show that our approach has a 72% reduction in wall time and scanning efforts compared to existing naive scanning approaches. Our approach can be directly applied to existing host based memory scanners to reduce scanning efforts by up to 46%.

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