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Detecting Hardware-assisted Hypervisor Rootkits within Nested Virtualized Environments

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DETECTING HARDWARE-ASSISTED HYPERVISOR ROOTKITS WITHIN NESTED VIRTUALIZED ENVIRONMENTS

THESIS

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Abstract

Virtual machine introspection (VMI) is intended to provide a secure and trusted platform from which forensic information is gathered about the true behavior of malware within a guest. However, it is possible for malware to escape a guest into the host and for hypervisor rootkits, such as BluePill, to stealthily transition a native OS into a virtualized environment. This suggests that VMI scenarios provide an environment where it is possible for malware to escape the guest, obtain privileged access to the processor, insert a thin hypervisor rootkit beneath the host, and gain near-perfect visibility into the guest and host by transitioning them into a nested virtualized environment. This research examines the effectiveness of selected detection mechanisms against hardware-assisted virtualization rootkits (HAV-R) within a nested virtualized environment. It presents the design, implementation, analysis, and evaluation of a hypervisor rootkit detection system which exploits both processor and translation lookaside buffer-based mechanisms to detect hypervisor rootkits within a variety of nested virtualized systems. It evaluates the effects of different types of virtualization on hypervisor rootkit detection and explores the effectiveness of a likely countermeasure which is tested for its ability to obfuscate the existence of a hardware-assisted hypervisor rootkit.

Experiments are performed in a laboratory environment consisting of a notional VMI system which is implemented using four different hypervisor configurations representing three different virtualization types. Detection measurements are taken on a non-subverted VMI system and compared to those taken after one of two notional

HAV-Rs (BluePill and ESXi) is installed on the VMI system resulting in a subverted VMI (SVMI) system. A third set of readings are taken on the SVMI system after an obfuscation agent is installed within the guest. When analyzed using the Wilcoxon rank sum test for non-parametric data, a p-value of $< 2.2e-16$ is obtained for all VMI to SVMI comparisons. This rejects the null hypothesis that the population distributions are identical and provides convincing evidence that the HAV-Rs are detectable in all SVMI scenarios, regardless of hypervisor type. Furthermore, it indicates that the selected detection techniques are effective at detection of HAV-R and that the type of virtualization implemented in a VMI system has minimal to no effect on HAV-R detection. Finally, the results indicate that in-guest obfuscation does not significantly obfuscate the existence of HAV-R.

Acknowledgments

My sincerest thanks and appreciation go to my wife whose patience, support, and love were a constant source of inspiration and energy during this research. You are an amazing woman, wife, and mother to our children. Next, my advisor Dr. Barry E. Mullins who never unduly constrained my work and let me see just how far the virtualization rabbit hole really goes. Also, Professor Cynthia C. Fry of Baylor University. All students have those teachers who leave a particularly lasting impression; thank you for your faith and guidance. Finally, special thanks go to Herr Hagen Fritsch who contributed the original driver framework which was used to develop HyperScan. *Ich bin Ihnen sehr dankbar*. I am very grateful for your help.

Daniel B. Morabito

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DETECTING HARDWARE-ASSISTED HYPERVISOR ROOTKITS WITHIN NESTED VIRTUALIZED ENVIRONMENTS

I. Introduction

Hardware-assisted Virtualization Rootkits (HAV-R) are a unique type of malware that exist at a lower level than normal native operating system (native OS) operation [RuT07a]. As such, detection of HAV-R is particularly unique since they are not vulnerable to usual kernel-based rootkit detection mechanisms. This makes HAV-R an attractive option for cyber adversaries who desire an undetected presence on a target system. However, HAV-Rs are not proven to be undetectable and previous work has successfully demonstrated several hypervisor detection techniques [Ada07] [Fer08] [Fri08]. These techniques are, for the most part, unique to hypervisor detection and are not generally implemented as part of a host-based defense such as anti-virus software.

Previous research focused on detection of a single hypervisor with the assumption that if the user had not previously installed a hypervisor and one is detected, that this is evidence of a HAV-R [Fer08] [Fri08]. This thesis extends this research by applying three of the most promising HAV hypervisor detection techniques (SMP Counting, SVME Check Timing, and TLB Profiling) to determine if it is possible to detect HAV-R within a nested virtualized environment. This is novel because a HAV-R detection system within a nested virtual environment cannot assume that simple detection of a hypervisor is sufficient for HAV-R detection.

The nested virtualized environment used for experimentation models a virtual machine introspection (VMI) scenario where a user within the native OS uses a trusted hypervisor to introspect a guest OS containing potential malware. This is a common, real-world forensics scenario where malware is likely to exist within a virtualized environment. This scenario is also easily extended to more benign scenarios such as those that use virtualized systems to isolate applications; for example, the use of virtualization to isolate banking applications from social media applications and personal files. From an organizational perspective, the ability of VMI to provide cyber situational awareness makes it a potentially attractive enterprise security solution for detecting, monitoring, and recovering from cyber attack [Dod10]. Complete Air Force implementation of VMI would have a significant impact on how the organization manages its information systems as well as its overall cyber security posture. VMI may also represent a cost-effective supervisory control and data acquisition (SCADA) security solution for monitoring and management of multiple diverse systems [KaC11].

Situational awareness based on VMI assumes that the introspection tool accurately represents the true state of the guest OS and that the tool remains trustworthy. It is therefore imperative that subversion techniques such as HAV-Rs are evaluated for their ability to remain undetected within nested virtualized environments. The effect of different virtualization types on HAV-R detection within nested virtualization environments must also be considered.

1.1. Goals

The goal of this research is to answer the following questions:

1. Is it possible to detect a HAV-R within a nested virtualized environment using the hypervisor detection techniques of SMP Counting, SVME Check Timing, and TLB Profiling?
2. How do different virtualization types affect HAV-R detection using selected techniques?
3. What is the effectiveness of in-guest execution designed to obfuscate the existence of a HAV-R?

Overhead is the additional workload encountered by a system as the result of virtualization. It is hypothesized that the overhead caused by a pre-existing, trusted hypervisor is sufficient to obfuscate the overhead caused by the existence of a HAV-R and that, in cases where the HAV-R is detectable, deliberate execution of privileged instructions within the guest OS is sufficient to obscure the HAV-R.

1.2. Assumptions and Limitations

This research is conducted under several assumptions. First, it is assumed that malware can escape from a guest OS and install a HAV-R beneath the native OS without detection. All experiments of subverted systems are therefore assumed to begin after the HAV-R has been installed and any installation agent has been removed from the target machine. Second, the HAV-R detection system is assumed to be trustworthy and to experience no direct interference beyond that which occurs due to normal operation of the native OS. Third, the detection system is assumed to provide the statistical analysis required for HAV-R detection. As part of the research effort, detection software is developed to collect detection-oriented data however, the statistical analysis is performed manually. It is left to future work to integrate the statistical analysis tools into the detection software.

Research evaluation is limited to 64-bit Windows Vista Business as the native OS and 64-bit Windows 7 Professional as the guest OS. BluePill, one of the two HAV-Rs used for experimentation, is designed for exclusive use with 64-bit Windows Vista which constrains the native OS to this platform. For the guest OS, 64-bit Windows 7 Professional is selected since it represents a current and commonly used OS.

This research is also limited in terms of the breadth of HAV-Rs examined. Of the two examples used for this research, BluePill is a true but purely academic example of a HAV-R that was created in 2006 and therefore may not be considered a state-of-the-art implementation of HAV-R. The second example, ESXi, is not a true HAV-R but is chosen as a simulated HAV-R - a thin hypervisor with HAV-R-like characteristics. While it is likely that other real-world implementations of HAV-R exist, they are difficult to locate, likely since this area of virtualization-based attack is relatively new and is seemingly not yet widely exploited. The two HAV-Rs selected are a best-effort representation of likely real-world HAV-Rs.

Finally, this research is limited to the AMD-V architecture as implemented by the Athlon 64 X2 7750 Black Edition Dual Core 2.70 GHz processor used during testing. While it is likely that the detection techniques work just as well for other architectures, this cannot be assumed.

1.3. Research Contributions

This research evaluates selected HAV-R detection techniques and compares the effects of different virtualization types on the detection of HAV-R within nested virtualized environments. This is an unexplored area of virtualization research which is particularly applicable to VMI environments used for forensics research. Additionally, existing hypervisor detection techniques are extended and consolidated into two software tools, HyperScan and Cloaker, which perform HAV-R detection and obfuscation respectively. These detection techniques, applied in the novel form of HyperScan, are used to perform the requisite data collection and analysis for this thesis and establish a previously non-existent foundation for automated detection of HAV-Rs.

1.4. Thesis Organization

This chapter presents an introduction to the research effort including thesis goals, assumptions, limitations, and research contributions.

Chapter II provides background information on general virtualization concepts, a description of the particular hypervisors used for this thesis, an examination of hypervisor and host subversion techniques as they specifically relate to virtualization, and discussion of the HAV-R detection techniques with special emphasis on those used for this research.

Chapter III presents the methodology used in this research to include system inputs, outputs, parameters, and a description of the factors and their levels. It also provides information on the software developed for this research effort.

Chapter IV presents an analysis of the results gathered by the HAV-R detection system. These are interpreted using statistical analysis and reveal the effectiveness of the detection techniques, the effectiveness of the obfuscation tool, and the effect of different virtualization types on HAV-R detection.

Chapter V presents a summary of the conclusions drawn from the analysis performed in Chapter IV and recommends future work.

Various appendices are included that detail how to reproduce the virtualized environments and experimentation conducted as part of this research effort. Additionally, statistical figures which are not included in Chapter IV due to size constraints are included in Appendix H for reference.

II. Background

This chapter provides a survey of virtualization concepts as well as offensive and defensive virtualization paradigms. The particular hypervisors, hypervisor rootkits, and detection techniques used for this research are discussed as well as general techniques for hypervisor and host subversion.

2.1. General Virtualization Concepts

2.1.1. The Roots of Virtualization

Virtualization's resurgence over the past decade as an attractive option for efficient use of server and computer resources may create the impression that virtualization is a new technology [Gol08]. In fact, virtualization concepts and applications have existed for at least fifty years [Cre81] and can be traced back to a desire that is as old as computing itself; to do more with less and to most efficiently use the tools that are available.

The initial concepts of virtualization originated in the early 1960s from the requirement to more efficiently use scarce and expensive computational resources [Cre81]. Computers during this time existed almost exclusively within the realms of military and academic research and were in such high demand that using them efficiently was a primary and constant concern [Cor63] [Cre81]. This led to intense interest in devices that could execute more than just a single program at a time and the corresponding development of machines which were capable of handling the execution of multiple programs simultaneously through the use of time-sharing and process scheduling. Time-sharing is the rapid time-division multiplexing of a central processor unit among the jobs of several simultaneous users [CoV65]. The result was a transformation from computers which could handle only a single process from beginning to end, to machines capable of handling multiple simultaneous processes from multiple simultaneous users.

One of the earliest examples of this transformation was the result of efforts by Massachusetts Institute of Technology (MIT) and International Business Machines (IBM) in the early 1970s and was called the Virtual Machine/370 Time-Sharing System (VM/370), originally called the pseudo-machine time-sharing system. This VM consisted of three separate systems; a Control Program, a Remote Spooling and Communications Subsystem, and a Conversational Monitor System. The Control Program and Remote Spooling and Communications Subsystem served as what is now referred to as a hypervisor, or virtual machine monitor (VMM). These systems were responsible for managing time-sharing and process scheduling while abstracting the underlying physical system in such a way that each user was presented with what appeared to be their own singularly dedicated system; their own VM. The Conversational Monitor System served as the guest operating system (guest OS) through which multiple users were able to simultaneously interact with the system [Cre81]. These basic concepts of a hypervisor and one or more guest OS's which share a physical architecture form the basic model for modern virtual machines.

The VM/370 software was provided with IBM's System/370 Model 138 (Figure 1) which boasted 1,048,576 characters of memory, double that of its immediate predecessor. The system could be purchased in 1976 for $350,000-$435,000 [IBM11]. The "million character memory" version could be leased for $11,415 a month, or approximately $45,120 in year 2012 dollars (adjusted for inflation)—this is an effective cost of approximately $1 (adjusted for inflation) per minute or $1,440 (adjusted for inflation) a day to lease this device [IBM11] [USB11]. Given the high cost of such systems, efficient use of the system was extremely important to consumers. The VM/370's design

Figure 1. IBM System/370 Model 138 [IBM11]

included Massachusetts Institute of Technology's Compatible Time-Sharing System (CTSS). CTSS provided a subset of the host machine for use by different programs through use of a time-sharing supervisor; a hypervisor component which balanced and allocated computational resources in a way that was completely transparent to guest programs. When implemented in the VM/370, it was able to provide multiple users with seemingly separate and independent computing systems [Cre81]. This design, along with many of its designers, heavily influenced the creation of MIT's ground-breaking time-sharing operating system called “Multiplexed Information and Computing Service” or MULTICS [Cre81]. MULTICS’ use of time sharing and ring-based access control, built upon the ideas expressed in the VM/370 design, went on to influence UNIX and, in turn, much of the modern computer functionality experienced today [Bis02].

Throughout the 1980s, computer technology advanced rapidly and the cost of hardware declined, consequently reducing interest in the efficiencies offered by virtualization. Then, in the 1990s, researchers at Stanford University took a renewed interest in virtualization as a tool to implement *massively parallel* processing machines with the goal of building increasingly powerful computers through the use of distributed computing [RoG05]. Ironically, the proliferation of computing machines caused by the lower hardware costs of the 1980s and early 1990s sparked renewed interest in finding ways to more efficiently use the combined resources of these disparate systems and instigated a resurgence of virtualization over the last decade [RoG05].

2.1.2. Virtualization Definition & Theory

Virtualization can be considered an abstraction of computer resources [JML10] and described as “an efficient, isolated duplicate of [a] real machine” [PoG74]. A more precise definition, as it specifically relates to virtual machines, describes virtualization as a technique by which the physical resources of one or more host machines are abstracted, managed, and shared to one or more guest OS’s in such a way that the guest OS’s perform as if they are interacting directly and independently with those physical resources [Bis02]. In this sense, “virtual” is different from “reality” only within the formal world [JML10]; within the computer world, which itself exists as a mathematical model and an abstraction of the “real” world, a virtual environment is perceived exactly the same as that of a real environment, regardless of any formal differences in the underlying mechanisms.

One of the first attempts to formerly model the concept of virtualization identified the following three essential characteristics for virtualized architectures [PoG74]:

- Equivalency – The effect of virtualization must be such that the guest OS is provided an environment essentially equivalent to the environment experienced when the guest OS is running directly on the hardware.
- Efficiency – Virtualization must achieve the performance of the virtualized hardware with minimal efficiency loss.
- Resource Control – Access to "real" resources must be managed by an arbitration agent (the hypervisor) which ensures that (1) it is impossible for a guest OS program to access any resource that is not explicitly allocated to it, and (2) the hypervisor can interrupt and regain control of resources which it has previously allocated to the guest OS.

Practically, these characteristics are achieved through use of an architecture consisting of "real" underlying hardware (the host machine), a virtual environment consisting of virtualized hardware (the VM), a management/arbitration agent (hypervisor) responsible for resource control, and a hosted guest OS (Figure 2).

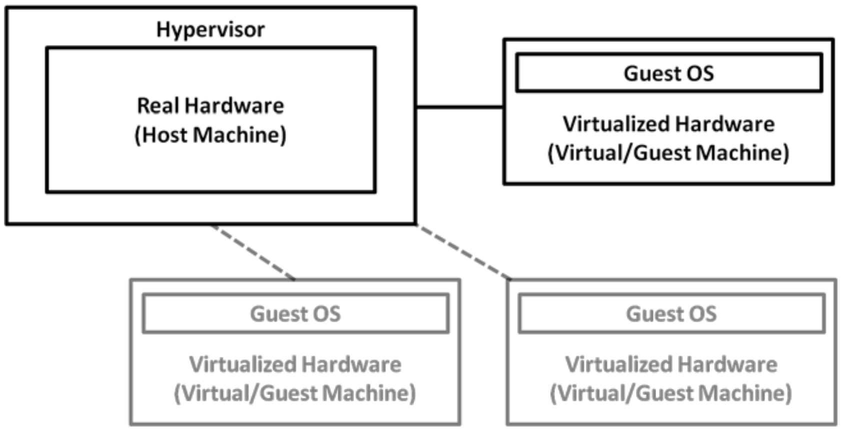

Hypervisor
Real Hardware (Host Machine)
Guest OS
Virtualized Hardware (Virtual/Guest Machine)
Guest OS
Virtualized Hardware (Virtual/Guest Machine)
Guest OS
Virtualized Hardware (Virtual/Guest Machine)

Figure 2. Virtualization Architecture

Note that the hypervisor's resource control capability is shown graphically to encapsulate the underlying hardware, that each virtual machine hosts its own guest OS, and that the host machine may support more than one virtual machine.

2.1.2.1. Real Hardware (Host Machine)

The underlying hardware is composed of any physical resources that directly support the VM. Typically, this includes one or more processors, memory, hard drives, other detachable storage devices, a network interface card, and input/output (IO) devices such as a mouse and keyboard.

Since each processor has its own particular instruction set architecture which specifies how it operates and how it handles access control, both the processor and its instruction set architecture must be considered when implementing virtualization. The Intel x86 instruction set architecture is a common architecture used for virtualization which uses a two-bit protection ring architecture to enforce access control. These two bits provide four possible modes of operation ("00", "01", "10", and "11"; referred to as Rings 0, 1, 2, and 3). This can be visualized as concentric circles of protection rings or *operational* *modes* where the innermost ring, Ring 0, has the most privileges, and the outermost ring, Ring 3, has the least (Figure 3).

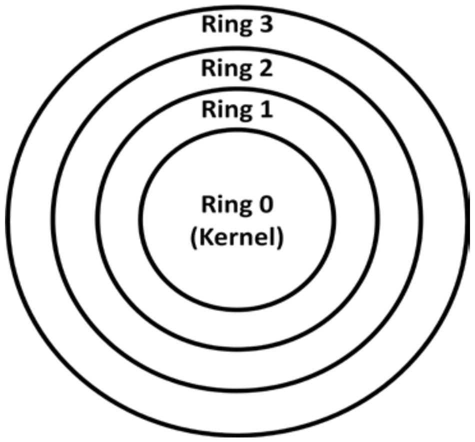


Figure 3. The x86 Protection Ring Architecture

This model enforces security by delineating modes of operation which limit operations performed at lower privilege levels from performing actions reserved for operations performing at higher privilege levels. This serves to isolate higher privilege processes, such as kernel-level processes (Ring 0) from interference from lower privilege processes. This separation is critical since the kernel is responsible for process management, file access, security, and memory management within the OS [HoB05]. In practical use, only Ring 0 (Kernel-mode) and Ring 3 (User-mode) are used by most OS's.

Since the innermost ring, Ring 0, belongs to the kernel, exceptions must be made for virtualization where the hypervisor must have the highest privilege level. This results in a situation where the hypervisor is considered to operate at Ring -1 (minus one), the kernel at Ring 0, and the user at Ring 3. The notional existence of a Ring -1 is referred to as Ring Compression.

Some hardware is specifically designed to support virtualization, although software-only virtualization is also common. Examples of hardware designed to support virtualization include AMD Virtualization (AMD-V) and Intel's Virtualization Technology for the IA-32 architecture (VT-x), which both provide x86 instruction extensions that can be used by the hypervisor for improved efficiency and security [AdA07]. This is further discussed in Section 2.1.3.4.

2.1.2.2. Hypervisor

The hypervisor, also referred to as a "virtual machine manager" (VMM), abstracts, manages, and shares the underlying physical architecture with one or more guest OSs by presenting them with a set of virtual interfaces which constitute a virtual machine [NSL06]. Since the resources of the underlying physical layer are abstracted by the hypervisor, the hypervisor has complete control over how those resources are allocated to the guest OSs. It can allocate as many or as few of the resources as its configuration settings and the physical limitations of the system allow. It is even possible to share the physical resources of different physical machines in such a way as to have them provided to a VM as a virtual, single, and unified physical layer [TrH09].

The hypervisor's functionality is similar to how an OS manages the state of each of its processes. Control is maintained by trapping (pausing execution and passing control to the hypervisor) whenever a privileged instruction is executed by the guest OS. This transfer of control within the processor is called a *context switch*. The hypervisor services the privileged instruction, providing the illusion that the instruction is executed directly on the hardware, and passes control back to the guest OS [Bis02]. There are configurations which, due to the hypervisor's ability to intercept all interesting events before they reach actual hardware, make the hypervisor more privileged then the host OS. In such configurations, the hypervisor is considered an *enhanced privileged host* and may be described as running at Ring -1 [RoG05] [Fer08]. The hypervisor uses various techniques to manage and present resources to the guest OS. Several of these techniques are covered in Section 2.1.3.

2.1.2.3. Virtual Machine

The virtual machine consists of the set of interfaces which simulate hardware and are supplied by the hypervisor to the guest OS.

2.1.2.4. Guest Operating Systems

Guest OSs run independently of each other and interact only with allocated parts of the underlying physical layer which comprise the virtual machine. Since the hypervisor provides these parts as simulated hardware interfaces, the guest OSs usually execute as if they are on their own stand-alone hardware, unaware that they exist as a VM and are sharing resources with other guest OSs.

2.1.3. Types of Virtualization

Two notional virtualization configurations are shown in Figures 4 and 5. Figure 4 depicts multiple VMs supporting a variety of OSs and running on a single host. Figure 5 also depicts multiple VMs supporting a variety of OSs but in this case, the hypervisor utilizes the resources of a distributed physical architecture consisting of multiple physical machines. Note that the abstraction of the physical layer presented by the hypervisor to the guest OSs makes it seem as though each VM is running directly on its own dedicated physical hardware.

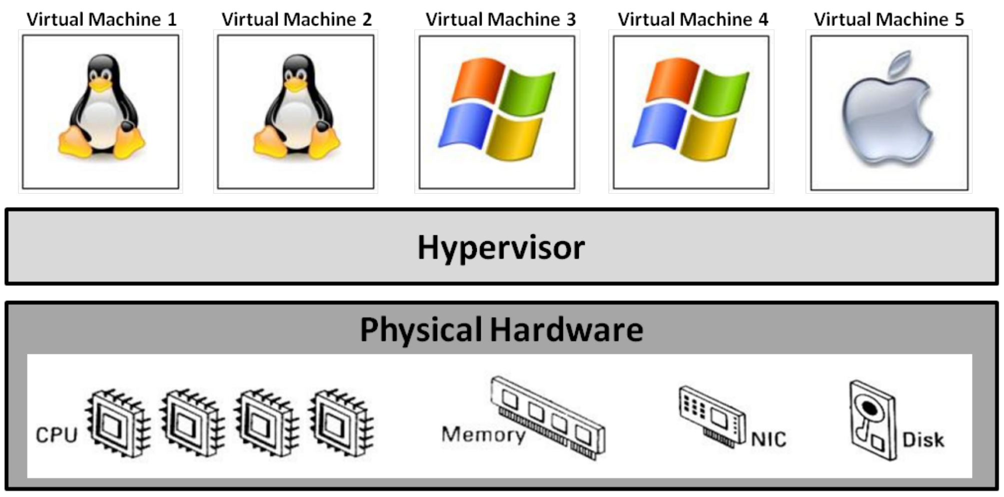


Figure 4. Multiple VMs Sharing a Single Host Machine
Adapted from [Dod10]

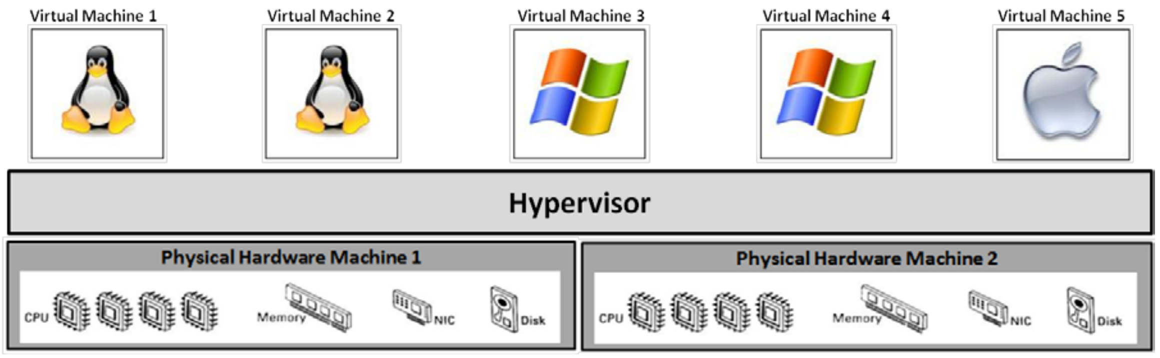


Figure 5. Multiple VMs Sharing Two Host Machines

Also note that it is possible for the hypervisor to reside within the native OS or beneath the native OS and directly on top of the underlying hardware. This is referred to as Type I or Type II virtualization. Type I virtualization is characterized by a VM which runs on a "bare metal" or "native" hypervisor that is implemented within or directly on the hardware and which controls all communication between the hardware and the guest machines [GrG11]. Type II virtualization is characterized by a VM which exists within a hypervisor that runs as an application within a host operating system environment [GrG11].

Virtualization methods can be differentiated based on three characteristics: the location of the hypervisor (Type I or Type II), the degree of modification required for the guest OS to operate, and the performance impact of virtualization on the system. From these characteristics, five distinct categories of virtualization are commonly identified: OS Virtualization, Emulation, Paravirtualization, Full Virtualization using Binary Translation, and Hardware-assisted Full Virtualization.

2.1.3.1. Operating System (OS) Virtualization

OS Virtualization, also known as "Partial Virtualization", "Single Kernel Image", and "Container-based Virtualization", is characterized by a design that does not abstract the underlying native OS's kernel or its physical resources through use of a hypervisor (Figure 6). Since the guest OS and the native OS share a common kernel, they must both be instances of the same OS – a critical characteristic of OS Virtualization. When multiple guest OSs, often referred to as "containers", run on the same physical machine, they do so independently, unaware of any other guest OSs. In this configuration, when one OS utilizes resources, it makes those resources unavailable to any of the other guest OSs [Dod10]. OS Virtualization is intended to enforce a degree of isolation between guest OSs while maintaining efficient use of system resources by removing the hypervisor emulation process between the guest and host machines [RoG05]. Use of this virtualization technique is primarily motivated by a desire for increased performance over other virtualization methods and has been demonstrated to provide up to twice the performance of hypervisor based systems for selected server-type workloads [SPF07]. In this virtualization type, a hypervisor is not used (although some sort of resource arbitration may occur within the kernel), the guest OSs do not require modification, and the performance impact of virtualization on the system is minimized.

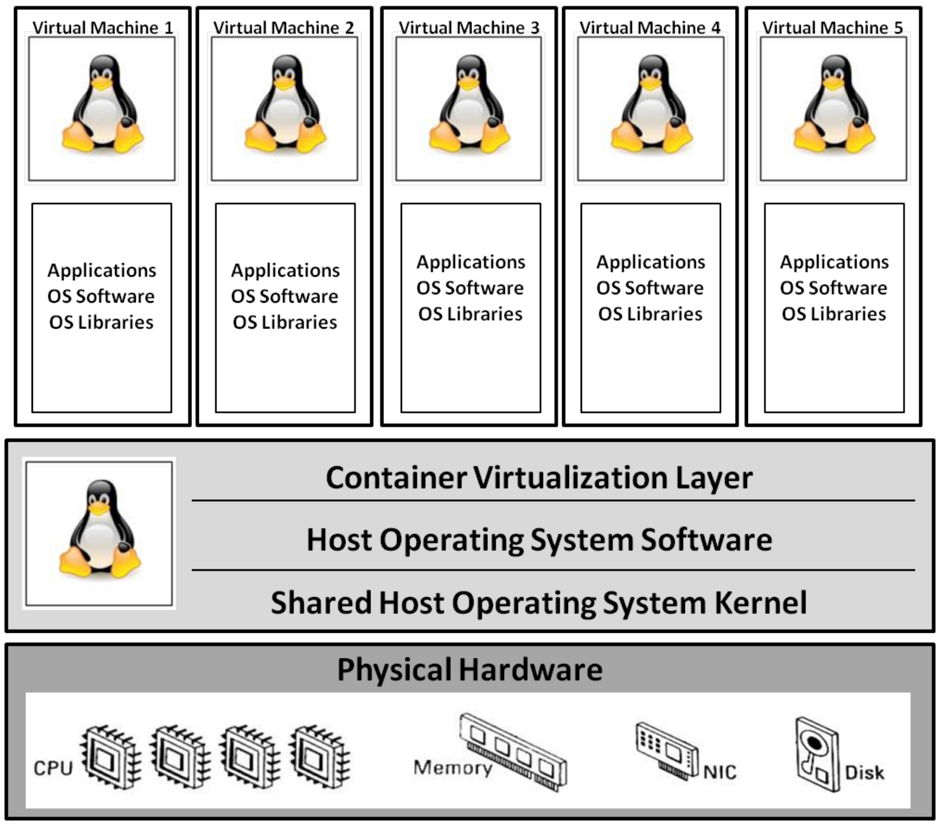


Figure 6. OS Virtualization
Adapted from [Dod10]

Examples of OS Virtualization include the Unix *chroot* operation, Linux-VServer, Open VZ, and the FreeBSD Jail mechanism (SPF07).

2.1.3.2. Emulation

Emulation, also called CPU simulation, is characterized by a Type II pure software hypervisor which runs as an application within the host OS and translates instructions received from the guest OS into instructions compatible with the underlying

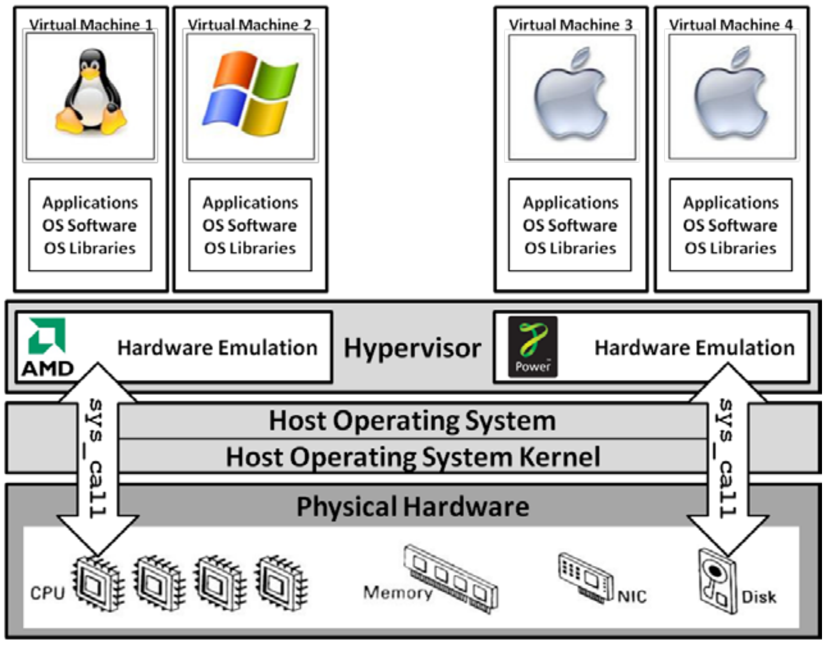


Figure 7. Emulation

Architecture (Figure 7). When a guest OS makes system calls to the virtualized hardware, the hypervisor translates those calls into instructions which are compatible with the underlying hardware using a process called dynamic binary translation. These translated instructions are passed to host OS which relays them to the underlying architecture. This process completely abstracts the physical layer, making it possible for the hypervisor to emulate physical features that do not actually exist, to include emulation of a CPU that does not match the underlying CPU [Fer08]. The chief benefit of emulation is the flexibility to run guest OSs that require physical hardware which may or may not physically exist within the system [Gol08]. This flexibility comes at a significant performance cost due to the overhead caused by the burden of dynamic translation and the added constraint that the emulator cannot directly access the hardware [DFL11]. A limited benefit of hardware emulation is its usefulness in providing backwards compatibility for older, obsolete technologies. This is helpful for retaining access to preserved data on legacy systems [HHK09]. Emulator examples include Bochs, Hydra, and QEMU [Bel05] [Fer08].

2.1.3.3. Paravirtualization

Paravirtualization is characterized by a hypervisor which does not fully abstract the underlying physical architecture of the system. Instead, as shown in Figure 8, it virtualizes some features of the physical layer while allowing the guest OS direct access to others. This direct access is sometimes referred to as a *hypercall*. The hypervisor itself resides on the hardware and is considered a Type I, "bare metal" virtualization architecture [Gol08]. In order for an OS to run properly on such a system, the kernel must be modified to interface both with the hypervisor and with those parts of the underlying system which it must directly access. Device interaction relies on native device drivers which operate within the host kernel. The host kernel is then responsible for coordination of device drivers as they are utilized by both the host and guest OSs [Kir07]. Such modified guest OSs are sometimes referred to as "aware" or "enlightened" since they have been altered and therefore can more easily detect that they

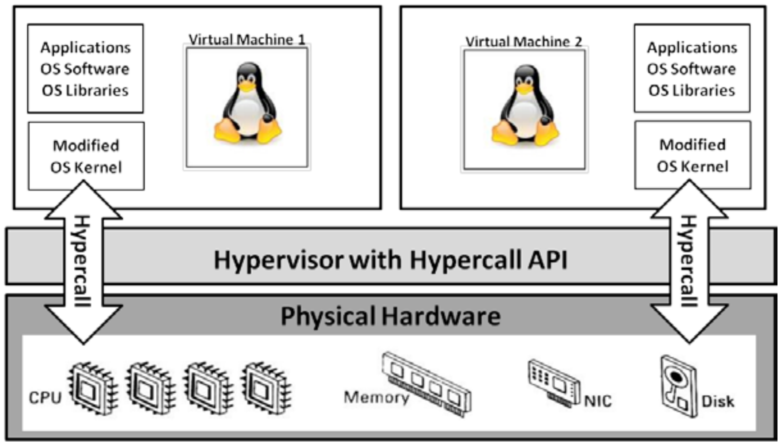


Figure 8. Paravirtualization
Adapted from [Dod10]

are running as a VM. Since the guest OS kernel must be modified in order to make direct calls to the physical hardware, only those OSs which can be modified can be implemented on a paravirtualized system. Closed source OSs, such as Microsoft Windows, cannot be paravirtualized since they are proprietary and their kernel cannot be modified. Hyper-V, a Microsoft-created, hypervisor-based virtualization system, has features that attempt to implement paravirtualization however, due to the inability to modify the OS kernel, Microsoft systems still cannot be paravirtualized in the strictest sense of the term. Open source OSs, such as Linux, often come with paravirtualization APIs which support paravirtualization. Paravirtualization provides increased system performance over dynamic binary translation techniques used by emulation and full virtualization through use of hypercalls. Hypercalls allow direct access to underlying hardware while avoiding the costs associated with trapping and interpreting every individual instruction. Additionally, through use of built-in paravirtualization APIs within the guest OS, such systems are particularly unique in their ability to share data between guest OSs [Kir07] [Dod10]. Examples of paravirtualization include some versions of VMware, ESX, and Xen.

2.1.3.4. Full Virtualization

Full virtualization simulates all aspects of a physical computer such that guest OSs are able to run unmodified directly on the simulated physical architecture of the host machine (Figure 9) [Dod10]. Full virtualization is similar to emulation in that it uses binary translation and requires no modifications to the guest OS; however, it is different in that full virtualization hypervisors are Type I while emulation hypervisors are

Type II. Full virtualization uses binary translation, hardware assisted virtualization, or a combination of both techniques.

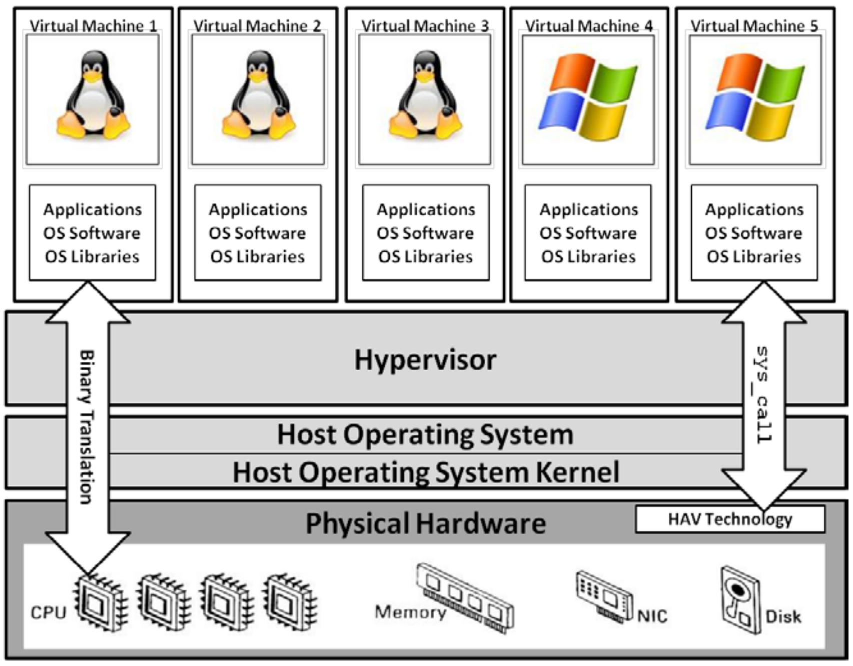


Figure 9. Full Virtualization and Hardware-assisted Virtualization

The primary method used by full virtualization to provide the effect of a virtualized processor is called binary translation. Binary translation provides on-the-fly translation of non-virtualizable processor instructions into equivalent virtualizable instructions. This allows non-virtualizable privileged instructions to execute as if they are privileged and does so with negligible overhead when compared to emulation and paravirtualization [RoG05].

In true full virtualization, the complete physical architecture of the underlying machine must be virtualized, to include all access to the CPU. A CPU's architecture can be virtualized if it supports direct execution of guest OS instructions while ensuring the hypervisor retains full control of the CPU [RoG05].

Up until recently, this practice was impractical for x86 processors since they were not designed with virtualization functionality built into the processor. Technologies such as Hardware-assisted Virtualization (HAV) address this constraint by extending the processor to support virtualization by direct execution.

To enable direct execution, the processor instruction set architecture is extended to provide extra instructions which directly support virtualization [Kir07] [Fer08]. The ability to support simultaneous states for both the hypervisor and the guest OS within the processor is critical to HAV and requires additional processor capabilities. Two examples of HAV are Intel's VT-x technology and AMD Virtualization (AMD-V). Both extend hypervisor operation into the CPU, allowing faster execution of guest OS code directly on the processor while maintaining the equivalency, efficiency, and control constraints required for virtualization [HeA11] [PoG74].

AMD-V offers Secure Virtual Machine (SVM) extensions which create and manage the virtualized and non-virtualized states (contexts) within the processor. Also included is a Virtual Machine Control Block (VMCB), a memory structure which stores both native and virtual machine context data. This enables two mutually exclusive modes of CPU access and execution for the hypervisor and guest OS. See [MyY07] for an excellent discussion of AMD-V functionality specifically as it relates to HAV-R.

Intel's VT-x also provides two mutually exclusive modes of CPU access and execution: VMX root operation (host mode) and VMX non-root operation (guest mode). An in-memory Virtual Machine Control Structure (VMCS), similar to AMD-V's VMCB, controls transitions between the two modes via two instructions: VM-Entry (transition from VMX root mode to non-root mode) and VM-Exit (transition from VMX non-root mode to VMX root mode). Figure 10 provides a state diagram depicting Intel VT-x's ability to context switch based on the VM-Entry and VM-Exit commands.

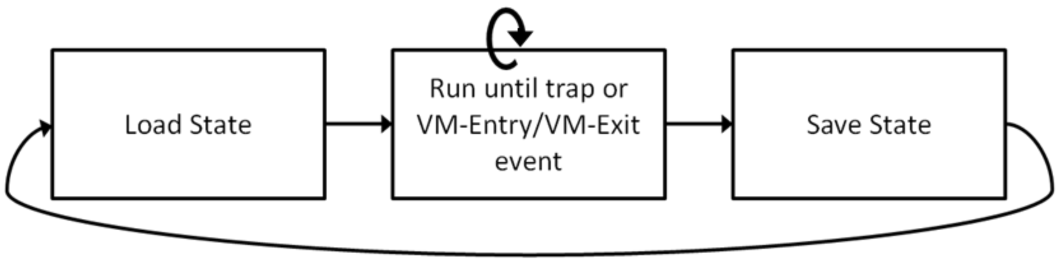


Figure 10. Intel VT-x Virtualization State Diagram

The VMCS contains host-state and guest-state areas which store processor state information for each mode of operation. This includes register values, the processor's interruptability state, and how it is configured to handle non-maskable interrupts. See [NSL06] for additional information on Intel VT-x Technology.

In practice, full virtualization is currently not usually implemented as pure binary translation or pure HAV, rather hypervisors use a blend of both techniques to achieve the best possible execution performance. Examples of full virtualization include Xen, VMware, VirtualBox, and Virtual PC.

2.1.4. Nested Virtualization

Nested virtualization describes the execution of a virtual machine within a virtual machine. This capability depends on the host hypervisor's ability to adequately provide virtualized hardware which supports virtualization within the guest hypervisor. It is observed that, for selected hypervisors, host hypervisors which use HAV are a likely suitable choice for nested virtualization and that paravirtualization and binary translation hypervisors are likely suitable as guest hypervisors; especially when the host hypervisor adequately virtualizes the processor's memory management unit [Ber10]. It is theorized that once a HAV hypervisor has been activated, no other HAV hypervisor installed later can gain complete control of the system. The first hypervisor is thought to retain ultimate control and therefore may have a prophylactic effect against hypervisor subversion [Fer08]. The extent of this potential prophylactic effect is unknown. Additionally, recent nested virtualization research concludes that efficient nested virtualization is feasible but notes that nesting hypervisors may have a multiplicative effect on the execution time of selected instructions. Most recent nested hypervisor developments have extended nested virtualization functionality from supporting only 32-bit innermost virtual machines to successfully nesting 64-bit virtual machines [BDD10].

2.1.5. Virtual Machine Introspection

Virtual Machine Introspection (VMI) is the practice of using the hypervisor to observe the internal state of a guest OS. This is used to analyze activity within the guest OS through use of *a priori* knowledge of the system [GaR03]. The VMI agent may reside within the hypervisor or outside the hypervisor and within the host OS. When the VMI agent exists outside the hypervisor, it uses an application programming interface provided by the hypervisor to gather data about the guest OS. VMI tools are classified as *monitoring* or *intervening*. *Monitoring* VMI reports on targeted behaviors of the guest OS while *intervening* VMI automatically intervenes in response to a targeted behavior. This distinction between monitoring and intervention parallels and is related to the security concepts of detection and response. To appropriately intervene, the VMI tool must have some pre-programmed way to interpret the behavior of the guest OS. This link, between behavior and meaning, is referred to as *semantic awareness* [NBH08].

2.1.5.1. Semantic Awareness

Semantic awareness is the ability to interpret an event or behavior based on context and knowledge [NBH08]. As discussed earlier, the computer can be considered a mathematical model and an abstraction of reality. As such, meaning is imparted solely by the programmer. From the hypervisor perspective, register values, memory pages, disk blocks and low-level events occurring within the emulated hardware are observed but not easily interpreted into particular OS-specific behaviors, much less categorized as malicious or benign activity. This uncertainty between the raw data which is observed by the hypervisor and the OS-specific contextual meaning of that data is referred to as the s*emantic gap* [Dod10]. Techniques for bridging the semantic gap generally rely on identifying pre-defined, OS-specific data structures and using them as templates to dynamically interpret the internal state of the guest machine [BJW10]. This ability to introspect the internal state of the machine provides enhanced situational awareness over other external-to-the-guest machine monitoring techniques because the guest OS has little to no control over the ability of the hypervisor to observe the guest OS's actions. As such, hypervisors are assumed to provide a trusted platform for VMI and enhanced situational awareness of the guest OS.

2.1.5.3. Forensics and Malware Analysis

Non-virtualized forensic tools suffer from incomplete and inaccurate information due to two common scenarios. The first occurs when the target machine is compromised and taken offline for forensics examination. The act of taking it offline disturbs the internal state of the machine and obscures evidence of the attack. The second occurs when forensics tools are applied to a target machine while it is experiencing a malicious attack. In this case, placing forensics tools on the target machine disturbs the state of the machine, also obscuring evidence of the attack and possibly notifying the attacker or malicious program that it is being monitored [NHB09].

VMI has particular value in the field of computer forensics where it provides security researchers with a presumed-to-be isolated laboratory which possesses an intimate introspective vantage point from which to observe malicious code as it acts on a target machine. As a forensic tool, VMI offers a unique opportunity to observe the internal state of the machine, both during and after a malicious event, without disturbing the malicious program or altering data [NHB09]. In this sense, it can be considered a covert forensics tool [Nen08]. Virtualization-based forensics provides the added benefit that once malware has been executed within a virtual machine, it can almost instantly be reverted back to a pre-infected state without the time-consuming manual reinstallation which would be required to restore a native OS. This reduces the overall time and cost of malware analysis and makes VMI an efficient tool for forensic examination [VPM11]. The forensic effectiveness of VM introspection has made VM-based malware analysis the primary research methodology for detection and infiltration of botnets and other malicious code [Fer08] [San09] [VuA11] [VPM11].

2.1.6. Benefits of Virtualization

The benefits of virtualization can be categorized in regard to efficiency and cost effectiveness, flexibility, disaster recovery, and security.

2.1.6.1. Efficiency and Cost Effectiveness

As discussed in Section 2.1, one of the earliest motivations behind the development of virtualization was a desire to more efficiently utilize computational resources [Cre81]. According to one source, many data centers have servers running at only 10% to 15% of total processing capacity [Gol08]. The ability of virtualization to dynamically share system resources among multiple guest OS's results in greater average usage of the overall system since idle resources, such as unused CPU cycles, can be used by whichever guest OS needs them [JML10]. Through virtualization techniques, hardware utilization rates can be raised as high as 70% to 80% [Gol08]. Virtualization is also cost efficient due to reduced downtime caused by the ability to migrate live machines from one physical system to another without interrupting service as well as the ability to upgrade portions of the physical system without taking the entire system offline [JML10]. Finally, the need for many small servers can be mitigated by installing virtual servers on fewer physical systems, resulting in fewer physical machines, lower overall purchase cost, and reductions in required manpower, floor space, utility costs, and cooling requirements.

2.1.6.2. Flexibility

The ability of the hypervisor to control the state of the guest OSs makes it possible to pause, restart, shutdown, and revert VMs to a previous state [JML10]. Additionally, in implementations where the hypervisor translates messages between the guest OS and underlying physical architecture, the machine itself can be easily replicated and transferred to any number of differently configured underlying architectures all without losing the ability to execute the VM [CPW09]. This makes VMs likely to stay compatible with future architectures as well as able to use older technologies that can be translated for execution on modern systems [HHK09]. Finally, virtualization enables the use of a wide variety of operating systems and applications on a single architecture, making it much easier and quicker to implement new OSs and applications when compared to non-virtualized architectures [Gol08].

2.1.6.3. Disaster Recovery

The ability to restore a virtual machine to a previous state with little to no availability loss in many ways captures the essence of disaster recovery. Since the physical architecture is fully abstracted by the hypervisor, a virtual machine can be dynamically saved and then rapidly restored even if the original physical architecture has been completely destroyed (this assumes the VM state was copied prior to the disaster). Virtualization monitoring software can be configured such that, if a virtual system catastrophically fails, it can be automatically instantiated at another geographic location with minimal service interruption [Gol08].

2.1.6.4. Security

With full virtualization and emulation, the guest OSs run within their own kernel. Since they do not directly interact with the host kernel, if a guest OS becomes infected with malware, it will likely stay contained within that guest OS's virtual environment [RoG05]. This is because the abstraction of the underlying physical architecture by the hypervisor effectively isolates each guest from the host machine and all other guests. To further leverage this benefit beyond simply protecting a single guest, critical applications and process are split among guests so that if one is compromised, other systems can continue to function correctly and provide a needed service [JML10]. The hypervisor itself provides a unique security capability through its ability to completely mediate interactions between the host software and the underlying hardware [GaR03].

2.2. Hypervisors (Virtual Machine Managers)

The following describes the particular hypervisors used in this thesis. They are QEMU, VirtualBox, VMware Workstation, and VMware ESXi. BluePill, a true hypervisor rootkit, is discussed in Section 2.4, *Subverting the Host: HAV Rootkits*.

2.2.1. QEMU 0.9.0

QEMU 0.9.0, The *Quick EMUlator* is an open source, software-based processor emulator which uses a read-decode-execute loop to translate instructions from those offered by the virtual machine to the guest OS into an instruction set compatible with the underlying hardware. QEMU does not support communication between the host and guest machine since it is designed to emulate a stand-alone system [Fer08]. It has two modes of operation: user-mode and full system emulation. User-mode emulation allows cross-compiled executables to run while full system emulation mode emulates a full system to include the corresponding hard disk image and all peripherals. Because it runs as an application within a host operating system environment, it is considered a Type II hypervisor. An extension for QEMU called KVM (Kernel-based Virtual Machine) exists which uses HAV to improve QEMU performance [KVM12]. QEMU detection techniques are documented in [Fer08].

2.2.2. VirtualBox 4.1.10

Oracle's VirtualBox was originally designed as a pure-software full virtualization hypervisor however, as of release 2.0, it also provides hardware-assisted full virtualization. It supports Windows, Mac OS X, Linux, and Solaris hosts. Because it uses binary translation, it can run both 32-bit systems on 64-bit machines and 64-bit systems on 32-bit machines, though at the risk of exceptionally high overhead for 64-bit systems on 32-bit machines. As of the time of this writing, VirtualBox required use of HAV for execution of 64-bit systems [Ora12].

2.2.3. VMware Workstation 8

VMware Workstation 8 is a hosted, Type II hypervisor which supports simultaneous execution of multiple virtual machine environments and their corresponding guest OSs. It is primarily designed to virtualize desktop OSs and is configurable for both binary translation and HAV full virtualization. Trivial VMware Workstation detection mechanisms are documented by [Fer08]. VMware Workstation 8 is able to virtualize the functionality of the underlying HAV processor and supports nested virtualization of 32-bit and 64-bit systems.

2.2.4. VMware ESXi 5.0

Whereas VMware Workstation is intended for desktop virtualization, ESXi 5.0 is a bare-metal Type I hypervisor intended for server use. In comparison with other hypervisors, it is relatively *thin*, with a code-base footprint of less than 150 MB compared to 1 GB for Citrix Xen Server 5.6, 2 GB for ESX and 3 GB for Microsoft's Hyper-V [VMW12]. ESXi achieves its small size by implementing its graphical user interface in a separate application, the vSphere client, which is used to remotely manage the hypervisor over a network connection (see Figure 11). It supports virtualization of the underlying Intel VT-x or AMD-V HAV-enabled processor which allows it to nest HAV VMs. It provides this functionality for both 32-bit and 64-bit guest OSs. It is observed that, for purposes of this research, ESXi exhibits characteristics which are desirable in a notional HAV-R.

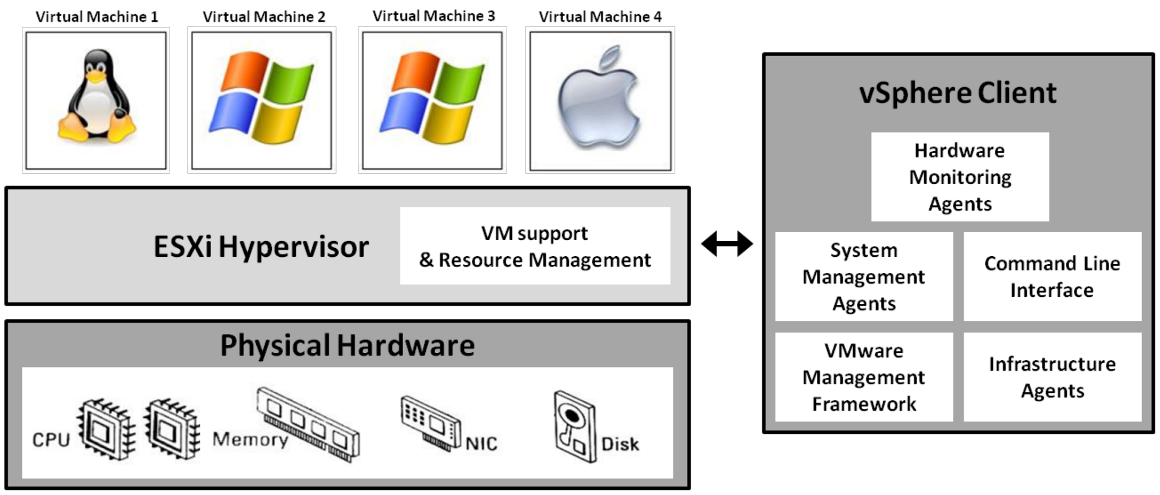


Figure 11. ESXi Hypervisor with vSphere Client

2.3. Subverting the Hypervisor: Detect, Evade, and Escape

In most cases, hypervisors are not designed to absolutely emulate all aspects of a system's underlying physical architecture, but to emulate the underlying system *good enough* so that the guest OS can reliably interact with the host machine while meeting the critical virtualization design requirements of equivalency, efficiency, and control [Fer08] [PoG74]. Unfortunately, these requirements often ignore the unique security issues that occur due to virtualization, capturing only those requirements that are incidental to equivalent, efficient, and trusted control of the system [Fer08]. The resulting disconnect between virtualization's efficiency-oriented design and its popular use as a security tool creates opportunities for malicious exploitation of virtualized systems. In some cases, this manifests itself as malware that simply terminates itself when it detects the presence of a virtual machine while in others the malware attempts to hide itself by attacking the hypervisor and causing the system to shut down. Perhaps most threateningly, it is possible for malware to escape its isolated guest OS and infect the host machine [Fer08]. This suggests the following three categories of hypervisor subversion: detection of the virtual environment, evasion of detection and VM introspection, and escape of malicious code out of the guest machine and into the host.

2.3.1. VM Detection

The smallest failure of a hypervisor to perfectly simulate "native" machinery in support of a VM creates disparities which suggest a non-native environment. Attackers that detect such disparities can alter their malware to evade and attack VMI or the VM environment [ZhC07]. This section addresses detection techniques used by attackers to detect a virtualized environment prior to compromise of the guest OS. As such, it focuses on those techniques that can be performed from within Ring 3 of the guest. Detection techniques used by a possibly compromised host to detect the presence of a HAV-R are addressed in Section 2.5.

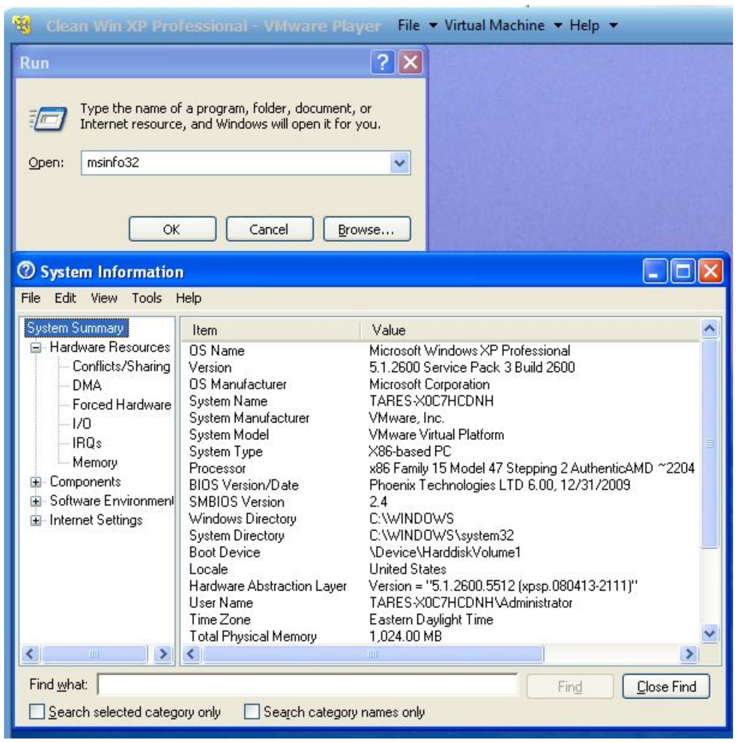
Indicators that suggest a virtual environment are referred to as *virtualization markers*. Several are discussed in this section, organized into the following taxonomy suggested by [CAM08]: Hardware, Execution Environment, Application, and Behavioral Virtualization Markers.

2.3.1.1. Hardware Virtualization Markers

Hardware virtualization markers are unique device or driver characteristics which can be used to differentiate virtualized from native hardware. This information is often non-privileged and is usually trivially detected by gathering information directly from a particular system's hardware during a process referred to as *hardware fingerprinting*.

Hardware fingerprinting uses built-in, user-level components of the standard operating system to query hardware settings. This data is checked for indications of the existence of virtualization [LeM08]. Two trivial methods of hardware fingerprinting using built-in features of the guest OS are Microsoft's System Information program and the `dmidecode` command in Linux.

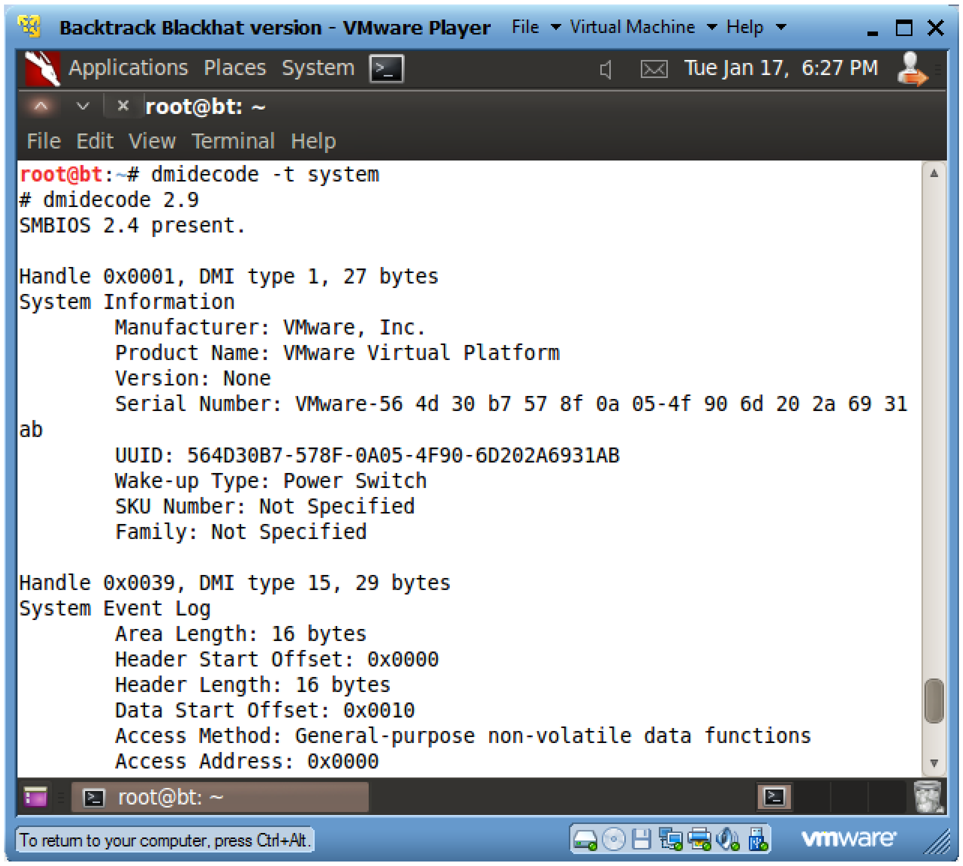
Microsoft's System Information program is accessed by simply executing `msinfo32` from the command line or from within the Windows Run dialog box. This generates a system summary report which lists hardware resources, components, software environment, and Internet settings data. An example, captured from within a guest Windows XP Professional machine running within VMware on a Compaq Presario Model SR1920NX computer, is shown in Figure 12. Note that, rather than reporting the true underlying physical hardware characteristics, the report provides the virtualized data provided by VMware, identifying the virtualized system manufacturer as *VMware, Inc.* and the virtualized system model as *VMware Virtual Platform*.



Item	Value
OS Name	Microsoft Windows XP Professional
Version	5.1.2600 Service Pack 3 Build 2600
OS Manufacturer	Microsoft Corporation
System Name	TARES-X0C7HCDNH
System Manufacturer	VMware, Inc.
System Model	VMware Virtual Platform
System Type	X86-based PC
Processor	x86 Family 15 Model 47 Stepping 2 AuthenticAMD ~2204
BIOS Version/Date	Phoenix Technologies LTD 6.00, 12/31/2009
SMBIOS Version	2.4
Windows Directory	C:\WINDOWS
System Directory	C:\WINDOWS\system32
Boot Device	\Device\HarddiskVolume1
Locale	United States
Hardware Abstraction Layer	Version = "5.1.2600.5512 (xpsp.080413-2111)"
User Name	TARES-X0C7HCDNH\Administrator
Time Zone	Eastern Daylight Time
Total Physical Memory	1,024.00 MB

Figure 12. Fingerprinting Windows XP Using `msinfo32`

The Linux `dmidecode` command is also run from the command line and provides various options for gathering specific information about the system's configuration. A particularly useful example is `dmidecode -t system` which causes the OS to report the computer's manufacturer, product name, serial number, and universally unique identifier (UUID). An example of this command executed on a Unix Backtrack 5, Release 1 OS running within VMware on a Compaq Presario Model SR1920NX is depicted in Figure 13. Once again artifacts indicating virtualization can be observed within the reported system information.

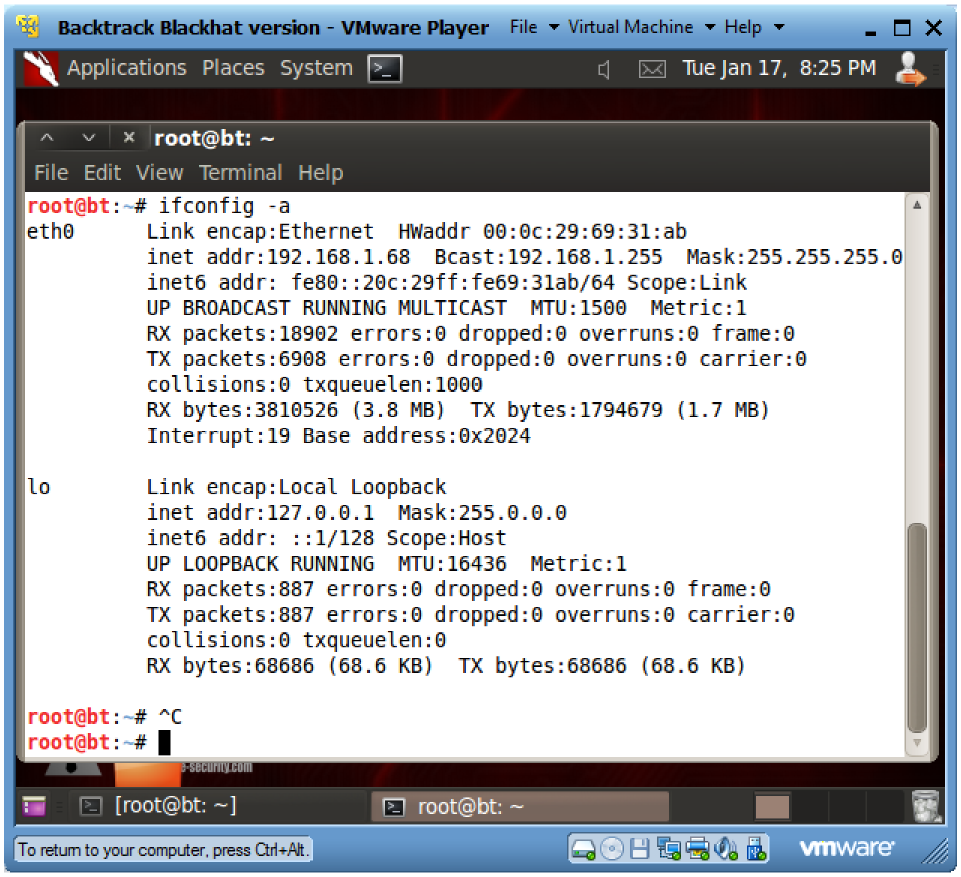

Backtrack Blackhat version - VMware Player
File Virtual Machine Help
Applications Places System
Tue Jan 17, 6:27 PM
root@bt: ~
File Edit View Terminal Help
root@bt: ~
To return to your computer, press Ctrl+Alt.
vmware

```
root@bt:~# dmidecode -t system
# dmidecode 2.9
SMBIOS 2.4 present.

Handle 0x0001, DMI type 1, 27 bytes
System Information
        Manufacturer: VMware, Inc.
        Product Name: VMware Virtual Platform
        Version: None
        Serial Number: VMware-56 4d 30 b7 57 8f 0a 05-4f 90 6d 20 2a 69 31
ab
        UUID: 564D30B7-578F-0A05-4F90-6D202A6931AB
        Wake-up Type: Power Switch
        SKU Number: Not Specified
        Family: Not Specified

Handle 0x0039, DMI type 15, 29 bytes
System Event Log
        Area Length: 16 bytes
        Header Start Offset: 0x0000
        Header Length: 16 bytes
        Data Start Offset: 0x0010
        Access Method: General-purpose non-volatile data functions
        Access Address: 0x0000
```

Figure 13. Fingerprinting Unix Using `dmidecode –t system`

In each case, information is gathered using built-in, user-level components of the standard OS to query hardware characteristics and settings.

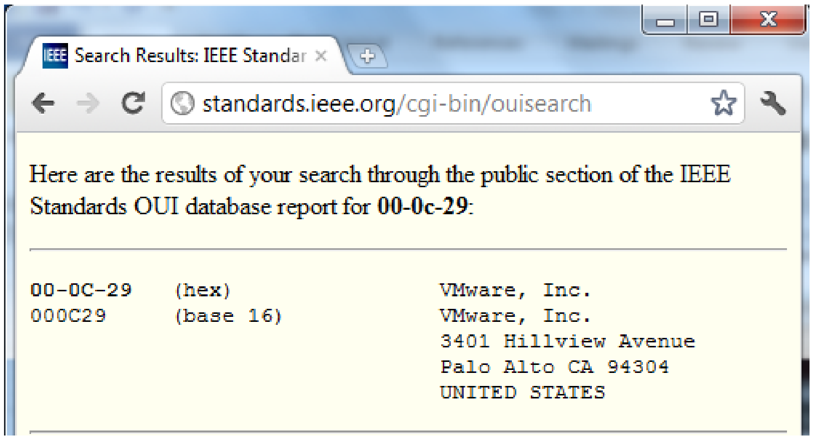
Another trivial example relies on Organizationally Unique Identifiers (OUIs) used to identify network interfaces. It is known that the VMware virtual network adapter self-identifies using a default three octet OUI, also commonly referred to as a MAC address prefix, that is specifically assigned to VMware-virtualized Ethernet devices. This OUI can be checked by any machine by simply executing the non-privileged command "`ipconfig /all`" (MS Windows) or "`ifconfig –a`" (Linux) to display the MAC address of the ethernet adapter (Figure 14). The OUI prefix is then checked against the publically-available OUI database to determine if it is known to be associated with a virtualization platform or a non-virtualized device [IEE11] [CAM08].


Backtrack Blackhat version - VMware Player
File
Virtual Machine
Help
Applications
Places
System
Tue Jan 17, 8:25 PM
root@bt: ~
File Edit View Terminal Help
[root@bt: ~]
root@bt: ~
To return to your computer, press Ctrl+Alt.
vmware

```
root@bt:~# ifconfig -a
eth0      Link encap:Ethernet  HWaddr 00:0c:29:69:31:ab
          inet addr:192.168.1.68  Bcast:192.168.1.255  Mask:255.255.255.0
          inet6 addr: fe80::20c:29ff:fe69:31ab/64 Scope:Link
          UP BROADCAST RUNNING MULTICAST  MTU:1500  Metric:1
          RX packets:18902 errors:0 dropped:0 overruns:0 frame:0
          TX packets:6908 errors:0 dropped:0 overruns:0 carrier:0
          collisions:0 txqueuelen:1000
          RX bytes:3810526 (3.8 MB)  TX bytes:1794679 (1.7 MB)
          Interrupt:19 Base address:0x2024

lo        Link encap:Local Loopback
          inet addr:127.0.0.1  Mask:255.0.0.0
          inet6 addr: ::1/128 Scope:Host
          UP LOOPBACK RUNNING  MTU:16436  Metric:1
          RX packets:887 errors:0 dropped:0 overruns:0 frame:0
          TX packets:887 errors:0 dropped:0 overruns:0 carrier:0
          collisions:0 txqueuelen:0
          RX bytes:68686 (68.6 KB)  TX bytes:68686 (68.6 KB)

root@bt:~# ^C
root@bt:~# 
```

Figure 14. Checking the OUI of a Unix machine

In the example it is observed that the `ifconfig -a` command reports an address for eth0 of 00:0c:29:69:31:ab. A simple check of the OUI database at [IEE11] reveals that 00:0c:29 is the UID assigned to VMware (Figure 15).


Search Results: IEEE Standar
standards.ieee.org/cgi-bin/ouisearch

Here are the results of your search through the public section of the IEEE Standards OUI database report for **00-0c-29**:

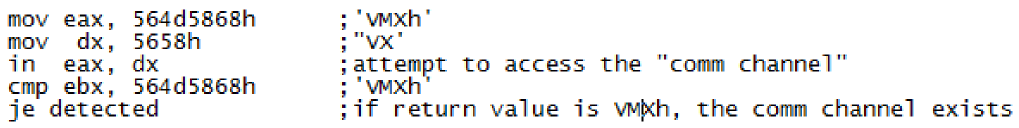
```
00-0C-29     (hex)                     VMware, Inc.
000C29       (base 16)                 VMware, Inc.
                                       3401 Hillview Avenue
                                       Palo Alto CA 94304
                                       UNITED STATES
```

Figure 15. The OUI Search Results

These hardware marker detection mechanisms are trivial to detect from userland (Ring 3) and are integrated into many virtualization detection tools including the *Doo* functionality included within the *ScoopyNG* VM detection suite [Kli11].

2.3.1.2. Execution Environment Virtualization Markers

Execution environment virtualization markers are characterized by memory and execution artifacts that occur due to the simultaneous existence of two or more environments (the host machine and one or more guests) which share the same physical resources. Hypervisors often introduce additional functionality which is not required or supported during native execution and which indicates the existence of virtualization. An example of this is VMware’s communication channel (Comm Channel) which is used to pass clipboard data and files, such as those transferred using drag-and-drop features, between the guest and host machine. The VMware hypervisor accomplishes this by augmenting the *"IN"* assembly instruction to handle additional functionality enabling the Comm Channel [Ome06]. This Comm Channel can be detected simply by attempting to access it using the *"IN"* instruction with the *magic* number 0x564D5868 (*'VMXh'* in ASCII) loaded into the EAX register, (see [LiS06] for details). The *"IN"* instruction is privileged and, when executed natively from Ring 3 (userland), it will throw an exception. However, it fails to throw an exception, the channel exists and the attacker assumes they are in a virtualized environment. Furthermore, if the magic number is returned in the EBX register, the attacker is likely within a VMware virtualized environment [LiS06]. This check can be performed in as little as five lines of assembly code (Figure 16).



```
mov eax, 564d5868h        ;'VMXh'
mov  dx, 5658h            ;"VX'
in  eax, dx               ;attempt to access the "comm channel"
cmp ebx, 564d5868h        ;'VMXh'
je detected               ;if return value is VMXh, the comm channel exists
```

Figure 16. Machine Code for Comm Channel Detection
Adapted from [Fer08]

Furthermore, use of additional special commands, such as passing the Comm Channel the value '*0x0A*', causes this method to leak additional information such as the specific VMware version in use.

Yet more sophisticated markers can be detected by analyzing the Descriptor Tables in kernel memory. An example of this is the VM detection technique called "Red Pill" [Rut04].

The Red Pill VM detection technique exploits a single, non-privileged instruction to access data stored within a privileged register which can indicate the existence of a VM. To do this, the attacker simply calls the SIDT (Store Interrupt Descriptor Table) instruction from within the guest OS and examines the return value. The SIDT instruction is designed to return the stored address of the system's Interrupt Descriptor Table (IDT). Since most x86 processors do not support true full virtualization and therefore do not provide a second IDT register (IDTR) for use by the guest OS, the hypervisor is forced to virtualize the guest OS's IDTR somewhere other than the real IDTR which is reserved for the host OS. If the SIDT instruction is invoked from within a virtual machine, it will receive the address of its virtualized IDT. When this address matches commonly used relocation addresses, typically higher in memory than when the OS is run natively, it is assumed to be operating within a virtualized environment [Rut04]. It was observed that on VMware VMs, the IDT is typically located at 0xffXXXXXX, and on Virtual PC VMs, it is typically located at 0xe8XXXXXX. Implementations of the Red Pill technique usually conclude the existence of virtualization if the IDTR is greater than 0xd0000000 [CLS07]. This test is effective for both Windows and Linux implementations and is not vendor specific. The technique is considered reliable for VMs running within a host machine with a single core processor however, if a multi-core processor or multiple processors are used, it is less conclusive. This is because within a single processor environment, the IDTR value is constant whereas with multiple processors (or cores) each will have its own IDT [QuS05]. There exist other methods, such as NoPill, and ScoopyNG that implement variations of the Red Pill method to detect virtualization [Ome06] [ZhC07]. Notably, NoPill relies on a similar algorithm but also examines the Local Descriptor Table (LDT) instead of just the IDT [QuS05]. ScoopyNG implements both the IDT and LDT check techniques but then goes a step further by checking the memory location of the Global Descriptor Table (GDT) [LiS06] [ZhC07].

Virtualization markers within the execution environment can also manifest themselves as disparities between how illegal opcodes are handled within a virtual versus a native machine. A good example was already discussed using a *magic value* to detect VMware's Comm Channel. Another example of this is the "Illegal Opcode Exception Trick" which is used to detect the existence of Virtual PC. Rather than using the "*IN*" instruction, as VMware does, Virtual PC alters how specific illegal opcodes are handled and uses them to pass information between the host and guest machine (another communication channel). When these illegal opcodes are executed natively, they generate an exception because they are undefined. However, when executed within a Virtual PC guest, no exception is generated since the hypervisor processes them as legitimate opcodes. An attacker needs only to execute one of Virtual PC's special opcodes and detect whether or not an exception is thrown to determine if the attacker is within a Virtual PC guest [Fer08].

Disparities between how illegal opcodes are handled by virtual rather than native machines are not limited to intentional differences such as in the Virtual PC example. They also manifest as unintentional implementation differences or anomalies. Virtual PC provides yet another example in that the hypervisor does not seem to limit the length of instructions that are handed to it. Usually, instructions over 15 bytes generate a general protection fault when run natively however, Virtual PC accepts such instructions without generating the fault, indicating that the attacker is not within a native machine [Fer08]. Whether such implementation inconsistencies are accidental or intentional, the altered execution behavior provides sufficient evidence of a non-native execution environment [CAM08].

Tools used to detect execution environment virtualization markers include *VMDetect*, *Jerry*, and *checkVM* [BaK10].

2.3.1.3. Application Virtualization Markers

Application virtualization markers include programs or executables that are installed within the guest OS to facilitate virtualization.

Registry entries and services that reference an underlying hypervisor, such as references to *VMware* or *VMtools*, are examples of application markers that can be used to detect virtualization [Ome06] [CAM08]. While detection of VM-related registry entries and services it trivial, it should be noted that it is also relatively simple to rename processes and registry entries in an attempt to thwart detection [CAM08].

2.3.1.4. Behavioral Virtualization Markers

Behavioral virtualization markers rely on anomalies caused by the hypervisor and hardware which alter some behavior within the system. Hypervisors, which abstract, manage, and share the underlying physical architecture, add workload (overhead) to the system. This overhead is a fundamental property of hypervisors which cannot be avoided since it is inherent to their function as a management agent within a system. Simultaneously, the system's processor(s) have a finite capacity for processing data. When the overhead caused by the hypervisor is added to the workload already experienced by the processor, it has the potential of causing a delay, a behavioral anomaly within the system.

Timing-based detection uses this delay to detect virtualization [Fer08]. It does this by noting the time that it takes to execute a certain set of instructions a specific number of times on a native machine and then comparing the time it takes to execute the same instructions on a suspect OS with the same hardware profile. This method relies on foreknowledge of how long these instructions take to execute on a native machine. The execution time is then compared to the execution time on a trusted system and, given a large enough disparity, it can be assumed to be running within a virtualized environment [Fer08]. The easiest way to do this is through use of a local time source such as the Time Stamp Counter (TSC) register. Local time sources within the processor present their own challenges since the hypervisor has complete control over their access and can intentionally misreport execution times to counter timing-based detection. This and other behavioral detection techniques are further addressed in Section 2.5, *HAV-R Detection*. They are not further addressed in this section as they require privileged access not likely to be available to a malicious actor in the initial detection stage of hypervisor subversion and are more likely to be used by the victim to detect HAV-R after subversion.

2.3.1.5. Detection Observations

For the attacker, software is usually more easily changed than hardware, therefore markers that occur due to a particular hypervisor's software implementation are generally more easily eliminated or hidden then those that are a result of a particular hardware implementation. Additionally, since hypervisor detection can be considered an attack on a virtualized system, hypervisor designers are likely to make their hypervisor software increasingly transparent to the guest OS as security risks to hypervisors become more well known. Those that wish to consistently detect virtualization should focus on detection of those markers which are the most difficult to eliminate from a virtualized system. Based on the survey of detection techniques discussed in this section, behavioral virtualization markers that occur due to hardware anomalies are the least susceptible to change and therefore comprise the most likely successful detection techniques.

2.3.2. Hypervisor Evasion

As discussed earlier, virtualization-based malware analysis has emerged as the primary research methodology for detection and infiltration of botnets and other malicious code [San09] [Dod10] [VuA11]. In response, attackers have crafted malware to behave differently when running within a virtual machine in order to evade detection and analysis [CAM08]. Malware which behaves differently when executed within a virtual environment is referred to as “analysis aware malware”, or “split personality malware” [VPM11]. In a 2008 study, more than forty percent of 6,900 malware samples examined altered or reduced their malicious behavior when executed within a virtual machine versus native execution [CAM08].

If an attacker detects the presence of a VM and reduces the malware’s malicious behavior, the attacker may also attempt to subvert any possible VMI. Such techniques have already been identified to hide from VMI; one example is Direct Kernel Structure Manipulation.

2.3.2.1. Direct Kernel Structure Manipulation

Subversion of VMI can be accomplished through compromising the kernel of the guest OS and manipulating the kernel’s internal data structures through a technique called Direct Kernel Structure Manipulation (DKSM). This attack was successfully demonstrated against an Ubuntu guest machine that was introspected by the XenAccess hypervisor. Most VMI tools assume that the guest OS will use its internal kernel data structures in well-defined, OS-specific and predictable ways. As discussed previously, these OS-specific definitions are relied upon to provide contextual meaning in order to bridge the semantic gap. By attacking the assumption that the guest OS adheres to these definitions, an attacker can successfully obscure the true state of the machine to include running processes, loaded modules, and active network connections [BJW10].

This attack is divided into three approaches: syntax-based manipulation, semantics-based manipulation, and a hybrid of both approaches termed "multifaceted combo manipulation." Syntax based manipulation involves adding or removing fields within the internal data structures to cause them to be misidentified by the VMI tool. This causes the VMI tool to use the wrong template when evaluating the data structure producing inadvertently garbled data. Semantics based manipulation involves modification of the underlying semantics of the kernel data structures so that, while the VMI tool identifies a given data structure, in reality, the data within that structure is being used differently than how it was defined and therefore will not be detected as suspicious by the VMI tool. Multifaceted combo manipulation mixes the two techniques to utilize the best approach to a given situation [BJW10].

2.3.2.2. Detecting VM Evasion

Evasion by malware within the guest machine is detected through use of two primary strategies.

The first strategy relies on what is already known about evasive and subversive malware to build a list of behaviors and binary signatures which are indicative of avoidance behavior. The detection mechanism then logs all sensitive instructions found within or generated by the suspicious binary and reports when they match the behavior signatures previously identified. This is performed statically or dynamically and is similar to commonly used signature-based malware detection methods. Unfortunately, its effectiveness is limited by what is known *a priori* about avoidance behavior rendering this method ineffective at detecting unknown virtualization and VMI evasion techniques.

The second strategy relies on the assumption that in order to change behavior based on detected VMI, the malware must, at some point, make a conditional jump. To exploit this, the second strategy logs all return values encountered by the potential malware and then reports if they affect a conditional jump later in the execution. While this method suffers from a higher rate of false positives, it may reveal novel VM detection methods [ZhC07].

Both strategies are implemented in Malaware, an academic proof-of-concept application has been shown to be effective in detection of real-world, VM-evasive malware [ZhC07].

Once evasive malware is detected, it can be analyzed on a native machine or analyzed through use of techniques which attempt to trick the malware into concluding that it is running natively when it is, in fact, running within a VM. The tool VMDetectGuard uses this technique to detect evasive malware [VPM11].

2.3.2.3. Virtualization as a Deterrent

It is suggested that the propensity of malware to evade virtual environments could be used as a malware deterrent by signaling that a native environment is virtualized even when it is not [CAM08]. Such signals are trivial to implement and are as simple as adding one or more of the detection markers discussed in Section 2.3.1 to a system. Such deception is intended to repel malware attacks and could also be used to funnel attacks towards intentionally vulnerable systems (honeypots) that are used for malware detection and research. It is also observed [CAM08] that as potential targets increasingly use virtualization, the motivation to create malware that can subvert virtualization also increases thus, as virtualization-oriented malware increases, the benefits of such a defensive strategy are reduced.

2.3.3. Escaping a VM

One of the unique characteristics of VMs is their ability to isolate the guest OS from the host and other guests. If that isolation is compromised, it destroys the assumption that many users have about the security of their virtualized environments. Because the physical resources of the underlying hardware are shared between the host and one or more guest OSs, covert channels are possible [Bis02]. The following are two examples.

In December 2005, it was discovered that VMware contained a vulnerability within vmnat.exe whereby the hypervisor fails to handle specially crafted “EPRT” and “PORT” FTP requests, enabling an attacker to overwrite the heap to create a buffer overflow within the host environment which could allow execution of arbitrary code [She05]. Additionally, in 2009 it was discovered that there were implementation bugs in certain SVGA 3D GPU device emulation applications which allowed memory to leak from the host machine to the guest via a shared buffer. Since the guest OS can also write to this buffer, it was demonstrated that data written to the frame buffer could be captured and executed within the host machine [Kor09].

There is also a possibility that virtual machines which are allowed to interact directly with third party devices, such as network and graphics cards, could escape their host environment by compromising those devices and using them to monitor the system [Fer08]. A notional example of this would be compromise of a system's off-board GPU and then using it to execute malicious code.

In conclusion, it is critically important to note that virtualization is a product of human programming and is therefore subject to imperfections which can enable unexpected execution and compromise by a malicious actor. From an attacker's perspective, bugs are backdoors.

2.4. Subverting the Host: Hardware-assisted Virtualization Rootkits

Rootkits, in their purest form, are concerned with stealth, avoiding detection by the target system. They generally achieve their stealth objective by existing at the highest level of privilege possible or by loading their code and hiding themselves before the system can detect them [Blu09]. HAV-Rs take the first approach, existing at the highest level of privilege possible, and use their fully trusted status to hide themselves from detection by the virtualized system. Such a rootkit is difficult if not impossible to find using traditional malware approaches since it does not exist within the user space or the kernel space; rather it exists beneath them, as a bare-metal hypervisor. As a result, rootkit techniques which look for kernel and user rootkit artifacts (hooking the Interrupt Descriptor Table or System Service Dispatch Table, patching the master boot record, Direct Kernel Object Manipulation, among others) are ineffective against HAV-R detection.

HAV-Rs are constrained to HAV-enabled processors such as those which provide AMD-V and Intel's VT-x virtualization technologies. This means that each HAV-R must be tailored to a specific HAV implementation within particular processor class.

Additionally, HAV-Rs effectively invert the forensics, cyber situational awareness, and VMI paradigm, giving the attacker the ability to introspect and modify execution within the target machine and making the host OS the introspected target.

Few HAV-Rs are publically known to exist today, two of which are the academic HAV-Rs BluePill and SubVirt.

2.4.1. BluePill

BluePill implements a novel approach to on-the-fly virtualization where the native machine is transitioned to a virtual machine through installation of a HAV hypervisor without rebooting or otherwise altering the formerly native OS. Installation is performed by loading BluePill using a kernel-mode driver. This can be problematic since current OSs use driver signing to avoid execution of malicious kernel drivers and bypassing these constraints is left to the attacker. In practice, bypassing driver signing is possible using techniques which include memory injection and exploitation of a kernel security flaws, among others [DFL11]. The kernel driver serves only to load BluePill, not as a container for BluePill [MyY07]. As such, it needs only exist within the native OS long enough for the BluePill installation to occur. BluePill's significance is that it demonstrates the potential for a malicious hypervisor to transition the native OS into a virtualized state and to monitor the target OS. Figure 17 graphically represents the following steps which are used to install the BluePill hypervisor [Fri08] [DFL11].

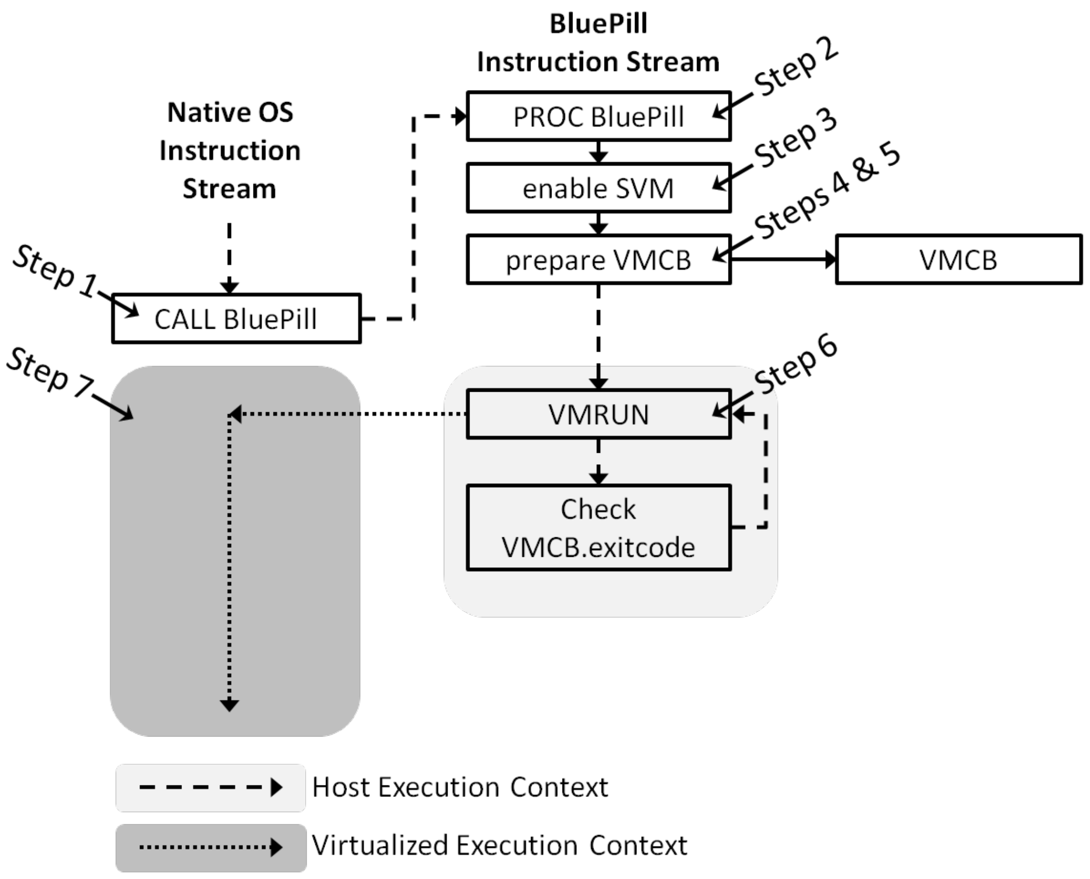


Figure 17. BluePill Installation and Operation
Adapted from [RuT07]

1. Load the BluePill driver
2. Check that BluePill is running in Ring 0 and that the appropriate HAV-enabled hardware is present
3. Enable Secure Virtual Machine; this causes the Secure Virtual Machine Enabled (SVME) flag to be set in the Extended Feature Enable Register (EFER)
4. Allocate and prepare the VMCB/VMCS by cloning the entire current state of the native environment into the VM environment VMCB/VMCS
5. Initialize and configure the VMEXIT handler trap based on a predetermined set of interrupt conditions
6. Execute VMRUN/VMLAUNCH such that the native OS begins to execute in the context of a VM
7. The native OS continues to execute until an event occurs which causes it to trap to the hypervisor

When a trap occurs, information about the event that caused the trap is placed into the VCMB/VMCS so that the hypervisor has access to it. Traps are caused by exceptions, interrupts, or instruction intercepts. When the hypervisor is ready, it returns execution to the formerly-native OS using the VMENTRY instruction. The formerly-native OS proceeds with the next instruction in its instruction stream, oblivious that its context has changed [MyY07] [RuT07] [DFL11].

Because BluePill exists only within memory on the processor, it cannot survive a system reboot without being reinstalled from the kernel. As an academic rootkit, it performs very few secondary functions, the most significant of which is trapping calls the EFER and flipping the SVME flag to indicate that a hypervisor is not present. BluePill functionality is currently limited to 64-bit Windows Vista.

2.4.2. SubVirt

Whereas BluePill virtualizes the host machine on the fly, the academic HAV-R SubVirt installs itself by manipulating the boot sequence such that it loads itself prior to loading the target OS. To do this, it must be installed within persistent storage on the target machine prior to a reboot of the system. This is implemented by storing the SubVirt code in the beginning of the first active partition. The master boot record is then edited to initiate SubVirt before the target OS. On boot, SubVirt is initiated prior to the target OS which enables it to create the VM structures necessary to place the target OS within a virtualized environment. It does this in a similar manner to BluePill in that the result is that the target OS executes in a virtualized context on the processor. SubVirt functionality is limited to Windows XP and Linux [KCW06] [Fer08].

2.4.3. Characteristics of HAV-R

The HAV-R must be stealthy and therefore must not only flawlessly virtualize the underlying hardware, it must also avoid any number of potential detection mechanisms. At a minimum, the following functionality should be implemented to provide a minimum of detection avoidance:

- Emulation of all processor feature extensions
- Interception of access to off-CPU local timers such as timers contained in the GPU
- Time Stamp Counter (TSC) manipulation
- Shadow paging implementation to avoid Translation Lookaside Buffer (TLB) profiling

Additionally, the HAV-R should survive reboot, include covert communication functionality, and use minimal system resources [MyY07].

2.5. HAV-R Detection

Since HAV relies on specific, iteratively-evolving, and well-defined virtualization technologies embedded within processor hardware (such as AMD-V and Intel VT-x), detection techniques which exploit processor behavior are among the most promising methods for consistent HAV-R detection. By definition, HAV-Rs intercept and arbitrate communication with underlying processors and memory. Detection techniques that rely on direct processor and memory access must account for ways that the HAV-R might misreport the state of the machine. This makes side-channel techniques, which exploit physical and logical constraints of the system and are difficult to subvert, the most promising method for consistent HAV-R detection.

2.5.1. Execution Profiling

Execution profiling relies on detecting additional processor execution (overhead) caused by a hypervisor's trapping of privileged instructions. This is measured temporally, usually in milliseconds or clock cycles.

While it is possible that software exists that virtualizes the host OS but never traps on any instruction, such software fails to meet the basic hypervisor requirement of resource control and arbitration as identified by [PoG74] and cannot be considered a true hypervisor. Furthermore, such software is likely useless since it would simply permit uninterrupted data flow between the guest machine and hardware. Hypervisors, by definition and practical application, must trap some instructions and thereby add execution overhead to the system.

Timing-based execution profiling using direct access to internal processor features such as the time stamp counter (TSC) is mentioned in Section 2.3.1. Other internal processor time sources include the high precision event timer, programmable interrupt timer, and advanced programmable interrupt timer. While detection using such timers is possible, it is also possible for the hypervisor to alter the data reported when attempting to read such counters. Both AMD-V and Intel's VT-x offer a TSC Offset feature designed to obscure the impact of virtualization on the TSC by subtracting an offset from the TSC value before reporting it to the guest OS [MyY07]. This underscores the importance of using side-channel detection techniques rather than direct techniques that rely on information that can be arbitrated by the HAV-R. Since the HAV-R is designed specifically for arbitration, identification of side-channel detection techniques that are unlikely to be compromised is a particularly challenging and important problem.

2.5.1.1. Timing Secure Virtual Machine Enabled Flag Checks

The Secure Virtual Machine Enabled (SVME) flag is a parameter within the Extended Feature Enable Register (EFER) that is set when a HAV hypervisor is installed on a machine. A quick way to check if a HAV hypervisor is installed on a system is to read the EFER to check if the SVME flag is set or clear. If this flag is set and the user is not explicitly using HAV, a HAV-R is likely present. Unfortunately, calls to the EFER are privileged and are trivially intercepted and falsified by a HAV-R. While directly reading the SVME value from the EFER is not a reliable way to detect HAV-R, an alternative technique is to detect the delay caused by a hypervisor trapping the read EFER instruction. [Rut07b] and [Fri08] demonstrate that execution of the Read from Model Specific Register (RDMSR) EFER instruction takes approximately 10 clock cycles on a particular non-virtualized system, but takes approximately 2,000 to 10,000 clock cycles respectively after installation of a HAV-R - a significant discrepancy which makes side-channel detection of EFER trapping a promising detection strategy. Of course, if the timer used exists within the processor, it is possible for the hypervisor to misrepresent the returned value. For example, if the TSC is used the HAV-R could simply trap all calls to the TSC and return a fake value, likely through use of the TSC Offset feature which subtracts a static value from the TSC. This is unlikely to provide consistently successful results since the HAV-R would need to generate an offset that, when subtracted from the value returned by the TSC (which could be in the range of 2,000 to 10,000 clock cycles) would be non-negative and relatively close to 10. Furthermore, it would need to do so without inducing additional delay to the system which would provide additional evidence of the HAV-R. This is unlikely and makes checking the Secure Virtual Machine Enabled Flag a promising detection technique [Fri08].

2.5.1.2. SMP Counting

Since it is possible to successfully cheat internal clocks, external timers and side-channel timing mechanisms are also used for detection. SMP Counting measures relative time through use of dual simultaneous processes. In this technique, proposed by [Bar07], two processes are created within a symmetric multiprocessing (SMP) environment as close to simultaneously as possible and such that each process executes on its own dedicated CPU or core. The first process serves as a counter and simply increments a counter until the second process completes. The second process simultaneously executes one or more privileged instructions in order to force any existing hypervisor to trap. Once the second process completes, it notifies the first process which returns the count value. If the count value is above a certain threshold, it is assumed that the process experienced one or more traps to a hypervisor. This technique requires previous measurements of a known non-virtualized system to establish the threshold and is shown to be effective at detection of non-nested hypervisors [Fri08].

2.5.1.3. Other Execution Profiling Methods

External timing-based detection uses timing sources which are not arbitrated by the HAV-R to detect processing delays. A potential source for this is the GPU of a graphics card which could be used to indirectly time execution of privileged instructions within the CPU. One way to implement such a scheme would be to take several benchmark readings immediately after the initial setup of the system, when it is assumed to be non-subverted. Further readings would be taken periodically and continually afterward to assess if the execution time has increased beyond a statistically significant range. If at any time this range is exceeded, the detection mechanism would report the possibility of overhead caused by a HAV-R. It is still possible that instructions to the GPU could be intercepted by the HAV-R however, it is also likely that, in an effort to make the HAV-R as small as possible, arbitration of extraneous devices such as the graphics card, might be avoided [MyY07]. Another example of external timing entails accessing a PCI device register which, on physical hardware, might normally take hundreds of cycles to read but, when virtualized and maintained within a processor cache, returns a value in a fraction of the time. Such an anomaly in performance speed, in this case faster than normal, can also be used for detection [GAW07].

An additional concern is the fidelity of measurements taken outside the processor, such as measurements in units of whole seconds, which require significantly more execution of privileged instructions within the suspect processor in order for a statistically significant reading to be obtained. The uncharacteristic repetition of specific instructions could make such detection techniques detectable by the HAV-R which could counter this method by temporarily suspending its trapping operations. This strategy, of uninstalling or suspending hypervisor trapping when a sustained series of privileged instructions are executed, is suggested by [Rut07] and is referred to as "BlueChicken". The BlueChicken strategy is not without its vulnerabilities since, in order to uninstall and then reinstall BluePill, it must move itself from Ring -1 to at least the kernel (Ring 0) where it would behave as a typical rootkit and could be detected using common kernel-level rootkit detection mechanisms. For the detector, it is less significant whether a

HAV-R is detected within the kernel or below the kernel, detection itself is what is most important therefore, timing-based detection remains a viable detection technique.

2.5.2. Translation Lookaside Buffer Profiling

Another detection mechanism relies on the behavior of hypervisor relative to the Translation Lookaside Buffer (TLB). The TLB is a fixed-size cache within the CPU that quickly maps (translates) virtual addresses to physical addresses. When a CPU attempts to access virtual memory for the first time, it will check its TLB to see if the memory location is already cached. If it is not, a situation referred to as a *TLB miss,* it performs extra work to translate the virtual address to its physical address and stores a copy of the pairing in the TLB. This process of translating the virtual address to a physical address requires a page-table walk, which costs three physical memory accesses, the memory is then accessed, incurring a fourth physical memory access. In contrast, if the memory was previously accessed and a TLB entry for it exists, the CPU can look up the physical address within the processor by referencing the TLB and access the location in just a single physical memory access, incurring only the cost of the TLB check and a single physical memory access. This is referred to as a *TLB hit* and makes accessing virtual locations stored in the TLB roughly four times faster than accessing the same memory without a pre-existing TLB entry. However, the TLB size is limited and as new locations are accessed, older pairings are copied over with the latest access pairings according to a TLB replacement policy [MoE02]. Virtualization adds complexity to the process because the hypervisor must provide a TLB for both the host and guest OS. Since usually only one TLB cache is available on the processor, the TLB is usually flushed during context switches between the guest and host mode. Even if it not flushed, it is likely that one or more TLB entries will be overwritten while the machine is operating in the alternate context.

To use the TLB to detect virtualization, the detection mechanism uses the TSC to calculate the time it takes to fill the TLB with new entries. Once the TLB is full, the detection mechanism executes a privileged instruction that is likely to be trapped but that minimally alters the TLB, such as the CPUID instruction. Upon interception by a hypervisor using Intel VT-x HAV, the TLB is completely flushed prior to returning the context back to the guest OS. The detection mechanism simply checks for this by accessing the same memory as it did before. If the time it takes to re-access the same memory locations is significantly less than the time it took to initially populate the TLB, it is likely that the TLB was not flushed when the CPUID instruction was executed and therefore the user is within a native OS. However, if the time is similar to the time it initially took to fill the TLB, the TLB was likely flushed and there is evidence of virtualization [Fer08].

Not all hypervisors flush the TLB during a context switch. AMD-V in particular uses an application specific identifier (ASID) to tag TLB entries and preserve them during a context switch. This leads to an alternate from of TLB detection, TLB Hit Counting, which also happens to be effective for Intel VT-x systems.

To perform TLB Hit Counting, the TLB is filled by deliberately accessing specific areas of memory. Once the TLB is full, the page table entries (PTEs) for each location likely to be cached by the TLB are redirected without altering the TLB to point to a page with known “magic” values. Next, an instruction that is likely to be trapped by the hypervisor is executed. In the case of Intel VT-x, the entire TLB is flushed. In other cases, such a with AMD-V systems, at least one entry is likely to change since any existing hypervisor must read the VMCB's exit code during the context switch which will alter at least one TLB entry. Next, the same memory locations that were accessed during the initial filling of the TLB are accessed a second time. Since the PTEs were modified to point to a "*magic*" value, if the TLB experiences a miss, the modified PTEs are accessed and return a "*Hit*" on the "*magic*" values, indicating that a TLB miss has occurred. The relative change in TLB hits or misses indicate the existence of a hypervisor [Ada07].

These TLB detection techniques are reliable for hypervisors that flush or otherwise alter the TLB during context switches. Improvements in how HAV handles the TLB (such as including a second TLB for virtualization within the processor, supporting tagged TLBs, or altering how the VMCB is accessed) could make the TLB persistent and would invalidate these methods [Ber10].

2.6. Conclusion

While not a new concept, the resurgence of virtual machines over the last decade has altered how we use computers in ways that must be carefully considered. The efficiency, cost effectiveness, flexibility, disaster recovery, and security benefits provided by virtualization will likely continue to propel virtualization techniques into mainstream computing. While these benefits are certainly worth exploiting, it is important to consider the potential unintended consequences that arise due to their widespread use. Assumptions, particularly with regard to security, have already proved to be less than completely valid. It is therefore imperative that virtualization and virtual machine introspection are thoroughly analyzed in order to harden virtualization’s defensive posture before it is exploited to the detriment of the user.

III. Methodology

This chapter discusses the methodology used for this research effort. Section 3.1 describes the problem, goals, and hypothesis of this thesis. Sections 3.2 and 3.3 discuss the development of the HAV-R detection tool and obfuscation agent which are created to assist with the experimentation. Sections 3.4 through 3.11 explain the system boundaries, system services, workload, performance metrics, system parameters, factors, evaluation technique, and experimental design. Finally, Section 3.12 provides a summary of the methodology.

3.1. Problem Definition

Virtual machine introspection (VMI) is assumed to provide a trusted platform for forensic inspection and behavior analysis of malware within a guest OS. However, previous research demonstrates that it is possible for malware to escape from the guest into the host and for hardware-assisted hypervisor rootkits (HAV-R) to stealthily transition the native OS into a virtualized environment [Kor09] [RuT07a]. This suggests that hypervisor-based VMI scenarios provide an environment where it is possible for malware to escape the guest into the host, obtain privileged access to the processor, insert a thin hypervisor rootkit beneath the host, and achieve near-perfect visibility into host and guest. Within such a scenario, it is not sufficient for a potential victim to simply detect the presence of a hypervisor, since a trusted hypervisor already exists within the system. Rather, the potential victim must detect the presence of a second hypervisor, in addition to the trusted one used for VMI. It is therefore imperative to determine if HAV-R can be detected within a nested virtualized environment, such as that potentially encountered by a VMI system subverted by a HAV-R.

3.1.1. Goals and Hypothesis

This research effort presents the implementation, analysis, and evaluation of a rootkit hypervisor detection system which exploits processor and translation lookaside buffer-based mechanisms to detect HAV-R within nested virtualized systems. It answers the questions (1) is it possible to detect HAV-R within a nested virtualized environment using selected detection techniques and (2) how do different virtualization types affect HAV-R detection using selected techniques? Finally, based on the selected detection mechanisms, likely countermeasures are implemented and evaluated for effectiveness at obfuscating the existence of a HAV-R.

The detection techniques used in this research rely on detecting the overhead (additional workload) encountered by a system as a result of virtualization. It is hypothesized that the overhead caused by a pre-existing, trusted hypervisor is sufficient to obfuscate the existence of a HAV-R and that, in cases where the HAV-R is detectable, deliberate execution of privileged instructions within the guest OS is sufficient to obscure the HAV-R.

3.1.2. Approach

The experimental approach models a VMI scenario where a user within the native OS uses a trusted hypervisor to introspect a guest OS containing potential malware. This is a common, real-world forensics scenario where malware is likely to exist within a virtualized environment (Section 2.1.5.3). It is assumed that malware within the guest OS has the ability to install a HAV- R beneath the native OS, causing the native OS to transition into a virtualized environment and resulting in a nested virtualized system (see Figure 18). To differentiate the virtualized native OS from the original guest OS, the native OS is henceforth referred to as the trusted OS since, unless a HAV-R is detected, it is assumed to be trusted.

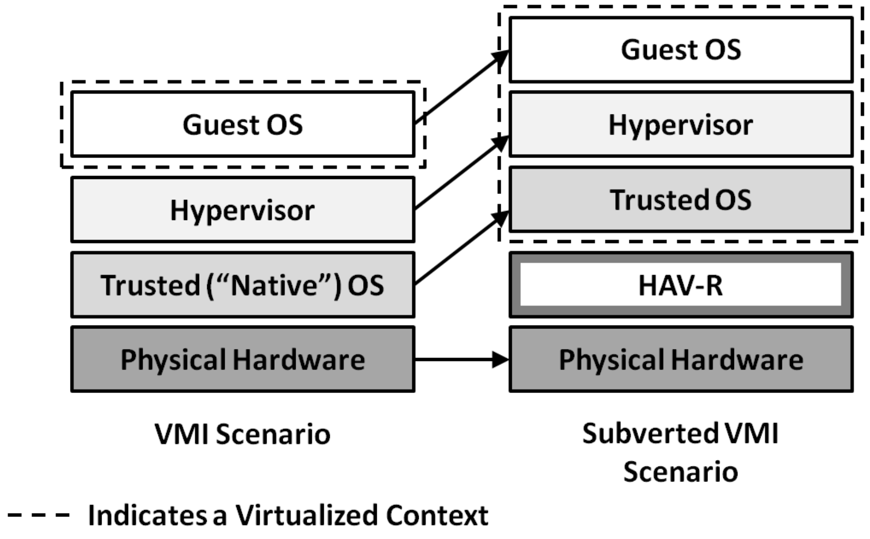


Figure 18. VMI Scenario Transitioned to Subverted VMI Scenario

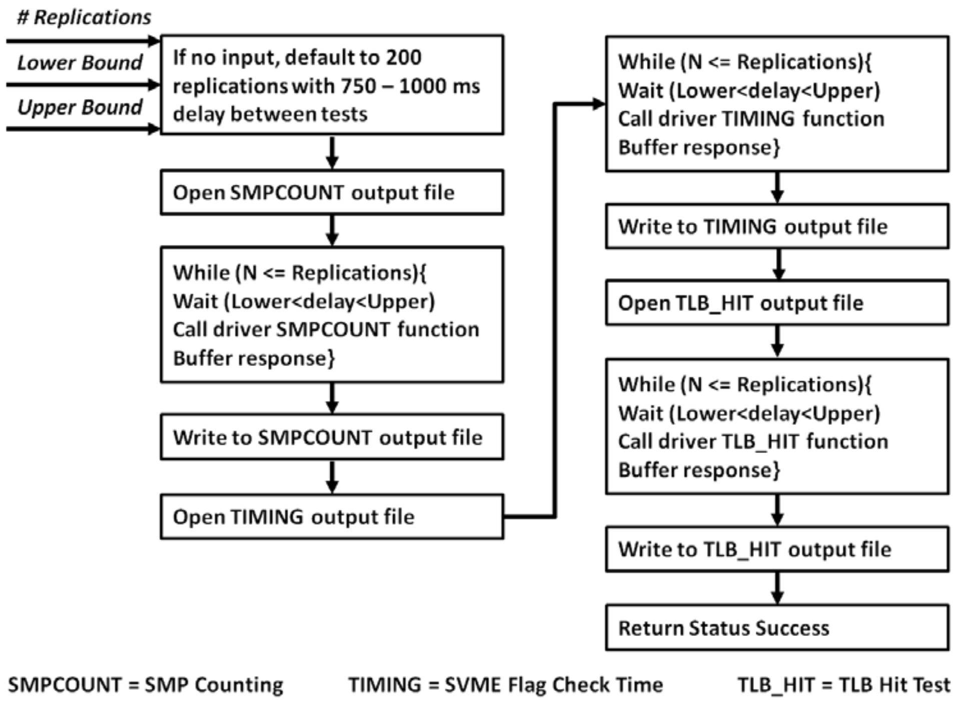
All experiments are performed from the perspective of the trusted OS which contains the HAV-R Detection System (HAV-R DS). The HAV-R DS implements three detection techniques to identify the presence of a HAV-R. For experimentation, various workload combinations are submitted to the HAV-R DS. These workloads vary the type of virtualization used by the VMI scenario, the particular HAV-R installed beneath the trusted OS, and the use of an obfuscation agent (Cloaker) within the guest OS. The HAV-R DS uses HyperScan to gather pertinent experimentation data which is used to determine the presence of a HAV-R within each virtualization scenario. These results are evaluated for accuracy and to determine how each hypervisor, HAV-R, and the obfuscation agent affects HAV-R detection. Note that the scope and conclusions of this thesis are limited to the specific hypervisors, HAV-R detection mechanisms, and HAV-Rs examined during this research.

3.2. HyperScan Software Development

The HyperScan application is created as part of this research and consists of an application and kernel-mode driver pair which gather and save system performance data used for hypervisor detection. The HyperScan driver adapts hypervisor detection techniques previously implemented by Rutkowska and Fritsch and extends them to support the Athlon 64 X2 7750 Black Edition Dual Core 2.70 GHz processor [Rut07b] [Fri08]. It implements the following hypervisor detection techniques (see Section 2.5 for details):

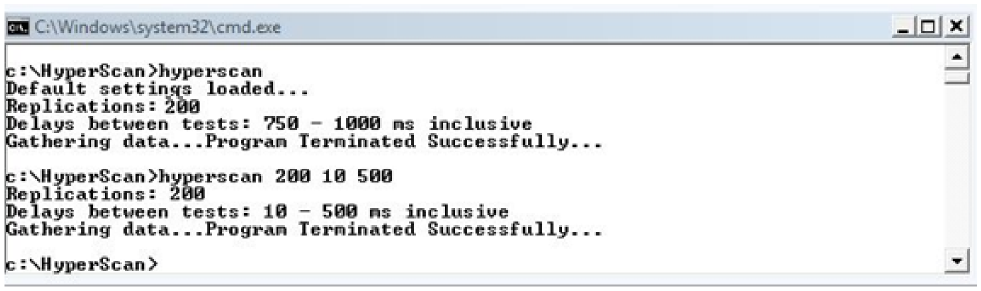
- SMP Counting
- SVME Check Timing
- TLB Profiling

The user-mode application uses the driver to gather detection data and save it to a comma-delimited file. It takes as input the number of desired replications and a lower and upper bound of randomized delay between individual tests (Figure 19). The delay parameters are input in milliseconds (ms) and calculated using the *C srand* function seeded with the *seconds* field of the system time. Since the particular detection techniques utilized in this thesis rely on detection of deviations from normal performance, it is desirable to minimize variation between tests on trusted systems. Pilot tests on the non-subverted, trusted OS revealed that delays of 750-1000 ms resulted in the least variation between tests while introducing randomness to the measurement and keeping each replication delayed by no more than a single second. The delay of 750-1000 ms and 200 replications are chosen as the default settings for the application and experimentation. When the application is initialized, it passes instructions to the kernel-mode driver which performs the appropriate test and returns the resulting data to the user-mode application. The results are saved to a file for analysis by the HAV-R DS. A screenshot of HyperScan operation is shown in Figure 20.



# Replications
Lower Bound
Upper Bound
If no input, default to 200 replications with 750 – 1000 ms delay between tests
Open SMPCOUNT output file
While (N <= Replications){
Wait (Lower<delay<Upper)
Call driver SMPCOUNT function
Buffer response}
Write to SMPCOUNT output file
Open TIMING output file
While (N <= Replications){
Wait (Lower<delay<Upper)
Call driver TIMING function
Buffer response}
Write to TIMING output file
Open TLB_HIT output file
While (N <= Replications){
Wait (Lower<delay<Upper)
Call driver TLB_HIT function
Buffer response}
Write to TLB_HIT output file
Return Status Success
SMPCOUNT = SMP Counting
TIMING = SVME Flag Check Time
TLB_HIT = TLB Hit Test

Figure 19. HyperScan Data Collection Process

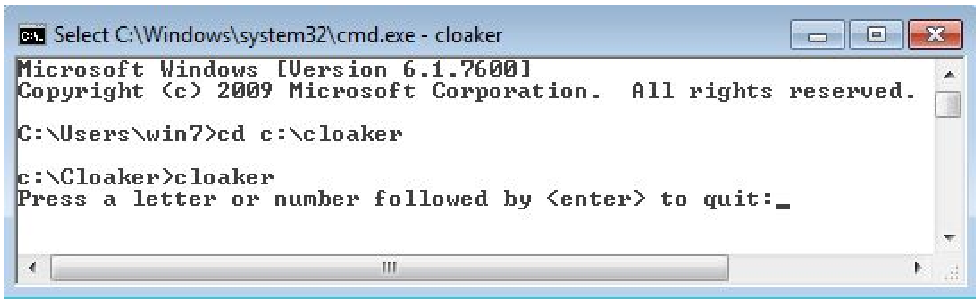


```
c:\HyperScan>hyperscan
Default settings loaded...
Replications: 200
Delays between tests: 750 - 1000 ms inclusive
Gathering data...Program Terminated Successfully...

c:\HyperScan>hyperscan 200 10 500
Replications: 200
Delays between tests: 10 - 500 ms inclusive
Gathering data...Program Terminated Successfully...

c:\HyperScan>
```

Figure 20. HyperScan Operation with Default and Manual Settings

3.3. Cloaker Software Development

The Cloaker software is also created as part of this research and is intended to obfuscate the existence of the HAV-R by interfering with the detection tests implemented by HyperScan. It is thought that the most direct and likely effective way to do this is to implement the same techniques used by the HyperScan driver such that they compete with HyperScan for resources and increase the variability of the detection data, thereby possibly obscuring the overhead induced by the HAV-R. As a result, Cloaker's implementation is similar to HyperScan in that it consists of a user-mode application and kernel-mode driver pair where the Cloaker driver's functionality is nearly identical to HyperScan's detection driver. The user-mode application simply causes the driver to randomly execute the same techniques implemented by the HyperScan detection driver in a tight loop until interrupted by a stop command from the command line. Because the Cloaker application rapidly loops until stopped, it typically uses approximately 100% of processer resources available to it during runtime. Cloaker operation is shown in Figure 21.



```
Microsoft Windows [Version 6.1.7600]
Copyright (c) 2009 Microsoft Corporation.  All rights reserved.

C:\Users\win7>cd c:\cloaker

c:\Cloaker>cloaker
Press a letter or number followed by <enter> to quit:_
```

Figure 21. Cloaker Operation

3.4. System Boundaries

The System Under Test (SUT), shown in Figure 22, consists of a virtualized system containing a trusted (native) OS, hypervisor, guest OS, and HAV-R. The component under test (CUT) is a HAV-R DS within the trusted OS. The physical hardware, guest OS, and CPU HAV settings are parameters that do not vary during the experiment. The hypervisor, HAV-R, and guest OS Obfuscation are all factors. Different combinations of workloads are submitted to the SUT and are referred to as *virtualization scenarios*.

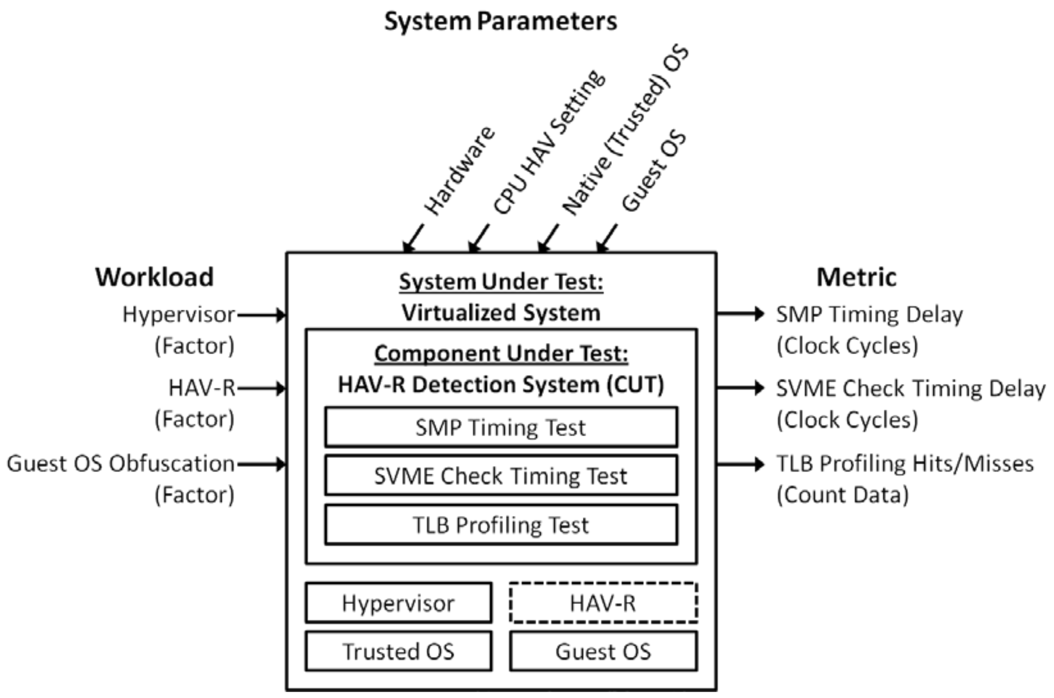


Figure 22. The System Under Test (SUT)

3.5. System Services

The detection system consists of three HAV-R detection methods: SMP Counting, SVME Check Timing, and TLB Profiling. These three particular detection methods are used because they rely on the processor's hardware implementation rather than anomalies caused by a particular hypervisor or HAV-R implementation. It is assumed that it is more difficult to change hardware than software for reasons explained in Section 2.3.1. See Section 2.5 for details on each method. The possible outcomes of the HAV-R DS, as depicted in Figure 23, are:

- HAV-R detected and present
- HAV-R detected and not present (false positive)
- HAV-R not detected and present (false negative)
- HAV-R not detected and not present

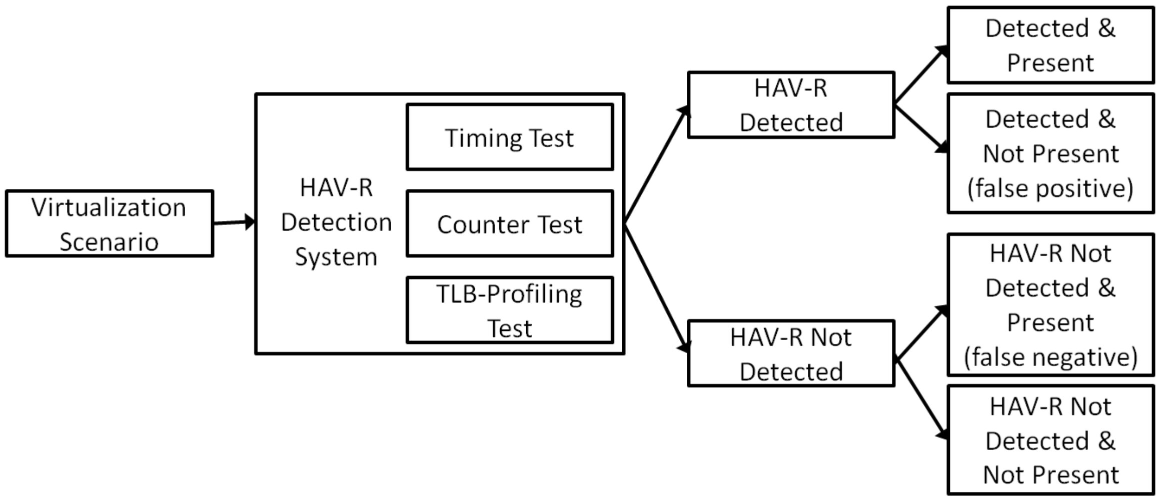


Figure 23. HAV-R DS Possible Outcomes

3.6. Workload

The virtualization scenarios which make up the workload consist of different combinations of the HAV-R, Hypervisor, and in-guest obfuscation. This follows the model of a typical VMI scenario containing a trusted OS, hypervisor, and guest OS where the VMI system may or may not have been compromised by an HAV-R.

3.7. Performance Metrics

Detection of HAV-R is based on the HAV-R's impact on the performance of the system. This performance is measured using clock cycles and by counting the number of TLB hits and misses. The individual experiments are evaluated based on a binary metric, the ability of the HAV-R DS to successfully detect the HAV-R. False positive and false negative results are considered failures while accurate detection, both detected and not detected, is considered success.

3.8. System Parameters

The system parameters include the hardware, trusted OS, guest OS, CPU HAV Setting, hypervisor, HAV-R, and in-guest obfuscation agent (guest obfuscation - *GO*). Factors which are also parameters are discussed in Section 3.9.

3.8.1. Hardware

The hardware used for experimentation consists of a HP Compaq DC5850 Microtower with the following specifications:

- AMD Athlon 64 X2 7750 Dual Core 2.70 GHz Processor, Black Edition
- 786F6 BIOS version 01.09
- 4 x 1 GB PC2-6400 RAM
- 232 GB hard drive

The processor includes AMD Virtualization Technology which provides Hardware Assisted Virtualization (HAV) operation. The overall system is designed to meet the minimum requirements for simultaneous support of the selected trusted OS, hypervisors, guest OSs, and HAV-R's considered for this research.

3.8.2. Trusted (Native) OS

The trusted OS is the lowest level OS within the nested virtualized system. The trusted OS used in this research is 64-bit Microsoft Windows Vista Business version 6.0.6000 Build 6000 (no service pack). Vista is chosen for its compatibility with BluePill. All virtualization scenarios use Vista as the trusted OS. Note that the trusted OS could also be called the host OS or native OS however, since it becomes virtualized during many of the experiments, it is referred to as the trusted OS to avoid confusion between it and the original guest OS within the original virtualized system.

3.8.3. Guest OS

Windows 7 Professional, 64-bit, Service Pack 1 is the guest OS for all experiments as it represents a current, widely-used commercial OS and a likely target for attackers.

3.8.4. CPU HAV Setting

The CPU HAV setting is enabled for all experiments, regardless of hypervisor requirements. This is because HAV must be enabled for installation of the HAV-R.

3.9. Factors

Factors are parameters that are varied between levels and submitted to the SUT. The results of varying these factors are measured by the performance metrics. A summary of factors and corresponding levels used in this study is provided in Table 1. The factors are the hypervisor, HAV-R, and in-guest obfuscation agent. Types within the hypervisor and HAV-R factor categories are mutually exclusive, e.g. BluePill or ESXi can be *on*, but not both simultaneously.

Table 1. Table of Factors

Factor	Type	Level
Hypervisors	QEMU (Emulation)	On/Off
	VMware Workstation (Binary Translation)	On/Off
	VirtualBox (HAV)	On/Off
	Vmware Workstation (HAV)	On/Off
HAV-R	BluePill	On/Off
	ESXi	On/Off
In-Guest Obfuscation		On/Off

3.9.1. Hypervisor

The hypervisor is used to virtualize the guest OS and is one of the following types: emulation, full virtualization using binary translation, and full virtualization using HAV. Four hypervisors are tested using each of these techniques with full virtualization using HAV represented twice. The hypervisors and their levels are:

- QEMU 0.9.0 (emulation), On/Off.
- VMware Workstation 8 (full virtualization using binary translation), On/Off.
- VirtualBox 4.1.10 (full virtualization using HAV), On/Off.
- VMware Workstation 8 (full virtualization using HAV), On/Off.

3.9.2. HAV-R

The HAV-Rs used for experimentation are BluePill 0.32 (Section 2.4.1) and ESXi 5.0, a thin, bare metal hypervisor with HAV-R-like behaviors (Section 2.2.4). While it is likely that other real-world implementations of HAV-R exist, they are difficult to find, likely since this area of virtualization-based attack is relatively new and is seemingly not yet widely exploited. The HAV-R levels are on and off.

3.9.3. Guest Obfuscation Agent

A guest OS that is capable of installing an HAV-R beneath the trusted OS may also attempt to hide the HAV-R by anticipating detection techniques and performing in-guest execution of privileged instructions in order to counter HAV-R detection. This is modeled through the inclusion of an in-guest obfuscation agent, Cloaker, which sends randomized privileged instructions to the processor and actively changes fields in the TLB. The guest obfuscation levels are on and off.

3.10. Evaluation Technique

The evaluation method is empirical measurement of a real system. Due to the complexity of nested virtualized systems, this is the most practical and meaningful test for detection of HAV-R since it provides results derived from execution within a real system.

To evaluate the ability of the HAV-R DS to detect the presence of a HAV-R, virtualization scenarios consisting of different combinations of factors are submitted to the HAV-R DS and direct measurements are obtained using HyperScan. This data is used to infer the existence of a HAV-R based on changes encountered during subsequent measurements of the system after an initial baseline measurement is performed on a trusted system which does not contain a HAV-R. Experiments are performed sequentially with sufficient delay between replications such that the non-subverted trusted system is assumed to reach a steady state with minimal variance between experiments. For this research, 750-1000 ms is considered sufficient delay between replications based on preliminary analysis accomplished during pilot testing (see Section 3.2). There is also a delay of 10 minutes prior to execution of HyperScan for each virtualization scenario. Pilot testing using the Windows Task Manager Performance Monitor revealed that a delay of 5 minutes is sufficient for the system to reach a steady state after a reboot of the system and once all required applications are running. This is doubled to a delay of 10 minutes as a precautionary measure. Variance is expected to be low due to the mechanical nature of the tests and the data is expected to be normally distributed. The resulting data is analyzed using statistical analysis of variance (ANOVA) techniques to determine if the data gathered before and after subversion are statistically different.

To perform the experiments, the following steps are taken for each virtualization scenario:

1. Gather performance metrics from a non-subverted VMI system
    a. Configure the host machine with the trusted OS, hypervisor, and guest OS; the guest OS will remain running and is not paused or stopped during experimentation.
    b. Install the data collection tool, HyperScan, within the trusted OS.
    c. Reboot the machine and, after a wait of 10 minutes during which the system is assumed to reach a steady state, execute HyperScan to gather non-subverted VMI baseline data for the non-subverted VMI system. Save the data for later analysis.
2. Gather performance metrics from the subverted VMI (SVMI) system
    a. Configure the SVMI system by adding a HAV-R to the non-subverted system resulting in a nested virtualized environment.

   b. After a wait of 10 minutes, during which the system is assumed to reach a steady state, execute the HyperScan to gather SVMI benchmark data for the SVMI system. Save the data for later analysis.

3. Gather performance metrics from SVMI system with GO
   a. Install and execute the GO program, Cloaker, within the guest OS; note that the guest OS will remain running and should not be paused or stopped during experimentation.
   b. After a wait of 10 minutes, during which the system is assumed to reach a steady state, execute HyperScan to gather SVMI with Guest Obfuscation benchmark data for the SVMI with Guest Obfuscation system. Save the data for later analysis.
4. Repeat steps 1-3 for each hypervisor configuration to be tested.
5. Repeat steps 1-4 for each HAV-R to be tested.
6. Upon completion, analyze the data to determine if detectable and statistically significant delays are caused by the existence of a HAV-R. Analyze the impact of each hypervisor and GO on HAV-R detection.

The results obtained from experimentation are validated through prior knowledge of hypervisor and x86 architecture interaction, statistical analysis of the data, and direct observation of the system.

3.11. Experimental Design

A factorial design is used to evaluate the interaction between factors. The factors include the HAV-R, hypervisor, and GO, with 3, 4 and 2 levels respectively. This results in 3 x 4 x 2 = 24 experiment virtualization scenarios [Figure 24]. Since GO is performed to hide the existence of an HAV-R, GO is not evaluated for those experiments which represent trusted systems used for initial baseline data collection. This reduces the

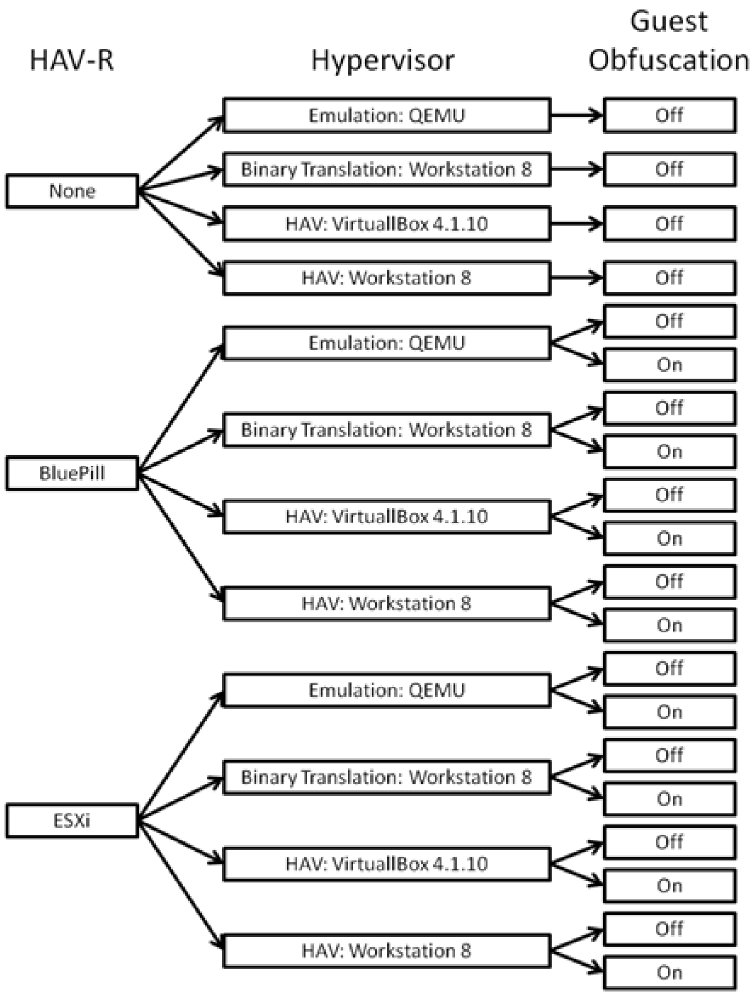


Figure 24. Chart of Factor Combinations (Virtualization Scenarios)

number of scenarios by 4 resulting in 20 virtualization scenarios. Each of the 20 virtualization scenarios is tested using three detection techniques, and these tests are repeated 200 times. This results in 20 * 3 * 200 = 12,000 total experiments. Consecutive tests are performed at semi-random intervals bounded between 0.75 and 1 second inclusive. Based on pilot studies, low variance and normality are assumed and the analysis is performed using a 95% confidence interval. Even if the data is non-normal, the central limit theorem states that the sampling distribution is approximately normal for *large* sample sizes (where the number of samples > 30). Since the average time between tests is a fraction of a second, 200 tests are performed which provide a relatively large number of measurements within a small amount of time.

3.12. Methodology Summary

This research effort is designed to accomplish the following goals:

- Determine if it is possible to detect HAV-Rs within a nested virtualized environment using selected detection techniques.
- Explore how different virtualization techniques affect HAV-R detection within a nested virtualized environment.
- Determine if in-guest obfuscation affects HAV-R detection.

To do this end, twenty virtualization scenarios are developed using three virtualization types, two HAV-Rs, and two levels of GO. Each scenario is evaluated using three detection techniques with 200 repetitions each. The results are statistically analyzed using ANOVA techniques to determine if HAV-Rs are detectable within a nested virtualized environment as well as how each factor affects HAV-R detection.

IV. Analysis

Twenty virtualization scenarios are tested using the three detection techniques of SMP Counting, SVME Check Timing, and TLB Profiling (referred to as SMPCOUNT, TIMING, and TLBHIT respectively; see Section 2.5 for a description of these detection techniques).

During testing, it is discovered that the guest obfuscation (GO) tool, Cloaker, causes deadlock and stop errors (the “blue screen of death”) within the trusted OS during three of the twenty virtualization scenarios. It is observed that the failures are not consistent with any particular factor, occurring during scenarios using both BluePill and ESXi HAV-Rs as well as configurations using emulation and HAV hypervisors. The failures are investigated by modifying the Cloaker software however, no solution is identified and the cause remains undetermined. It is possible that each failure occurs due to a unique reason and it is noted that such failures could originate within the guest OS, trusted OS, or within the HAV-R. While data is unavailable for these three failed virtualization scenarios, the challenges encountered underscore the complexity of developing software designed to exploit nested virtualization.

Of sixty virtualization environment/detection technique pairs consisting of twenty virtualization scenarios with three detection techniques each, only fifty-one experiments are successfully performed since three scenarios using three tests each are not completed due to Cloaker problems. The resulting data is referenced using the following naming convention: <Hypervisor>_<VMI or SVMI>_<HAV-R (if present)>_<GO (if present)>_<Detection Technique>. A complete list of data set names is shown in Table 2.

The nine data sets which correspond to the three virtualization scenarios which are impossible to test are shown in bold and included in the list for completeness.

Table 2. Experiment Data Set Labels

QEMU_VMI_SMPCOUNT	VBOXHAV_VMI_TIMING	VMWAREBT_VMI_TLBHIT
QEMU_SVMI_BP_SMPCOUNT	VBOXHAV_SVMI_BP_TIMING	VMWAREBT_SVMI_BP_TLBHIT
QEMU_SVMI_ESX_SMPCOUNT	VBOXHAV_SVMI_ESX_TIMING	VMWAREBT_SVMI_ESX_TLBHIT
QEMU_SVMI_BP_GO_SMPCOUNT	**VBOXHAV_SVMI_BP_GO_TIMING**	VMWAREBT_SVMI_BP_GO_TLBHIT
QEMU_SVMI_ESX_GO_SMPCOUNT	VBOXHAV_SVMI_ESX_GO_TIMING	VMWAREBT_SVMI_ESX_GO_TLBHIT
QEMU_VMI_TIMING	VBOXHAV_VMI_TLBHIT	VMWAREHAV_VMI_SMPCOUNT
QEMU_SVMI_BP_TIMING	VBOXHAV_SVMI_BP_TLBHIT	VMWAREHAV_SVMI_BP_SMPCOUNT
QEMU_SVMI_ESX_TIMING	VBOXHAV_SVMI_ESX_TLBHIT	VMWAREHAV_SVMI_ESX_SMPCOUNT
QEMU_SVMI_BP_GO_TIMING	**VBOXHAV_SVMI_BP_GO_TLBHIT**	**VMWAREHAV_SVMI_BP_GO_SMPCOUNT**
QEMU_SVMI_ESX_GO_TIMING	VBOXHAV_SVMI_ESX_GO_TLBHIT	VMWAREHAV_SVMI_ESX_GO_SMPCOUNT
QEMU_VMI_TLBHIT	VMWAREBT_VMI_SMPCOUNT	VMWAREHAV_VMI_TIMING
QEMU_SVMI_BP_TLBHIT	VMWAREBT_SVMI_BP_SMPCOUNT	VMWAREHAV_SVMI_BP_TIMING
QEMU_SVMI_ESX_TLBHIT	VMWAREBT_SVMI_ESX_SMPCOUNT	VMWAREHAV_SVMI_ESX_TIMING
QEMU_SVMI_BP_GO_TLBHIT	VMWAREBT_SVMI_BP_GO_SMPCOUNT	**VMWAREHAV_SVMI_BP_GO_TIMING**
QEMU_SVMI_ESX_GO_TLBHIT	VMWAREBT_SVMI_ESX_GO_SMPCOUNT	VMWAREHAV_SVMI_ESX_GO_TIMING
VBOXHAV_VMI_SMPCOUNT	VMWAREBT_VMI_TIMING	VMWAREHAV_VMI_TLBHIT
VBOXHAV_SVMI_BP_SMPCOUNT	VMWAREBT_SVMI_BP_TIMING	VMWAREHAV_SVMI_BP_TLBHIT
VBOXHAV_SVMI_ESX_SMPCOUNT	VMWAREBT_SVMI_ESX_TIMING	VMWAREHAV_SVMI_ESX_TLBHIT
VBOXHAV_SVMI_BP_GO_SMPCOUNT	VMWAREBT_SVMI_BP_GO_TIMING	**VMWAREHAV_SVMI_BP_GO_TLBHIT**
VBOXHAV_SVMI_ESX_GO_SMPCOUNT	VMWAREBT_SVMI_ESX_GO_TIMING	VMWAREHAV_SVMI_ESX_GO_TLBHIT

4.1. Exploratory Data Analysis

Each virtualization scenario experiment consists of 200 repetitions for each detection technique. During initial analysis it is noted that in some cases, the SMPCOUNT and TIMING detection mechanisms report values of zero for particular experiments. It is theorized that these results are caused by interruption of the counting process during the delay between when the experiment starts and when the counter first increments. This is possible since the detection tool is not programmed to run at a non-interruptible level within the trusted OS. Avoiding interruptions during execution within Windows systems is usually accomplished by raising the process to *dispatch* level. This was attempted during the software development phase of this thesis and it was discovered that this causes intermittent deadlock which prohibits successful testing. In response, the program was allowed to execute at a lower priority level which greatly improved its stability. Since the detection tool does not run at the highest level, it is possible for other processes to interrupt the counter process. If the timed process finishes and returns a completion signal while the timing process is interrupted, once the timing process begins to execute again it will immediately detect completion of the timed process and return the counter value which may not have incremented. Since it is impossible for the detection techniques to legitimately complete within zero clock cycles, these zero values are considered invalid and removed from the data. All other data, including possible outliers, are retained for analysis. Table 3 provides summary statistics for all experiments performed.

The values indicate that most of the data possess a relatively high standard deviation which indicates high variability among data elements. This is further supported by the box plots in Figures 25-30 which depict the data organized by detection technique. For each technique, two aggregate box plot graphs are presented; the first depicts raw, untransformed data while the second plots the data on a logarithmic scale which stabilizes the variance, mutes the effect of outliers, and better reveals the differences between data sets. Note that in the logarithmic box plots for each detection technique, the vertical distance between the non-subverted data and the other data suggests that the distributions are not equal. Experiment numbers correspond to the ID column in Table 3 and non-subverted VMI data is indicated by an asterisk.

Table 3. Virtualization Scenario Summary Statistics

ID	Virtualization Scenario Name	n	Mean	Median	Std Dev
1	QEMU_VMI_SMPCOUNT	197	20.848	20.000	6.574
2	QEMU_SVMI_BP_SMPCOUNT	200	1346.205	1348.500	109.456
3	QEMU_SVMI_BP_GO_SMPCOUNT	197	1072.635	1038.000	195.130
4	QEMU_SVMI_ESX_SMPCOUNT	200	1055.280	908.000	945.303
5	QEMU_VMI_TIMING	200	214.700	213.000	21.425
6	QEMU_SVMI_BP_TIMING	200	19688.720	18337.500	2473.851
7	QEMU_SVMI_BP_GO_TIMING	200	17791.310	17680.500	670.628
8	QEMU_SVMI_ESX_TIMING	200	9144.830	6915.000	11885.690
9	QEMU_VMI_TLBHIT	200	54.100	53.500	2.736
10	QEMU_SVMI_BP_TLBHIT	200	70.030	69.000	2.950
11	QEMU_SVMI_BP_GO_TLBHIT	200	69.580	69.000	3.723
12	QEMU_SVMI_ESX_TLBHIT	200	166.095	147.000	56.928
13	VMWAREBT_VMI_SMPCOUNT	185	24.292	21.000	7.800
14	VMWAREBT_SVMI_BP_SMPCOUNT	165	519.667	482.000	134.222
15	VMWAREBT_SVMI_BP_GO_SMPCOUNT	133	759.617	543.000	1022.582
16	VMWAREBT_SVMI_ESX_SMPCOUNT	191	984.021	1033.000	371.568
17	VMWAREBT_SVMI_ESX_GO_SMPCOUNT	145	1341.876	1081.000	1409.071
18	VMWAREBT_VMI_TIMING	200	216.085	213.000	17.919
19	VMWAREBT_SVMI_BP_TIMING	200	7020.840	6126.000	9133.327
20	VMWAREBT_SVMI_BP_GO_TIMING	200	3247.645	3137.000	563.020
21	VMWAREBT_SVMI_ESX_TIMING	200	10183.840	9646.500	19950.620
22	VMWAREBT_SVMI_ESX_GO_TIMING	200	14949.620	6290.000	55053.600
23	VMWAREBT_VMI_TLBHIT	200	54.250	55.000	2.044
24	VMWAREBT_SVMI_BP_TLBHIT	200	72.410	73.000	1.957
25	VMWAREBT_SVMI_BP_GO_TLBHIT	200	71.895	72.000	3.353
26	VMWAREBT_SVMI_ESX_TLBHIT	200	220.605	260.000	78.598
27	VMWAREBT_SVMI_ESX_GO_TLBHIT	200	201.655	197.500	112.806
28	VMWAREHAV_VMI_SMPCOUNT	180	33.217	25.000	19.271
29	VMWAREHAV_SVMI_BP_SMPCOUNT	189	494.249	489.000	82.991
30	VMWAREHAV_SVMI_ESX_SMPCOUNT	185	1509.973	1287.000	1864.571
31	VMWAREHAV_SVMI_ESX_GO_SMPCOUNT	139	949.288	932.000	281.142
32	VMWAREHAV_VMI_TIMING	200	218.505	213.000	27.032
33	VMWAREHAV_SVMI_BP_TIMING	200	13376.430	6282.000	60077.060
34	VMWAREHAV_SVMI_ESX_TIMING	200	11795.740	9399.000	21475.500
35	VMWAREHAV_SVMI_ESX_GO_TIMING	200	6446.365	5636.000	2510.947
36	VMWAREHAV_VMI_TLBHIT	200	54.995	54.000	15.794
37	VMWAREHAV_SVMI_BP_TLBHIT	200	70.145	70.000	2.824
38	VMWAREHAV_SVMI_ESX_TLBHIT	200	123.345	86.000	101.454
39	VMWAREHAV_SVMI_ESX_GO_TLBHIT	200	160.570	121.500	102.871
40	VBOXHAV_VMI_SMPCOUNT	197	26.472	25.000	9.861
41	VBOXHAV_SVMI_BP_SMPCOUNT	199	531.819	489.000	171.655
42	VBOXHAV_SVMI_ESX_SMPCOUNT	182	1244.418	1191.500	244.978
43	VBOXHAV_SVMI_ESX_GO_SMPCOUNT	75	1096.160	855.000	2057.879
44	VBOXHAV_VMI_TIMING	200	216.170	213.000	15.702
45	VBOXHAV_SVMI_BP_TIMING	200	6351.200	5968.500	1335.813
46	VBOXHAV_SVMI_ESX_TIMING	200	6989.935	5497.500	7580.405
47	VBOXHAV_SVMI_ESX_GO_TIMING	200	18525.520	5417.500	178528.800
48	VBOXHAV_VMI_TLBHIT	200	53.905	54.000	2.331
49	VBOXHAV_SVMI_BP_TLBHIT	200	70.935	71.000	2.635
50	VBOXHAV_SVMI_ESX_TLBHIT	200	139.335	121.500	68.457
51	VBOXHAV_SVMI_ESX_GO_TLBHIT	200	192.405	151.500	73.669

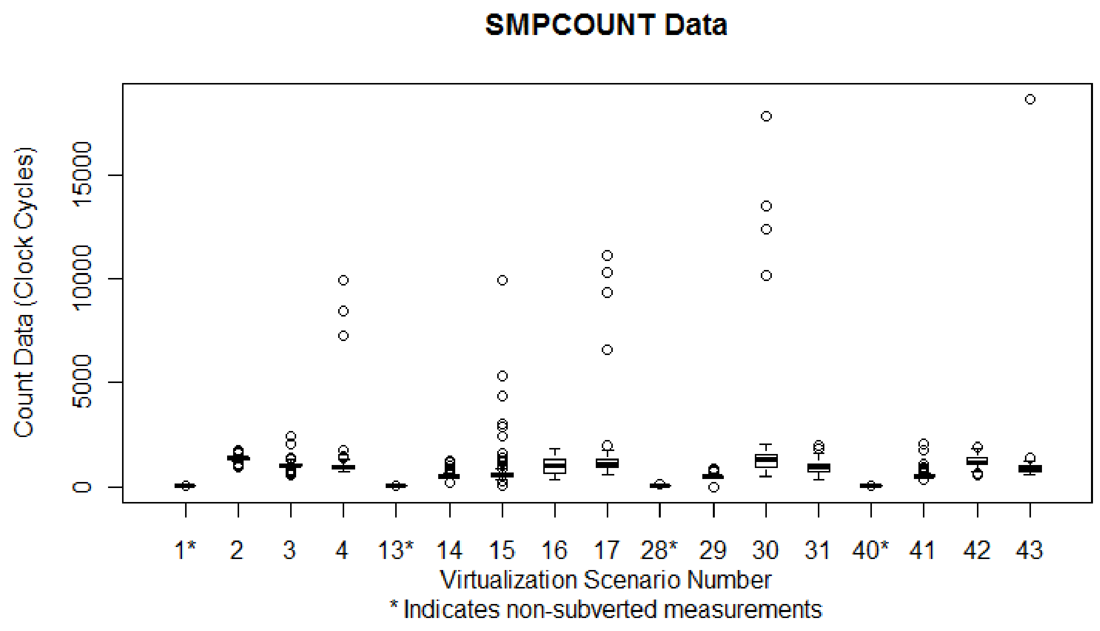


Figure 25. Untransformed SMPCOUNT Data

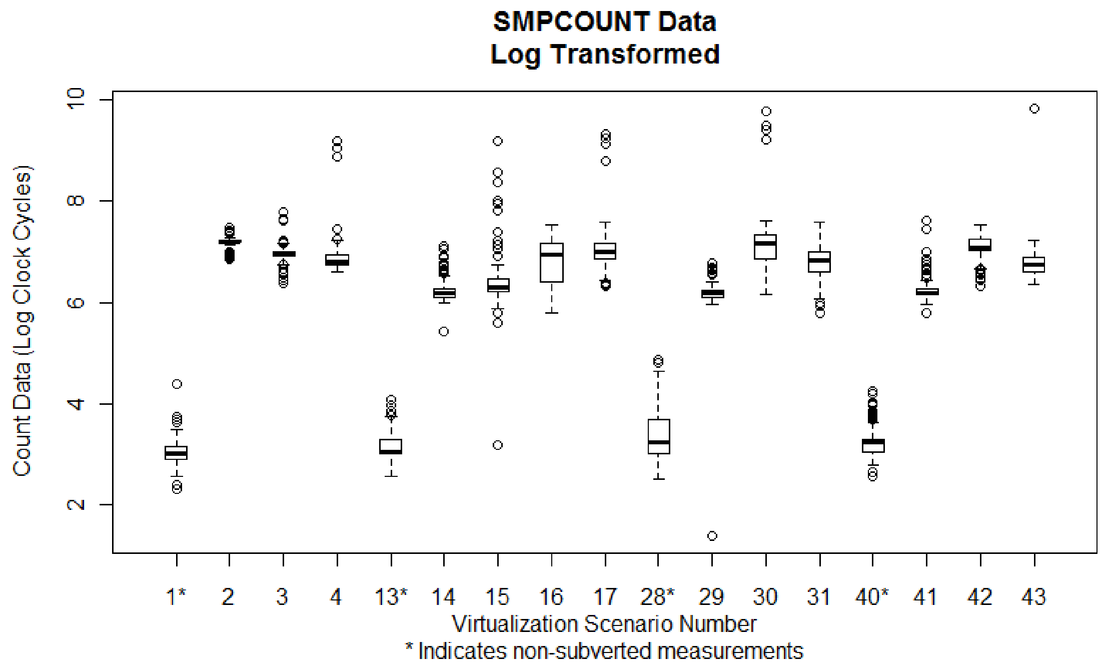


Figure 26. Log Transformed SMPCOUNT Data

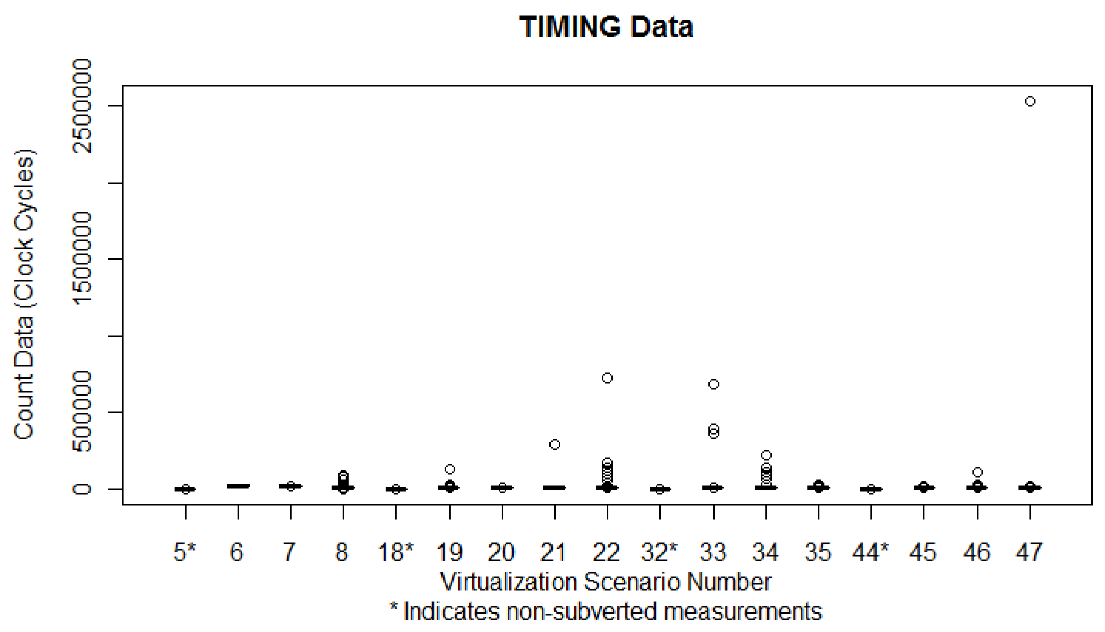


Figure 27. Untransformed TIMING Data

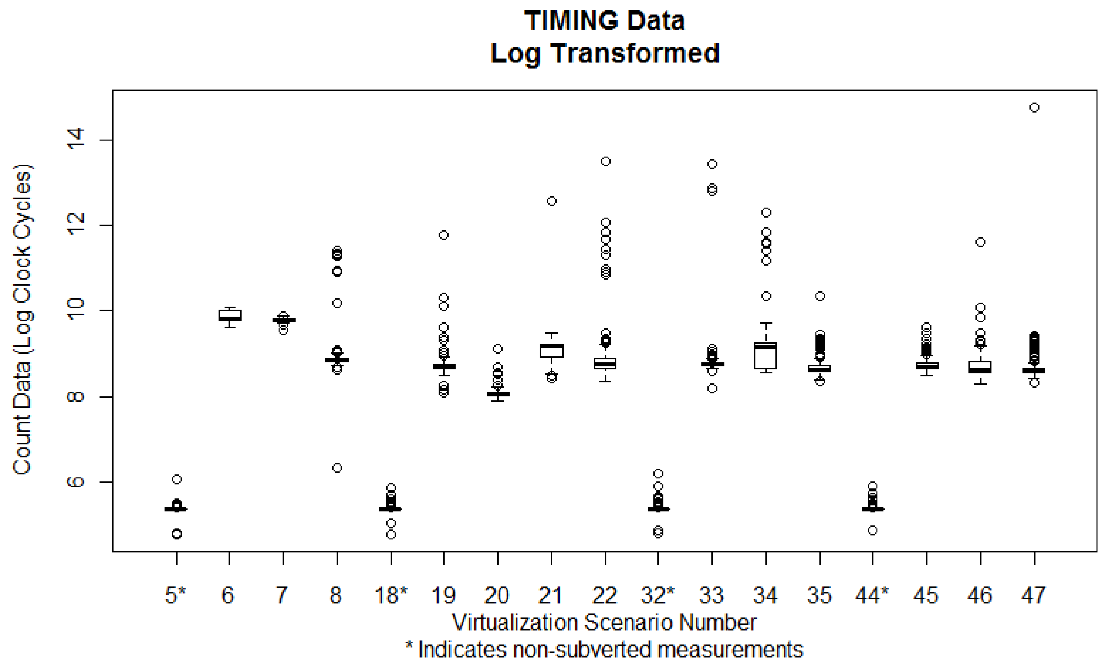


Figure 28. Log Transformed TIMING Data

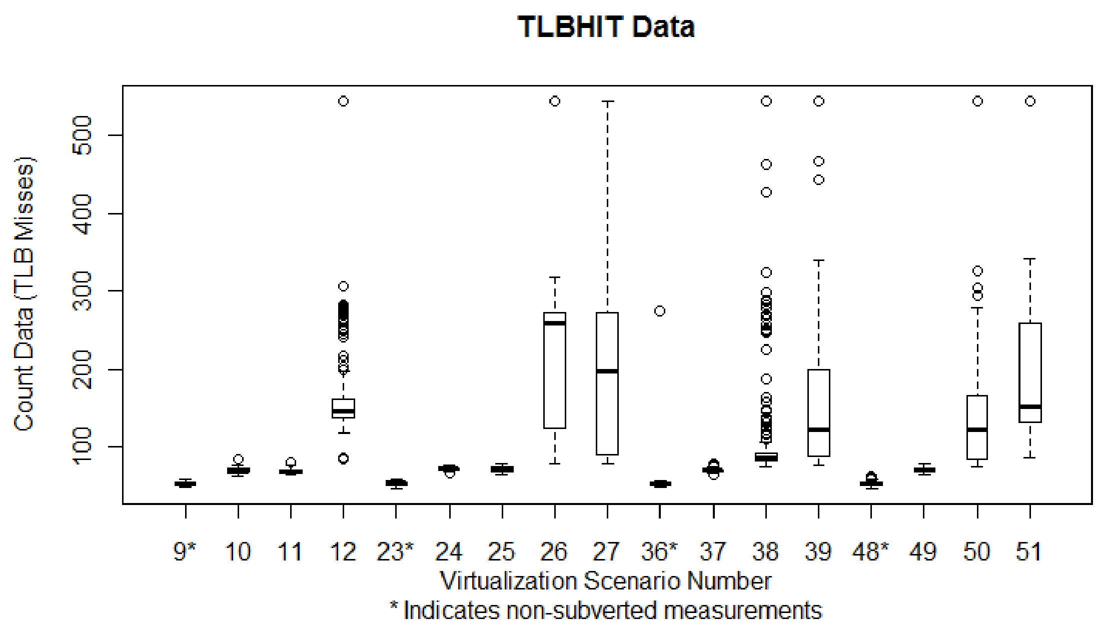


Figure 29. Untransformed TLBHIT Data

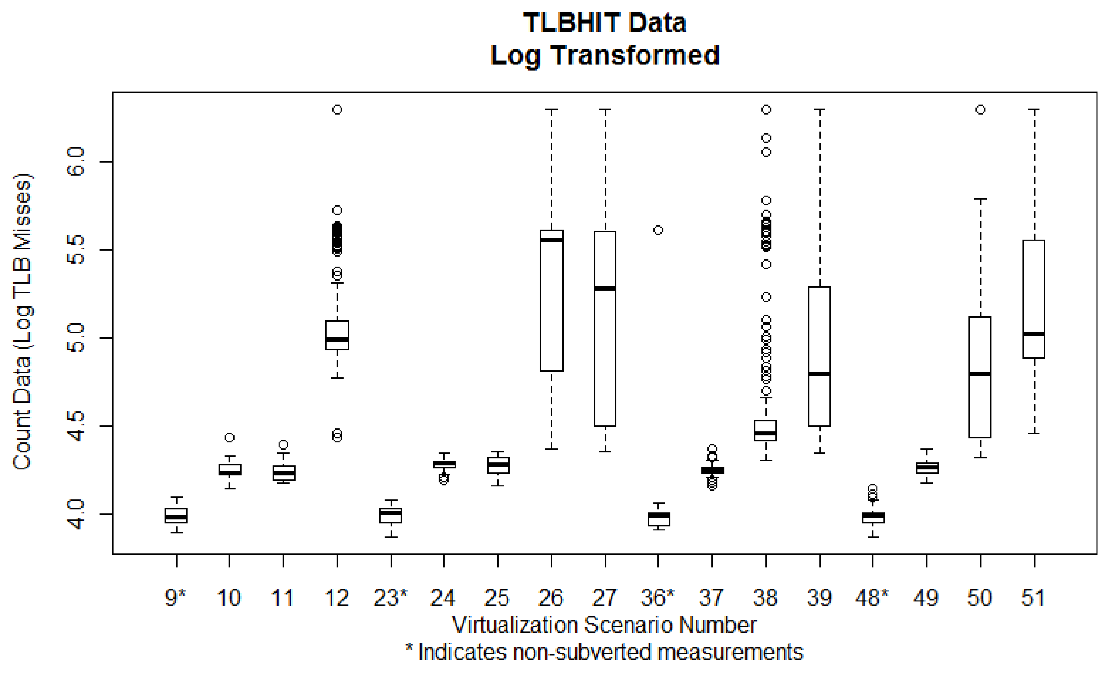


Figure 30. Log Transformed TLBHIT Data

Box plots, along with quantile quantile plots and density plots of each data set further indicate that much of the data is highly skewed with several outliers (See Appendix H for quantile quantile and density plots not included here). Overall, the results appear to consist of non-normal, skewed, and occasionally long tailed data with outliers. Such data is considered non-parametric since it cannot be assumed to be normally distributed [GiC11]. This is surprising and invalidates earlier assumptions of normality expressed in Chapter III. As a result, non-parametric statistical tools are employed.

To determine if two non-parametric populations are statistically different, the null hypothesis that they are identical is tested using the Wilcoxon rank sum test. This test is equivalent to the Mann-Whitney *U* test, assumes independent ordinal observations, and is particularly powerful for non-parametric data. It is considered by many statisticians to be the best non-parametric test for location. In instances where the two populations are normal, the asymptotic relative efficiency (a measure of the closeness of the selected procedure to a notional "best possible" procedure) is 0.9550, making it robust for both normal and non-parametric data [GiC11] [SaS05]. This is significant since some of the experimental data used in this thesis may exhibit normality though most samples are non-parametric. Relative to the two-sample Student's *t* test, a commonly used parametric tool mathematically equivalent to the one-way analysis of variance test for comparison of two populations, the Wilcoxon rank-sum test has an asymptotic relative efficiency of, at minimum, 0.864 and performs better than the *t* test for some non-normal distributions. Since the *t* test is questionable for non-parametric data (due to its reliance on normality and susceptibility to outliers), the Wilcoxon rank sum test is an appropriate statistical tool for data analysis [GiC11].

4.2. Detection of HAV-R within Nested Virtualized Environments

The baseline VMI scenarios are compared with each of the SVMI scenarios using the Wilcoxon rank sum test. The null hypothesis for these tests is that the baseline sample is less than or equal to the SVMI sample. This hypothesis is rejected for one-sided *p*-values < 0.05.

The BluePill SVMI scenarios are examined first, and it is determined that the calculated *p*-value for all tests is < 2.2e-16. This is extremely small and provides convincing evidence that the BluePill SVMI scenarios are statistically different from the non-subverted VMI scenarios for all detection techniques (see Table 4).

Table 4. Non-subverted VMI vs. BluePill SVMI

Test Type	Hypervisor	VMI (Control) Mean	VMI (Control) Std Dev	SVMI-BP Mean	SVMI-BP Std Dev	VMI / SVMI-BP *p*-value*
SMPCOUNT	QEMU	20.848	6.574	1346.205	109.456	< 2.2e-16
	VMware Binary Translation	24.292	7.800	519.667	134.222	< 2.2e-16
	VMware HAV	33.217	19.271	494.249	82.991	< 2.2e-16
	VirtualBox HAV	26.472	9.861	531.819	171.655	< 2.2e-16
TIMING	QEMU	214.700	21.425	19688.720	2473.851	< 2.2e-16
	VMware Binary Translation	216.085	17.919	7020.840	9133.327	< 2.2e-16
	VMware HAV	218.505	27.032	13376.430	60077.060	< 2.2e-16
	VirtualBox HAV	216.170	15.702	6351.200	1335.813	< 2.2e-16
TLBHIT	QEMU	54.100	2.736	70.030	2.950	< 2.2e-16
	VMware Binary Translation	54.250	2.044	72.410	1.957	< 2.2e-16
	VMware HAV	54.250	15.794	70.145	2.824	< 2.2e-16
	VirtualBox HAV	54.250	2.331	70.935	2.635	< 2.2e-16

*One sided *p*-value

The ESXi SVMI scenarios are also evaluated against the non-subverted VMI scenarios and yield *p*-values of < 2.2e-16 for all tests, providing convincing evidence that that the ESXi SVMI scenarios are statistically different from the non-subverted VMI scenarios for all detection techniques (see Table 5).

Table 5. Non-subverted VMI vs. ESXi SVMI

Test Type	**Hypervisor**	**VMI (Control) Mean**	**VMI (Control) Std Dev**	**SVMI-ESX Mean**	**SVMI-ESX Std Dev**	**VMI / SVMI-ESX *p*-value***
SMPCOUNT	QEMU	20.848	6.574	1055.280	945.303	< 2.2e-16
	VMware Binary Translation	24.292	7.800	984.021	371.568	< 2.2e-16
	VMware HAV	33.217	19.271	1509.973	1864.571	< 2.2e-16
	VirtualBox HAV	26.472	9.861	1244.418	244.978	< 2.2e-16
TIMING	QEMU	214.700	21.425	9144.830	11885.690	< 2.2e-16
	VMware Binary Translation	216.085	17.919	10183.840	19950.620	< 2.2e-16
	VMware HAV	218.505	27.032	11795.740	21475.500	< 2.2e-16
	VirtualBox HAV	216.170	15.702	6989.935	7580.405	< 2.2e-16
TLBHIT	QEMU	54.100	2.736	166.095	56.928	< 2.2e-16
	VMware Binary Translation	54.250	2.044	220.605	78.598	< 2.2e-16
	VMware HAV	54.250	15.794	123.345	101.454	< 2.2e-16
	VirtualBox HAV	54.250	2.331	139.335	68.457	< 2.2e-16

*One sided *p*-value

Bar charts of the data with 95% confidence intervals validate the results and show that the count data for SVMI are significantly and consistently higher than the count data for the non-subverted VMI data (Figures 31-33). Comparison of median values is appropriate due to the presence of non-parametric data. For this same reason, the statistical resampling method of bootstrapping is used to generate bias-corrected and accelerated confidence intervals which are validated using Wilcoxon rank sum test confidence interval calculations [LuC00].

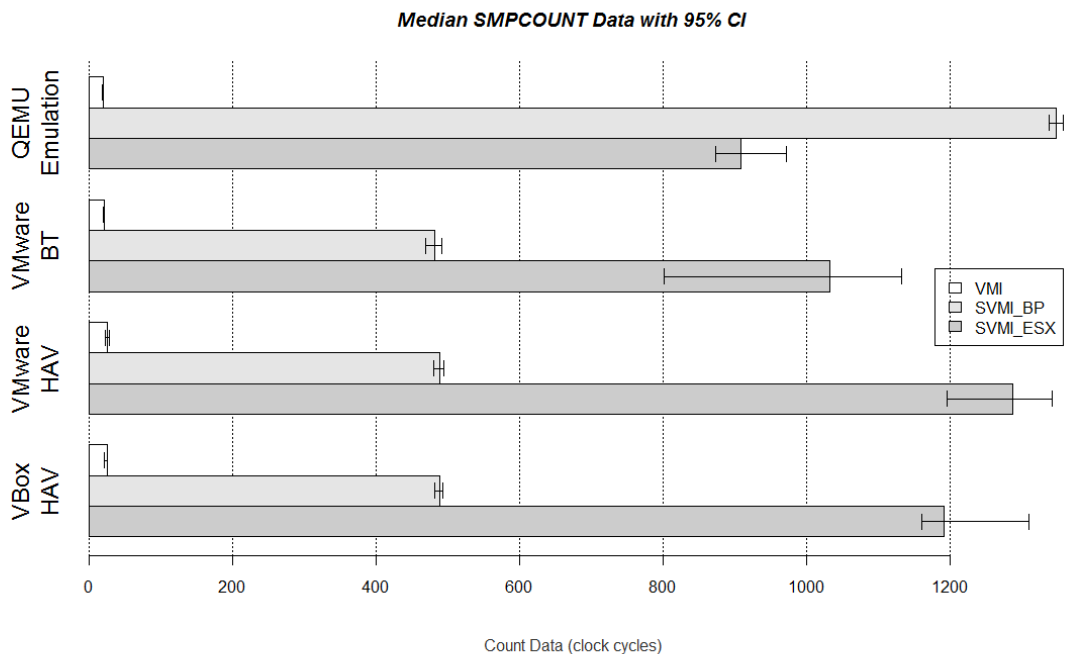


Figure 31. Comparison of Median SMPCOUNT Data with 95% CI

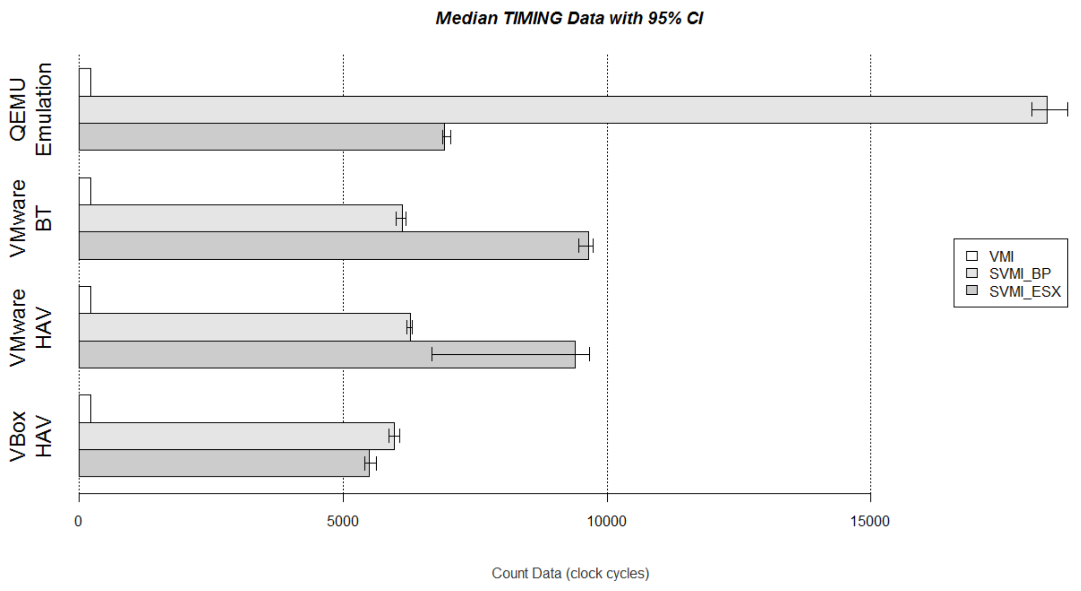


Figure 32. Comparison of Median TIMING Data with 95% CI

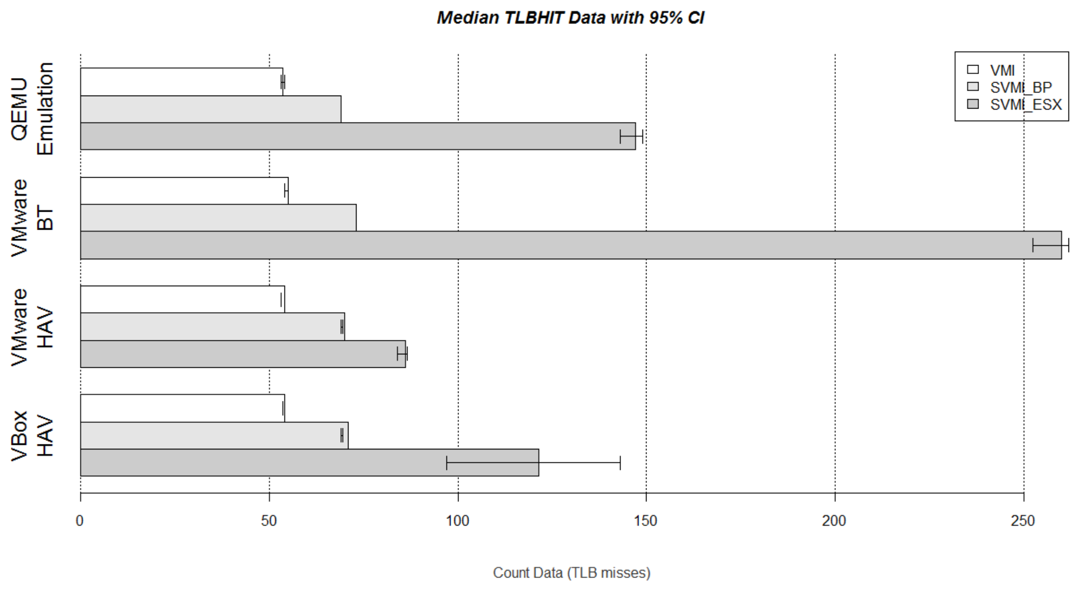


Figure 33. Comparison of Median TLBHIT Data with 95% CI

In all cases, regardless of hypervisor or particular HAV-R, the data shows an increase in execution overhead when the machine is transitioned from a pure to a subverted VMI environment. The Wilcoxon rank sum test analysis indicates that this increased execution is detectable and statistically convincing in all cases.

4.3. Effects of Obfuscation (Cloaker)

The SVMI with guest obfuscation scenarios are evaluated first against the baseline VMI scenarios and then against the non-obfuscation SVMI scenarios. The first set of tests determine if guest obfuscation successfully conceals the HAV-R by inducing overhead that is not statistically different from the pure VMI environment. The second tests if guest obfuscation significantly changes the overhead created by SVMI. Both are evaluated using a two-tailed Wilcoxon rank sum test with the hypothesis that the populations are the same. Bar charts organized by detection technique and depicting the median of the data along with corresponding confidence intervals are included to graphically represent the data. Recall that three of the virtualization scenarios are not completed due to incompatibility constraints. The resulting missing data is indicated by asterisks in the table and manifest as *missing* bars in the bar graphs.

The two-sided p-values of < 2.2e-16 provide convincing evidence that the VMI and BluePill and ESXi SVMI scenarios with GO are statistically different (Tables 6-7). This is supported by bar charts which reveal that the SVMI with guest obfuscation medians are significantly greater than the VMI medians in all cases (Figures 34-36).

Table 6. Analysis of VMI vs. BluePill SVMI with GO (Cloaker)

Test Type	Hypervisor	VMI (Control) Mean	VMI (Control) Std Dev	SVMI-BP with GO Mean	SVMI-BP with GO Std Dev	VMI / SVMI-BP with GO *p*-value
SMPCOUNT	QEMU	20.848	6.574	1072.635	195.130	< 2.2e-16
	VMware Binary Translation	24.292	7.800	759.617	1022.582	< 2.2e-16
	VMware HAV	33.217	19.271	*	*	*
	VirtualBox HAV	26.472	9.861	*	*	*
TIMING	QEMU	214.700	21.425	17791.310	670.628	< 2.2e-16
	VMware Binary Translation	216.085	17.919	3247.645	563.020	< 2.2e-16
	VMware HAV	218.505	27.032	*	*	*
	VirtualBox HAV	216.170	15.702	*	*	*
TLBHIT	QEMU	54.100	2.736	69.580	3.723	< 2.2e-16
	VMware Binary Translation	54.250	2.044	71.895	3.353	< 2.2e-16
	VMware HAV	54.250	15.794	*	*	*
	VirtualBox HAV	54.250	2.331	*	*	*

*Denotes data from scenarios that were not completed due to incompatability constraints

Table 7. Analysis of VMI vs. ESXi SVMI with GO (Cloaker)

Test Type	Hypervisor	VMI (Control) Mean	VMI (Control) Std Dev	SVMI-ESX with GO Mean	SVMI-ESX with GO Std Dev	VMI / SVMI-ESX with GO *p*-value
SMPCOUNT	QEMU	20.848	6.574	*	*	*
	VMware Binary Translation	24.292	7.800	1341.876	1409.071	< 2.2e-16
	VMware HAV	33.217	19.271	949.288	281.142	< 2.2e-16
	VirtualBox HAV	26.472	9.861	1096.160	2057.879	< 2.2e-16
TIMING	QEMU	214.700	21.425	*	*	*
	VMware Binary Translation	216.085	17.919	14949.620	55053.600	< 2.2e-16
	VMware HAV	218.505	27.032	6446.365	2510.947	< 2.2e-16
	VirtualBox HAV	216.170	15.702	18525.520	178528.800	< 2.2e-16
TLBHIT	QEMU	54.100	2.736	*	*	*
	VMware Binary Translation	54.250	2.044	201.655	112.806	< 2.2e-16
	VMware HAV	54.250	15.794	160.570	102.871	< 2.2e-16
	VirtualBox HAV	54.250	2.331	192.405	73.669	< 2.2e-16

*Denotes data from scenarios that were not completed due to incompatability constraints

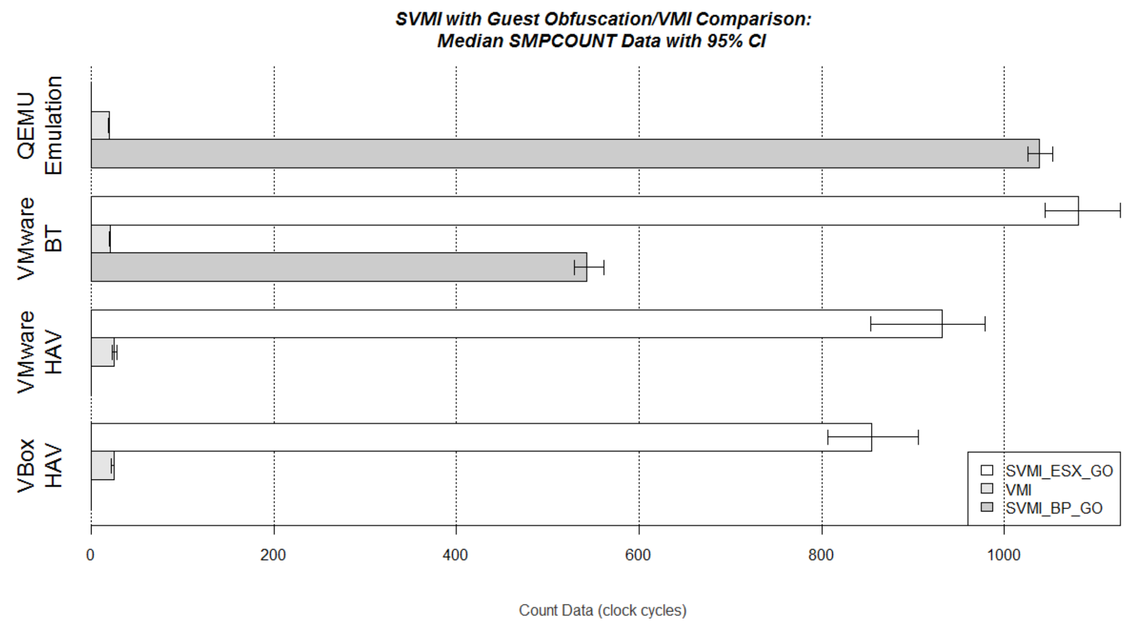


Figure 34. Comparison of SMPCOUNT VMI vs. SVMI with GO Medians with 95% CI

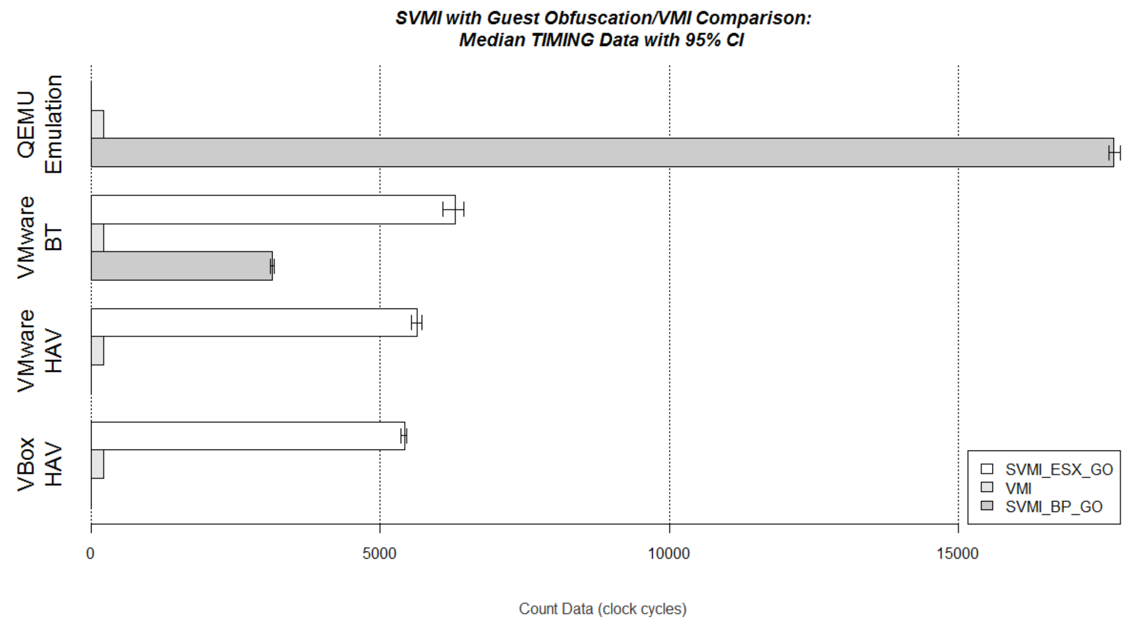


Figure 35. Comparison of TIMING VMI vs. SVMI with GO Medians with 95% CI

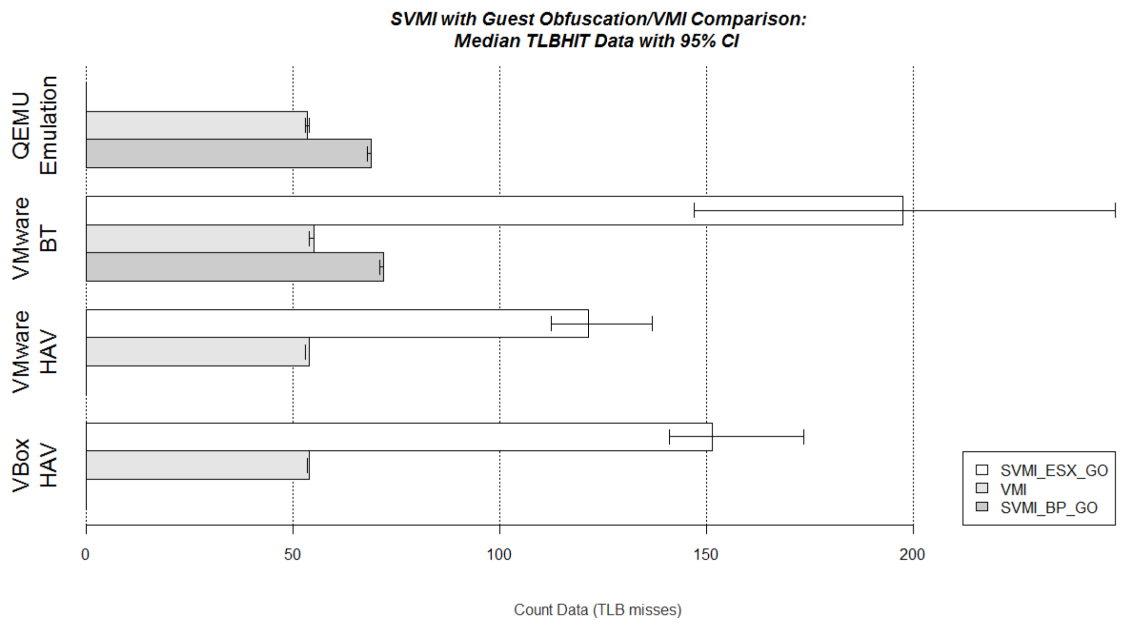


Figure 36. Comparison of TIMING VMI vs. SVMI with GO Medians with 95% CI

Next, the SVMI with guest obfuscation scenarios are evaluated against the SVMI scenarios to determine the effect of guest obfuscation on the SVMI data (Tables 8-9).

Table 8: Analysis of BluePill SVMI vs. BluePill SVMI with GO (Cloaker)

Test Type	Hypervisor	SVMI-BP Mean	SVMI-BP Std Dev	SVMI-BP with GO Mean	SVMI-BP with GO Std Dev	VMI / SVMI-BP with GO *p*-value
SMPCOUNT	QEMU	1346.205	109.456	1072.635	195.130	< 2.2e-16
	VMware Binary Translation	519.667	134.222	759.617	1022.582	4.36E-08
	VMware HAV	494.249	82.991	*	*	*
	VirtualBox HAV	531.819	171.655	*	*	*
TIMING	QEMU	19688.720	2473.851	17791.310	670.628	1.35E-10
	VMware Binary Translation	7020.840	9133.327	3247.645	563.020	< 2.2e-16
	VMware HAV	13376.430	60077.060	*	*	*
	VirtualBox HAV	6351.200	1335.813	*	*	*
TLBHIT	QEMU	70.030	2.950	69.580	3.723	6.37E-02
	VMware Binary Translation	72.410	1.957	71.895	3.353	7.42E-01
	VMware HAV	70.145	2.824	*	*	*
	VirtualBox HAV	70.935	2.635	*	*	*

*Denotes data from scenarios that were not completed due to incompatability constraints

Table 9. Analysis of ESXi SVMI vs. ESXi SVMI with GO (Cloaker)

Test Type	Hypervisor	SVMI-ESX Mean	SVMI-ESX Std Dev	SVMI-ESX with GO Mean	SVMI-ESX with GO Std Dev	VMI / SVMI-ESX with GO *p*-value
SMPCOUNT	QEMU	1055.280	945.303	*	*	*
	VMware Binary Translation	984.021	371.568	1341.876	1409.071	5.16E-04
	VMware HAV	1509.973	1864.571	949.288	281.142	2.61E-13
	VirtualBox HAV	1244.418	244.978	1096.160	2057.879	< 2.2e-16
TIMING	QEMU	9144.830	11885.690	*	*	*
	VMware Binary Translation	10183.840	19950.620	14949.620	55053.600	2.19E-09
	VMware HAV	11795.740	21475.500	6446.365	2510.947	< 2.2e-16
	VirtualBox HAV	6989.935	7580.405	18525.520	178528.800	1.82E-02
TLBHIT	QEMU	166.095	56.928	*	*	*
	VMware Binary Translation	220.605	78.598	201.655	112.806	5.05E-04
	VMware HAV	123.345	101.454	160.570	102.871	< 2.2e-16
	VirtualBox HAV	139.335	68.457	192.405	73.669	1.56E-13

*Denotes data from scenarios that were not completed due to incompatability constraints

For all scenarios, with the exception of QEMU_SVMI_BP_TLBHIT and VMWAREBT_SVMI_BP_TLBHIT, there is a statistically significant difference between the SVMI and SVMI with guest obfuscation data (*p*-value < 0.05). The relative differences between the medians of the data are shown using bar charts for all detection techniques with BluePill and ESXi (Figures 37-42). Of particular interest is that, in instances where a comparison is made between BluePill SVMI and BluePill SVMI with guest obfuscation, the medians of five out of six samples decrease in the presence of guest obfuscation (Figures 37-39). This is particularly interesting since three of the five decreasing BluePill comparisons also have *p*-values < 0.05, indicating that the decrease is statistically significant. ESXi provides similar results with six of nine comparisons of VMI to SVMI with guest obfuscation exhibiting a significant decrease (*p*-value < 0.05) in encountered overhead (Figures 40-42). This indicates that the presence of guest obfuscation execution (Cloaker) significantly decreases the overhead encountered by the detection tool running within the trusted OS when compared to non-obfuscated data in some cases. While this decrease is statistically significant, in none of the cases does it reduce the overhead such that it is not distinguishable from pure VMI.

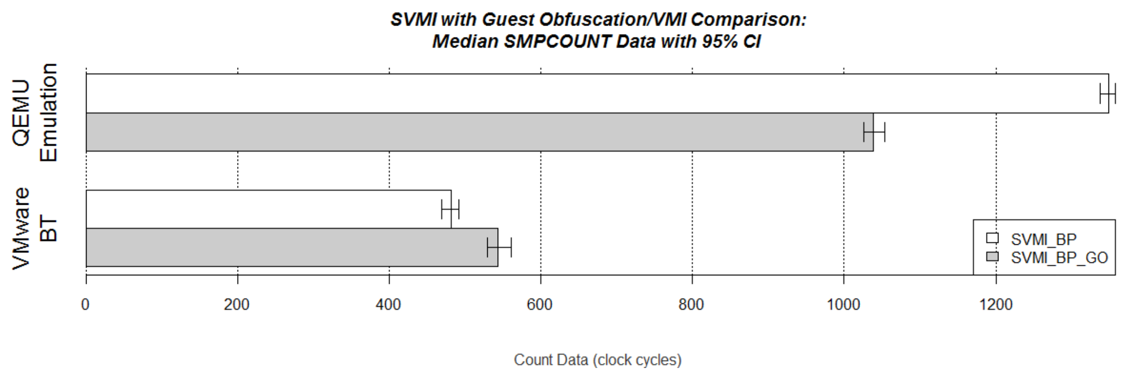


Figure 37. Comparison of BluePill Median SVMI to SVMI with GO SMPCOUNT Data

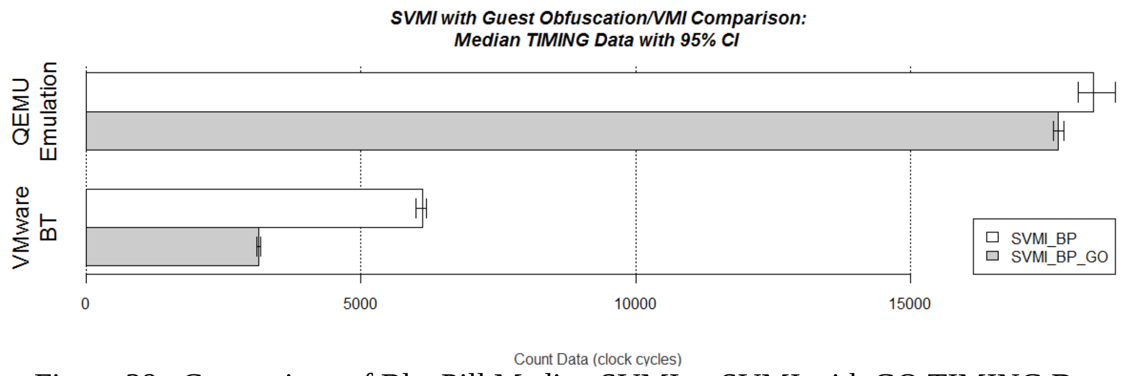


Figure 38. Comparison of BluePill Median SVMI to SVMI with GO TIMING Data

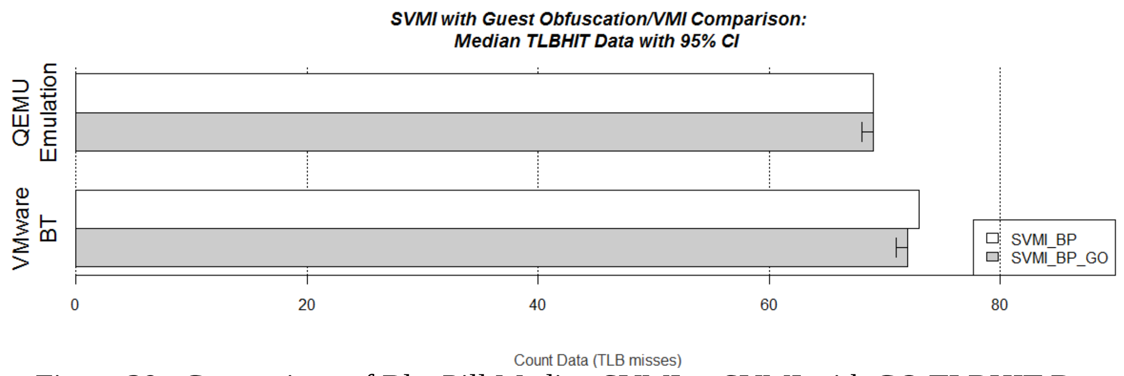


Figure 39. Comparison of BluePill Median SVMI to SVMI with GO TLBHIT Data

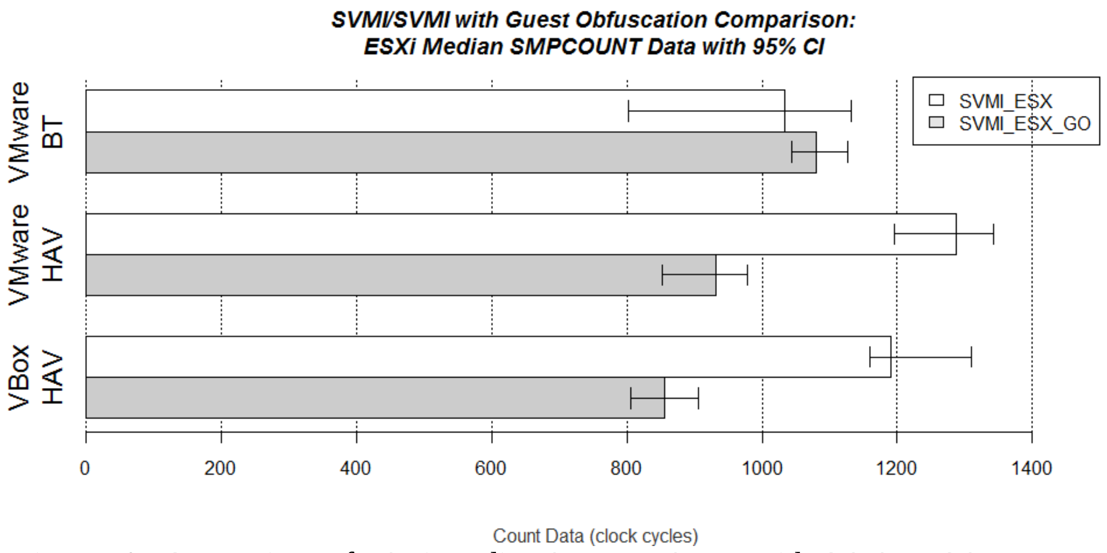


Figure 40. Comparison of ESXi Median SVMI to SVMI with GO SMPCOUNT Data

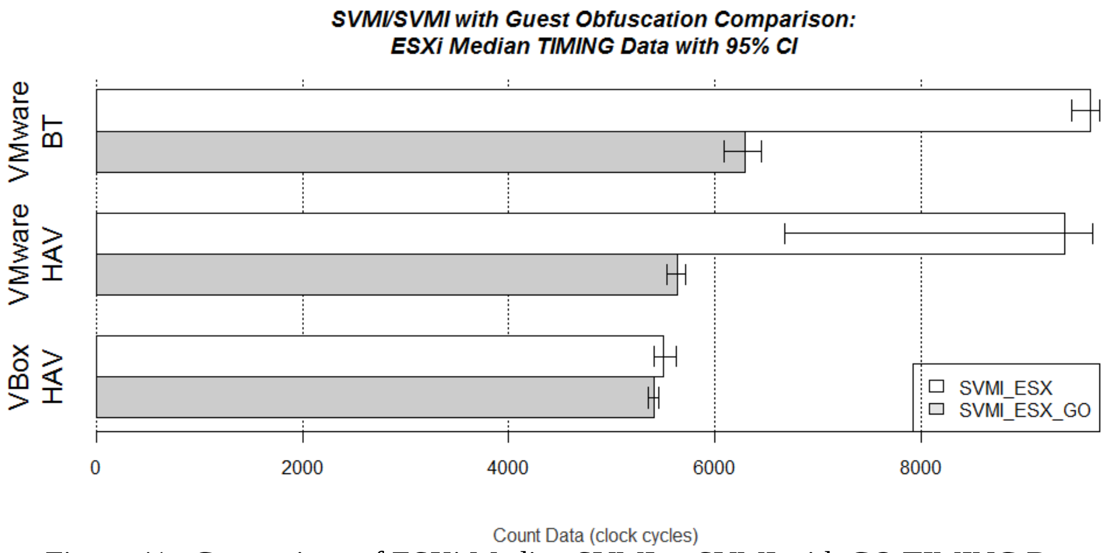


Figure 41. Comparison of ESXi Median SVMI to SVMI with GO TIMING Data

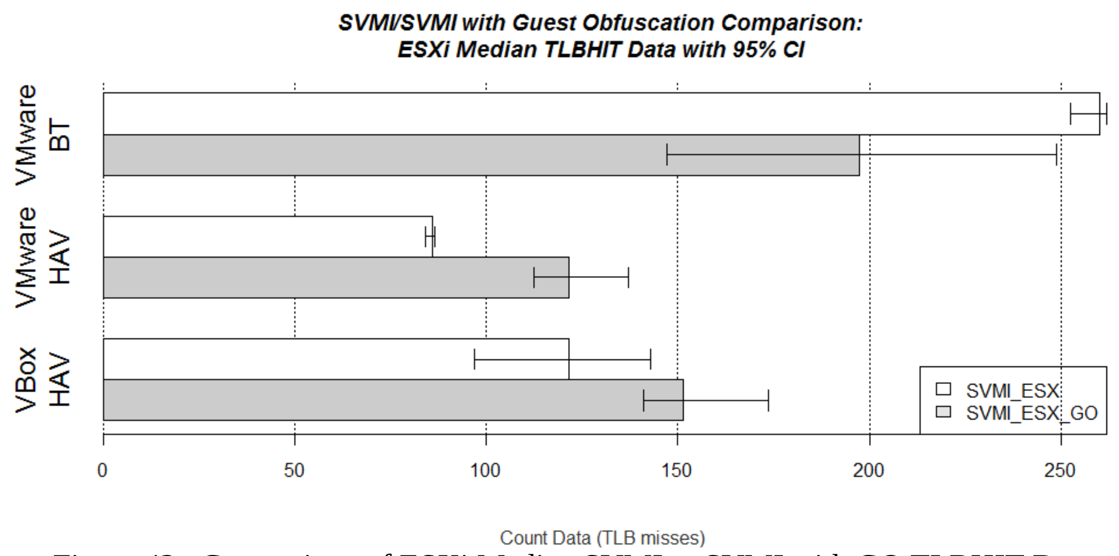


Figure 42. Comparison of ESXi Median SVMI to SVMI with GO TLBHIT Data

4.4. The Effect of Different Virtualization Types on HAV-R Detection

The analysis presented in Section 4.2 provides convincing evidence that each SVMI BluePill and ESXi scenario is different from its corresponding VMI scenario regardless of which virtualization type is utilized. Detection relies on the ability of the HAV-R DS to record a delay or change within the system. Therefore, the effects of different virtualization types are directly related to the detectable differences captured by the detection techniques. Inspection of the differences between medians (taken by subtracting the VMI medians from their corresponding SVMI medians) reveals no consistent relationship between overhead caused by a HAV-R relative to a particular hypervisor or virtualization type (Figures 43-45). It is noted that BluePill with emulation (QEMU) is particularly vulnerable to detection by the SMP Counting and SVMI Check Timing detection techniques and that ESXi with binary translation (VMware Workstation 8) is particularly vulnerable to detection by TLB Profiling relative to the other testing techniques. Overall, HAV-Rs are statistically detectable for all virtualization types using each of the selected HAV-R detection techniques.

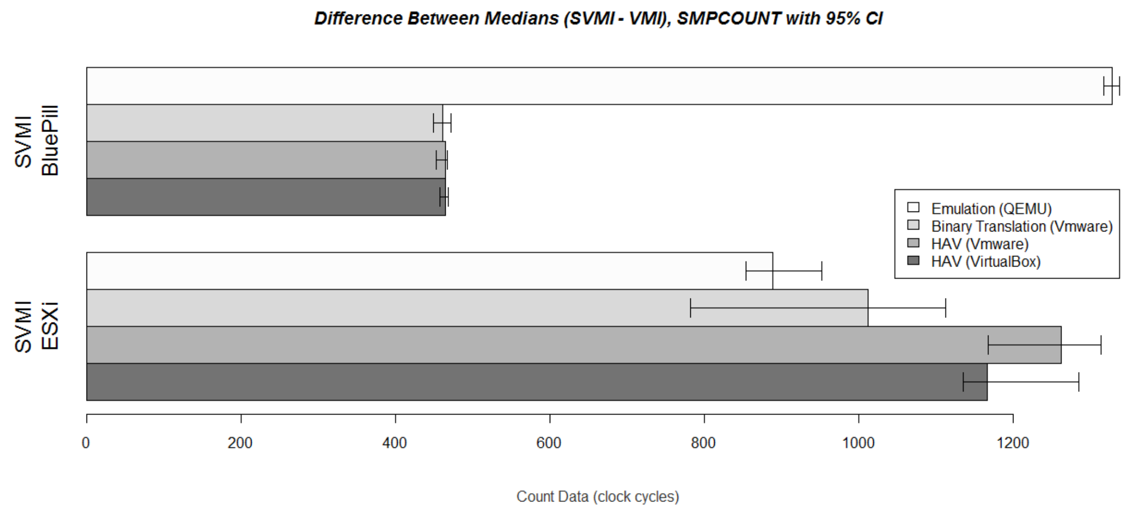


Figure 43. Difference Between Medians (SVMI-VMI), SMPCOUNT with 95% CI

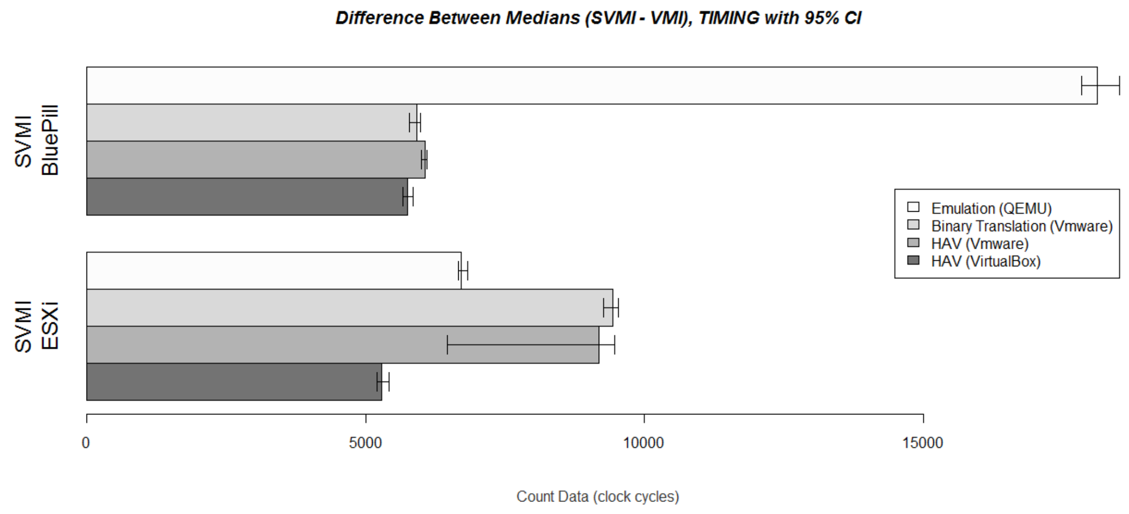


Figure 44. Difference Between Medians (SVMI-VMI), TIMING with 95% CI

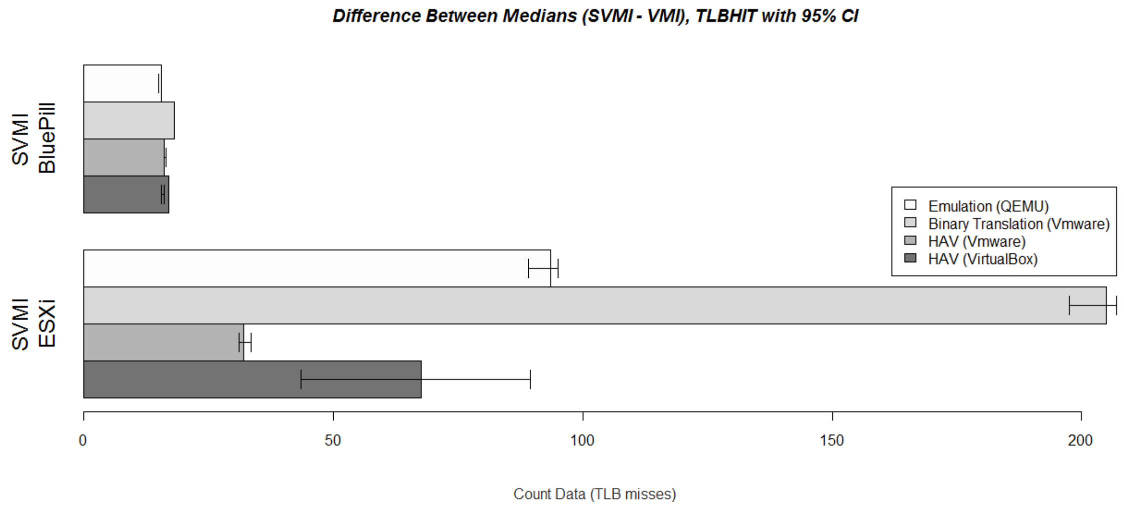


Figure 45. Difference Between Medians (SVMI-VMI), TLBHIT with 95% CI

4.5. Summary

A total of fifty-one unique experiments are performed consisting of two hundred replications each. The resulting data contains several zero count values which are considered invalid and removed; all other data including outliers are retained. The data is determined to be non-parametric therefore the Wilcoxon rank sum test is selected as an appropriate statistical analysis tool for comparison of two samples.

First, the pure VMI scenarios are compared to the SVMI scenarios, and it is determined that there is convincing evidence that the SVMI scenarios are statistically higher than the non-subverted VMI scenarios for all detection techniques.

Second, the pure VMI scenarios are compared to the SVMI with GO scenarios, and it is again determined that there is convincing evidence that the SVMI scenarios are statistically higher than the non-subverted VMI scenarios for all detection techniques.

Third, the SVMI GO scenarios are tested against their corresponding SVMI scenarios, and it is determined that, with the exception of two scenarios, each are statistically significantly different. It is noted that for many of the scenarios, the impact of SVMI with guest obfuscation is a statistically significant decrease in encountered overhead. This indicates that the presence of in-guest obfuscation significantly decreases the overhead encountered by the detection tool running within the trusted OS when compared to non-obfuscated data in some cases. In no cases does this obfuscate the existence of HAV-R.

Fourth, the effect of different virtualization types on HAV-R detection is evaluated, and it is observed that no virtualization type significantly impacted the ability of the detection techniques to determine the existence of HAV-Rs.

Finally, it is noted that BluePill within a nested virtualized environment using emulation is particularly susceptible to detection by the SMP Counting and SVME Check Timing detection techniques, and that ESXi within a nested virtualized environment using binary translation is particularly susceptible to detection by TLB Profiling.

V. Conclusions

This chapter provides a summary of key findings and recommendations for future work. Section 5.1 contains an executive summary of the results, Section 5.2 gives recommendations for future research, and Section 5.3 provides concluding remarks.

5.1. Results

This research examines the detection of hardware-assisted hypervisor rootkits (HAV-R) within nested virtual environments. It specifically examines the effectiveness of the three detection techniques of SMP Counting, SVME Check Timing, and TLB Profiling against detection of two notional HAV-Rs within environments using three types of virtualization: emulation, binary translation full virtualization, and hardware-assisted full virtualization. The nested virtual environments use 64-bit Windows Vista Business as the native OS and 64-bit Windows 7 Professional as the guest OS. The hypervisors are QEMU, VMware, and VirtualBox.

It was originally hypothesized that the overhead caused by a pre-existing, trusted hypervisor is sufficient to obfuscate the existence of a HAV-R and that, in cases where the HAV-R is detectable, deliberate execution of privileged instructions within the guest OS is sufficient to obscure the HAV-R. The research goals specifically addressed by this research and their corresponding findings are as follows:

1. **Is it possible to detect HAV-R within a nested virtualized environment using selected detection techniques?** Yes, for all nested virtualized environments examined, a difference in overhead is experienced during

execution of the HAV-Rs which is statistically significant and greater than the overhead experienced within the non-subverted virtualized environments.

2. **Do different virtualization types significantly affect HAV-R detection using the selected detection techniques?** No, of the three virtualization types evaluated (emulation, full virtualization using binary translation, and full virtualization using HAV) no significant difference in detectability is observed. In all cases, the difference in overhead experienced during execution of the HAV-R is statistically significant and provided convincing evidence of the presence of a HAV-R. It is observed that within nested virtualized environments using emulation, the HAV-R BluePill seems particularly susceptible to detection by the SMP Counting and SVME Check Timing detection techniques. Furthermore, within a nested virtualized environment using binary translation full virtualization, the HAV-R ESXi seems particularly susceptible to detection by TLB Profiling. These are relative increases in detectability defined as the difference in overhead before and after execution of the HAV-R and do not change the fact that the HAV-Rs are detected in all cases.

3. **What is the effectiveness of in-guest execution designed to obfuscate the existence of a HAV-R?** The chosen obfuscation technique, a variant of the detection tool which is intended to compete for processor resources, fails to successfully obfuscate the overhead caused by the HAV-R in all cases. In

nine of fifteen cases the overhead experienced during execution of a HAV-R is statistically lowered during obfuscation execution. At no time is this significant enough to obfuscate the HAV-R for the cases examined however, these results indicate that obfuscation efforts within the guest can have a dampening effect on the overall overhead experienced when a HAV-R is present.

The findings disprove the original hypothesis that overhead caused by a pre-existing, trusted hypervisor is sufficient to obfuscate the existence of a HAV-R and that, in cases where the HAV-R is detectable, deliberate execution of privileged instructions within the guest OS is sufficient to obscure the HAV-R. To the contrary, the results indicate that in cases when emulation, full virtualization using binary translation, or full virtualization using HAV are used as the hypervisor, the presence of BluePill and ESXi are statistically detectable and that in-guest obfuscation does not successfully obfuscate the existence of the HAV-R.

5.2. Future Work

The following items remain unresolved and are suggested for future work:

- Explore the effect of guest obfuscation to determine why, in some scenarios, it causes a statistically significant reduction in overhead encountered by the detection tool. Determine if there are situations where this significant reduction in overhead could result in successful HAV-R obfuscation.

- Evaluate the HAV-R detection system against HAV-R detection within nested virtualized environments using a paravirtualization hypervisor, such as Xen. This was not accomplished during this research due to incompatibility between BluePill, which is designed for Windows systems, and open-source systems required for paravirtualization.
- Explore the functionality of registers which are poorly documented but included as extended functionality in HAV-enabled processors. Identify ways to exploit these registers in the form of new or modified hypervisor and HAV-R detection techniques.
- Integrate the statistical tests used for detection directly into the HyperScan application such that it provides data collection, statistical analysis, and a probable indication of the likeliness of HAV-R presence.
- Extend the HyperScan detection driver to support a Unix/Linux OS.
- Improve HyperScan such that it runs all tests at *dispatch* level. It is expected that this will remove the preponderance of zero counts thought to result from interruption of the counting process and will eliminate outliers thought to result from interruption of the timed process.
- Perform analysis on current malware samples to determine if they possess a HAV-R component.

5.3. Concluding Remarks

Hardware-assisted hypervisor rootkits are particularly interesting precisely because they are not known to be in widespread use. It is unknown if this is because they lack utility or if it is the result of a shortfall in detection mechanisms. It is also likely that less sophisticated rootkit techniques are already overwhelmingly successful for the majority of attacks and therefore sufficient for the requirements of most attackers. When the Sony copy protection rootkit scandal occurred in 2005, security analyst Bruce Schneier chastised computer security companies for failing to detect and report the infection, noting that the malware had existed for over a year and infected more than half a million computers without any detection, action, or comment from major security companies. Ominously he described a *deafening silence* from the computer security industry, not before, but after the malware was publically reported [Sch08].

Similarly, when Joanna Rutkowska introduced the BluePill hypervisor rootkit in 2006, there was incredible interest and controversy within the computer security community as to its effectiveness as a potentially undetectable malware [RuT07a]. It was soon demonstrated to be detectable and, over the past several years, academic interest in this and similar HAV-Rs has waned. Today there is a *deafening silence* regarding HAV-R research. It is unknown to what extent the HAV-R detection mechanisms mentioned in this research are already implemented by existing anti-malware software but it is clear that traditional techniques that detect rootkit malware within the OS kernel are not sufficient to detect malware at the HAV hypervisor level. Word-playing off an American colloquialism, it is said that you miss 100% of the malware that you fail to look for. It is hoped that this thesis serves as a stepping stone towards increasingly robust hypervisor rootkit prevention and detection techniques.

Appendix A. Experimentation

The following provides step-by-step instructions which explain how to set up and configure the non-subverted VMI scenarios, subverted VMI scenarios, and subverted VMI scenarios with in-guest obfuscation used for this research effort.

A-1. Setup the Non-Subverted VMI Scenario and Install the HyperScan Files

1. Install the host operating system, 64-bit Microsoft Windows Vista Business version 6.0.6000 Build 6000 (no service pack).
2. Install the Hypervisor; for demonstration, VMware Workstation 8 version 8.0.0 build 471780 is used.
3. Install the Guest OS, 64-bit Windows 7 Professional, Service Pack 1.
4. Prepare both the host and the guest for test kernel-mode drivers by enabling test signing, disabling integrity checks, and installing WinDK as explained in Appendix B. Complete this step for both the host and guest OS. Reboot both OSs prior to proceeding to step 5.
5. Copy the “HyperScan” and “BluePill” folders to the C:\ location of the host machine and “tools” folder to the host machine’s desktop.
6. Copy the “Cloaker” folder to the C:\ location of the guest machine, and copy the “Tools” folder to the guest machine’s desktop (See Figure 46).

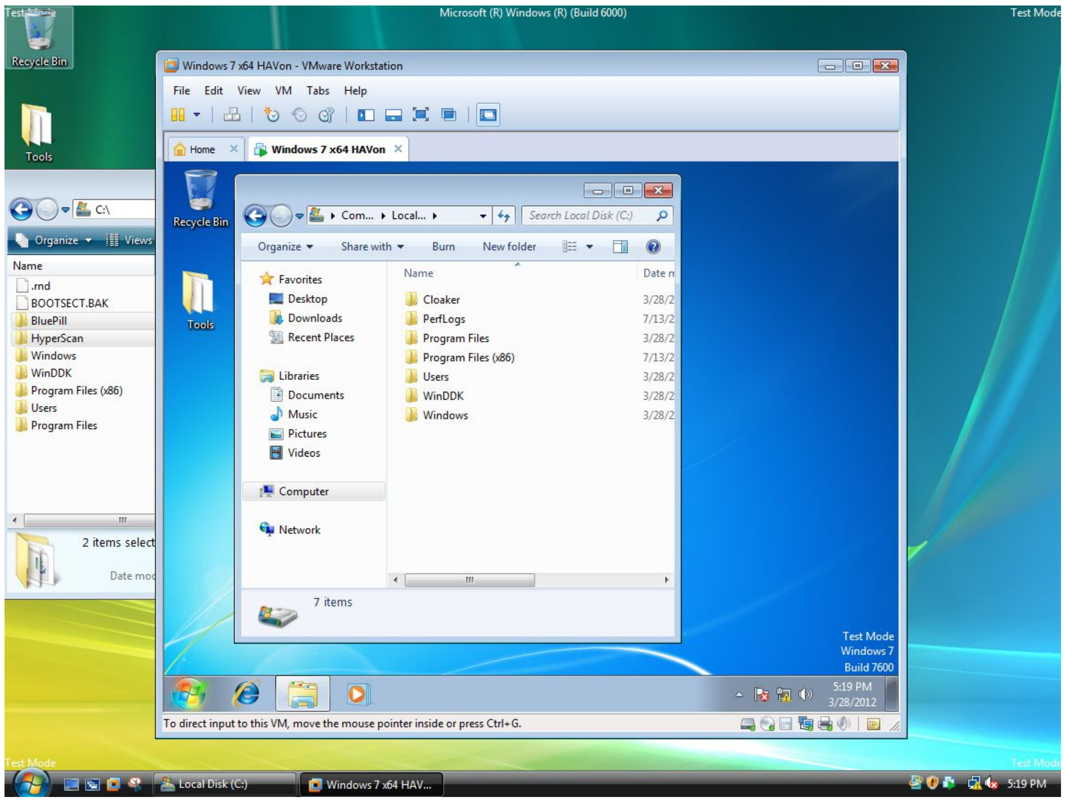
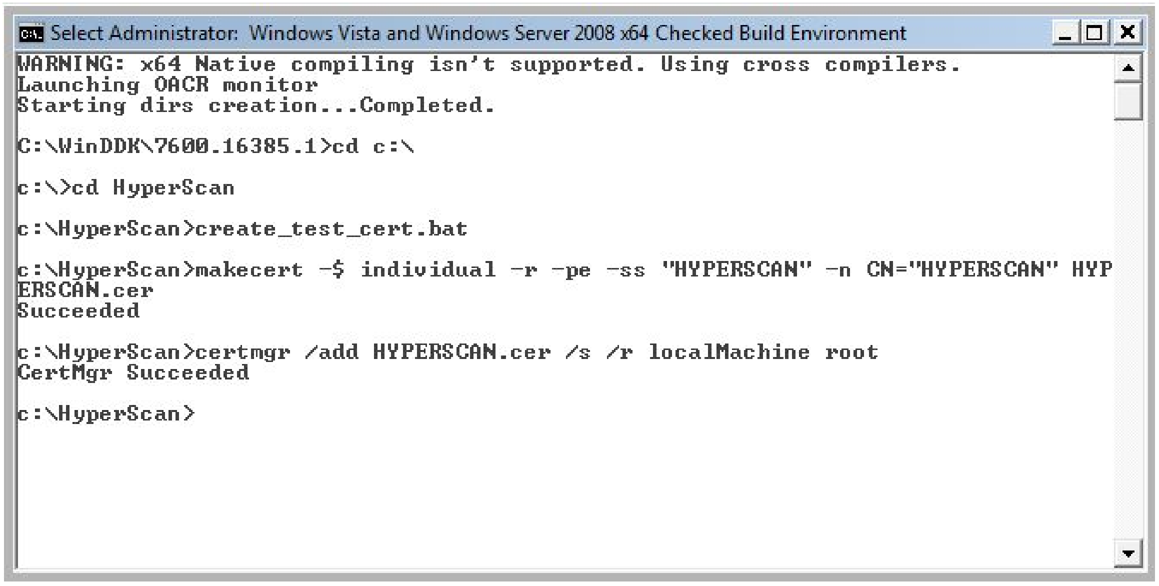


Figure 46. Configuring the Host and Guest Machine: File Placement

A-2. Create Test Certificates and Sign Drivers within the Host and Guest OS

1. On the host machine, open an elevated WinDK command window. Click Start > All Programs > Windows Driver Kits > WDK[build number] > Build Environments > Windows Vista and Windows Server 2008 and right click x64 Checked Build Environment and select Run as Administrator. Windows will ask for your permission, click continue.

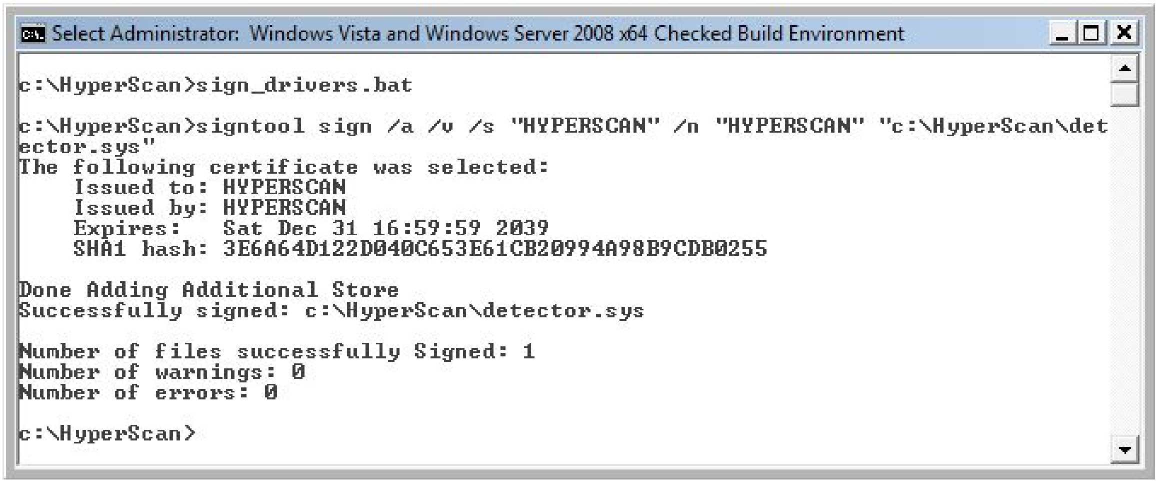
2. Create the test certificate by navigating to the HyperScan folder and execute create_test_cert.bat (Figure 47).


Select Administrator: Windows Vista and Windows Server 2008 x64 Checked Build Environment

```
WARNING: x64 Native compiling isn't supported. Using cross compilers.
Launching OACR monitor
Starting dirs creation...Completed.

C:\WinDDK\7600.16385.1>cd c:\

c:\>cd HyperScan

c:\HyperScan>create_test_cert.bat

c:\HyperScan>makecert -$ individual -r -pe -ss "HYPERSCAN" -n CN="HYPERSCAN" HYP
ERSCAN.cer
Succeeded

c:\HyperScan>certmgr /add HYPERSCAN.cer /s /r localMachine root
CertMgr Succeeded

c:\HyperScan>
```

Figure 47. Execution of `create_test_cert.bat`

3. Sign the driver with the test certificate by executing sign_drivers.bat within the elevated WinDK command window (Figure 48).


Select Administrator: Windows Vista and Windows Server 2008 x64 Checked Build Environment

```
c:\HyperScan>sign_drivers.bat

c:\HyperScan>signtool sign /a /v /s "HYPERSCAN" /n "HYPERSCAN" "c:\HyperScan\det
ector.sys"
The following certificate was selected:
    Issued to: HYPERSCAN
    Issued by: HYPERSCAN
    Expires:   Sat Dec 31 16:59:59 2039
    SHA1 hash: 3E6A64D122D040C653E61CB20994A98B9CDB0255

Done Adding Additional Store
Successfully signed: c:\HyperScan\detector.sys

Number of files successfully Signed: 1
Number of warnings: 0
Number of errors: 0

c:\HyperScan>
```

Figure 48. Execution of `sign_drivers.bat`

4. Repeat steps 2-3 within the Bluepill folder on the host machine.

5. Repeat steps 1-3 within the Cloaker folder on the guest machine which was copied to the C:\ drive. Be sure to use the Windows 7 x64 Checked Build Environment, not the Vista one used in steps 1 and 2.

A-3. Non-Subverted VMI Scenario Experiments

Before proceeding with this step, you must have the host OS, hypervisor, and guest OS installed and configured as directed in steps A-1 to A-2.

1. <OPTIONAL> Run DebugView if you want to see debug statements during driver execution. This is not necessary for experimentation but is helpful for troubleshooting. To do this, within the Tools folder, locate Dbgview.exe, right click on it and select "Run as Administrator". Ensure that you are capturing kernel messages by selecting the capture menu and clicking next to "Capture Kernel" and "Enable Verbose Kernel Output".
2. Start the Guest OS and minimize it so that it is still running, but will not encounter interference from mouse movements or other possible inadvertent interaction.
3. Within the Tools folder, locate INSTDRV.exe, right click on it and select "Run as Administrator". Enter the full path and name of the detector.sys driver and click "Install" than "Start" (Figure 49).

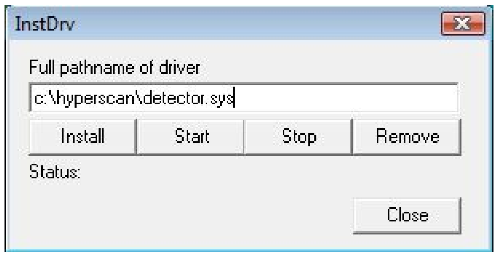
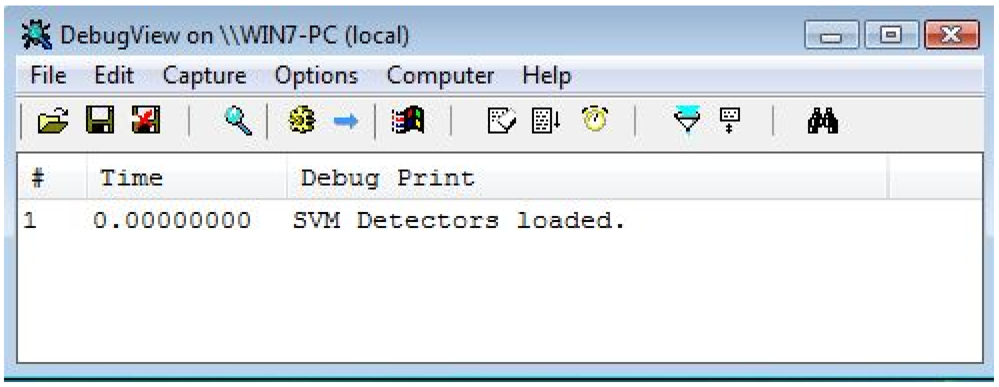

InstDrv
Full pathname of driver
c:\hyperscan\detector.sys
Status:

Figure 49. Using InstDrv to Install `detector.sys`

If you are using debug view, you will see the below message displayed when the driver successfully loads (Figure 50).



```
#   Time         Debug Print
1   0.00000000   SVM Detectors loaded.
```

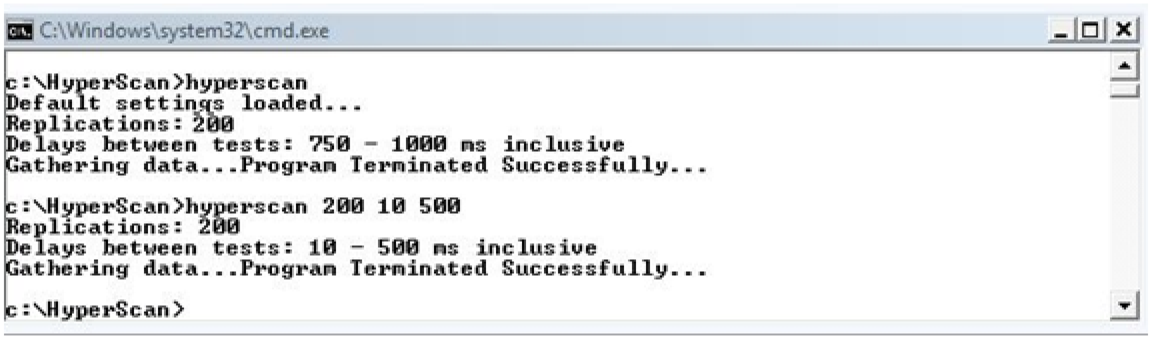
Figure 50. SVM Detectors Loaded Message

If the driver does not install successfully, verify that you copied and signed the driver correctly in earlier steps.

4. From a command window, navigate to the HyperScan folder and prepare to execute `hyperscan.exe`. hyperscan.exe takes three possible arguments:

   - Number of Replications
   - Delay Lower-bound (in milliseconds)
   - Delay Upper-bound (in milliseconds)

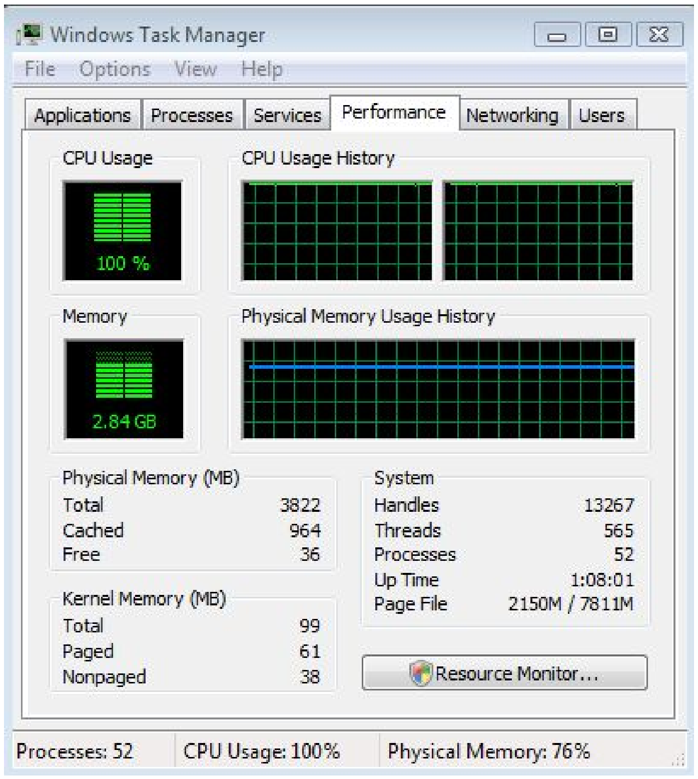
   If no arguments are provided, it will default to 200 replications of each detection technique with a random delay between experiments of 750 to 1000 milliseconds (0.75 to 1 second). Figure 51 shows examples of both default and user-specified execution. For this research, all experiments are performed using the default settings.



```
c:\HyperScan>hyperscan
Default settings loaded...
Replications: 200
Delays between tests: 750 - 1000 ms inclusive
Gathering data...Program Terminated Successfully...

c:\HyperScan>hyperscan 200 10 500
Replications: 200
Delays between tests: 10 - 500 ms inclusive
Gathering data...Program Terminated Successfully...

c:\HyperScan>
```

Figure 51. HyperScan Example

5. Wait 10 minutes for the system to reach a steady state then execute hyperscan.exe. Preliminary testing showed that a wait of approximately 10 minutes was sufficient for CPU use within the Guest and OS to reach a steady state for all hypervisors. During testing, resource usage can be observed using the Performance tab within Windows Task Manger (Figure 52).



Physical Memory (MB)	
Total	3822
Cached	964
Free	36

Kernel Memory (MB)	
Total	99
Paged	61
Nonpaged	38

System	
Handles	13267
Threads	565
Processes	52
Up Time	1:08:01
Page File	2150M / 7811M

Processes: 52 CPU Usage: 100% Physical Memory: 76%

Figure 52. Performance Manger

Note that detector.sys uses asynchronous timers which are a potential source of race conditions and may freeze the system. In practice this is rare however, if the computer freezes during testing, a full reboot is required [RuC05].

6. HyperScan outputs four CSV files into the directory where the HyperScan was executed. Each contains the values captured during experimentation using a particular technique and must be archived for further analysis. All experiment results are archived in a folder labeled using the following naming convention: HY[qu/vm/vb/xe]_ HAV[bp/es/no]_GO[on/off]

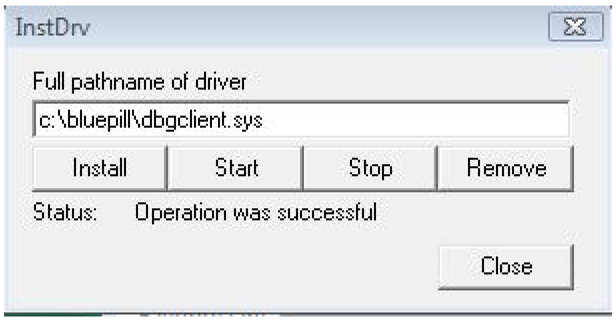
   - HY represents the Hypervisor
     - qu: QEMU
     - vm: VMware
     - vb: VirtualBox
   - HAV represents the type of HAV-R
     - bp: BluePill
     - es: ESXi
     - no: None
   - GO represents Guest Obfuscation; on or off

   Also include in each folder a readme.txt containing a short description of the configuration and any anomalies encountered and a screenshot of the particular hypervisor implementation settings used if applicable.

A-4. Subverted VMI Scenario Experiments

Before proceeding with this step, you must have completed A-4 and saved the experimentation data in an appropriately named folder and location.

1. Install the BluePill driver on the host machine by opening InstDrv, entering the full patch the dbgclient.sys and clicking "Install" and then "Start" (Figure 53).



InstDrv

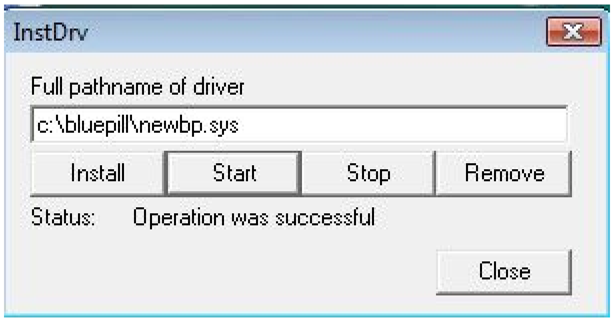
Full pathname of driver

c:\bluepill\dbgclient.sys

Status: Operation was successful

Figure 53. Using InstDrv to Install `dbgclient.sys`

2. Repeat step 1 but use the full path for the BluePill driver, newbp.sys (Figure 54).



InstDrv

Full pathname of driver

c:\bluepill\newbp.sys

Status: Operation was successful

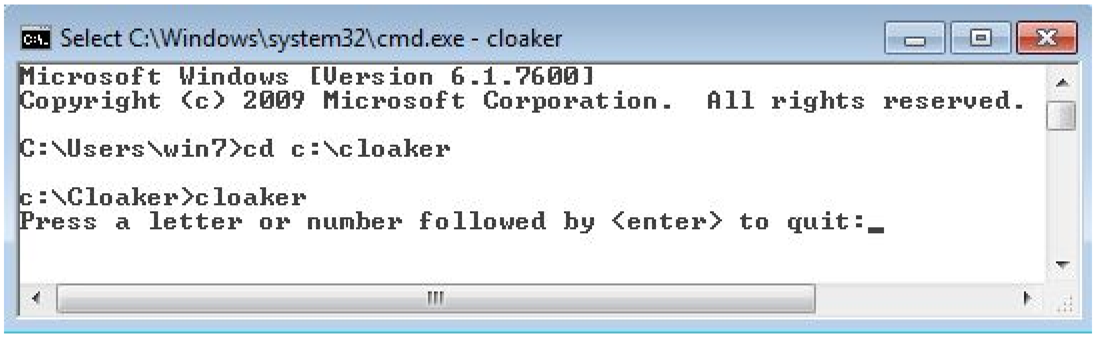
Figure 54. Using InstDrv to Install `newbp.sys`

3. BluePill is now installed. Repeat steps A-3, 1-6 to perform the Subverted VMI Scenario Experiments. Be sure to save the experimentation data in an appropriately named folder and location.

A-5. Subverted VMI Scenario with Guest Obfuscation Experiments

Before proceeding with this step, you must have completed steps A-1 to A-4 which setup the host and guest Oss, created test certificates, signed the drivers, and started BluePill.

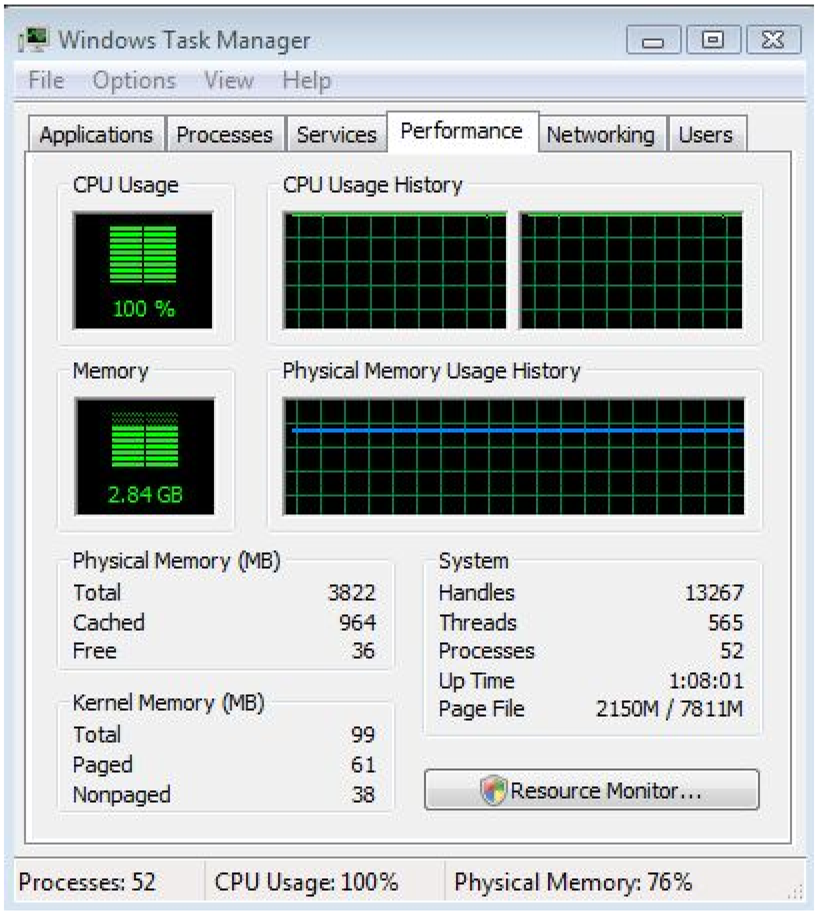
1. Install the Cloaker driver on the guest machine by opening InstDrv, entering the full path to cloakdriver.sys and clicking “Install” and then “Start”.
2. Open a command window and navigate to the Cloaker folder which was placed on the C:\ drive.
3. Start Cloaker by typing “Cloaker” and pressing enter. Cloaker will continue to execute until you enter a letter or number and press the “Enter” key (Figure 55).



```
Microsoft Windows [Version 6.1.7600]
Copyright (c) 2009 Microsoft Corporation.  All rights reserved.

C:\Users\win7>cd c:\cloaker

c:\Cloaker>cloaker
Press a letter or number followed by <enter> to quit:_
```

Figure 55. Cloaker Execution

4. Note that Cloaker takes an extreme approach to obfuscation which will make maximum use of guest OS resources and may cause the guest OS to appear to freeze. You can check that guest obfuscation is still occurring by using the Windows Task Manager on the Host OS and observing the level of CPU usage (Figure 56).



Physical Memory (MB)

Total	3822
Cached	964
Free	36

Kernel Memory (MB)

Total	99
Paged	61
Nonpaged	38

System

Handles	13267
Threads	565
Processes	52
Up Time	1:08:01
Page File	2150M / 7811M

Processes: 52 CPU Usage: 100% Physical Memory: 76%

Figure 56. Performance Manager

5. Repeat steps A-3, 1-6 to perform the Subverted VMI Scenario with Guest Obfuscation Experiments. Be sure to save the experimentation data in an appropriately named folder and location.
6. Perform statistical analysis on the resulting data.

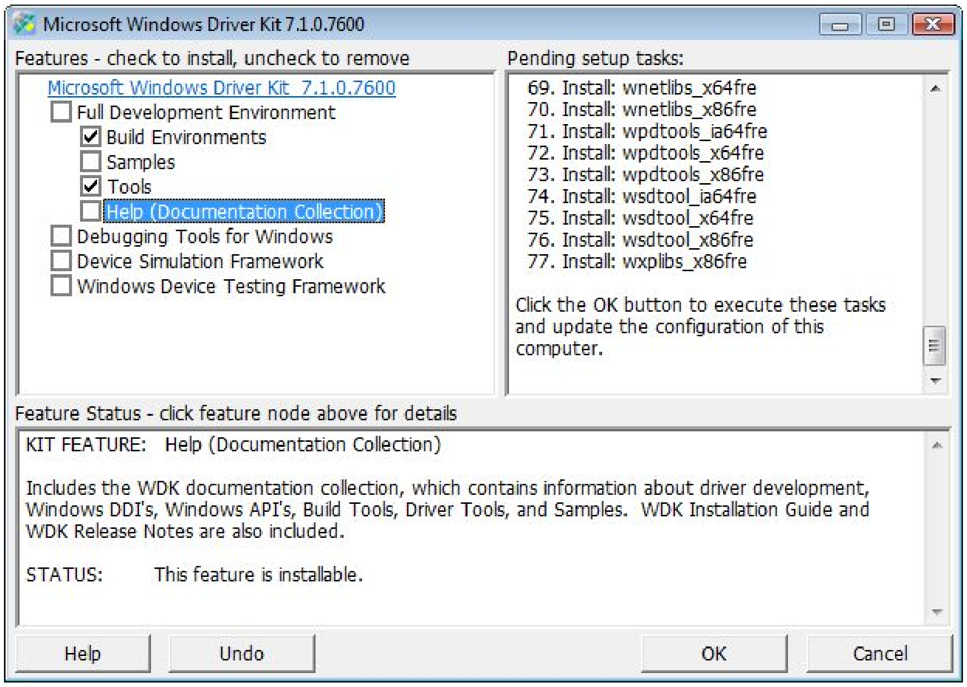
Appendix B. Windows Driver Kit Installation & Configuration

Windows Driver Kit (WinDK) is used to compile windows drivers. To install unsigned drivers on systems that use require driver signing, you must also enable test-signing and disable integrity checks. Both are covered in this appendix.

B-1. Install Windows Driver Kit (WDK)

Windows Driver Kit is similar to the compilers used for Java or C++, only this one is designed specifically for Windows Device Drivers. It is used to build and test sign the BluePill driver.

1. Download the WinDK iso from http://www.microsoft.com/download/en/details.aspx?displaylang=en&id=11800
2. Burn the .iso to a CD or DVD.
3. Install WinDK from the CD/DVD using the settings shown in Figure 57.


Microsoft Windows Driver Kit 7.1.0.7600
Features - check to install, uncheck to remove
Pending setup tasks:
Feature Status - click feature node above for details
Help
Undo
OK
Cancel

Microsoft Windows Driver Kit 7.1.0.7600
- [ ] Full Development Environment
  - [✓] Build Environments
  - [ ] Samples
  - [✓] Tools
  - [ ] Help (Documentation Collection)
- [ ] Debugging Tools for Windows
- [ ] Device Simulation Framework
- [ ] Windows Device Testing Framework

```
69. Install: wnetlibs_x64fre
70. Install: wnetlibs_x86fre
71. Install: wpdtools_ia64fre
72. Install: wpdtools_x64fre
73. Install: wpdtools_x86fre
74. Install: wsdtool_ia64fre
75. Install: wsdtool_x64fre
76. Install: wsdtool_x86fre
77. Install: wxplibs_x86fre

Click the OK button to execute these tasks
and update the configuration of this
computer.
```

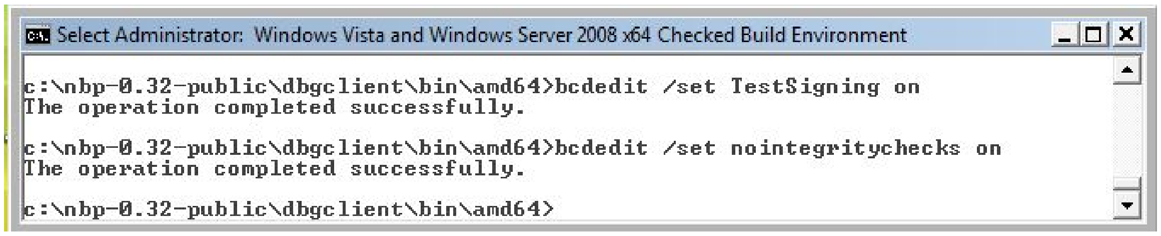
```
KIT FEATURE:   Help (Documentation Collection)

Includes the WDK documentation collection, which contains information about driver development,
Windows DDI's, Windows API's, Build Tools, Driver Tools, and Samples.  WDK Installation Guide and
WDK Release Notes are also included.

STATUS:        This feature is installable.
```

Figure 57. WinDK Installation Settings

B-2. Enable Test-signing and Disable Integrity Checks

1. Click Start > All Programs > Accessories and right click on Command Prompt and select "Run as Administrator" followed by "Continue". Enter the following two commands (Figure 58):

```
bcdedit /set TestSigning on

bcdedit /set nointegritychecks on
```


Select Administrator: Windows Vista and Windows Server 2008 x64 Checked Build Environment

```
c:\nbp-0.32-public\dbgclient\bin\amd64>bcdedit /set TestSigning on
The operation completed successfully.

c:\nbp-0.32-public\dbgclient\bin\amd64>bcdedit /set nointegritychecks on
The operation completed successfully.

c:\nbp-0.32-public\dbgclient\bin\amd64>
```

Figure 58. Enabling Test-Signing and Disabling Integrity Checks

2. Reboot the computer to complete the configuration.

Appendix C. VMware Workstation 8 and Windows 7 Setup

The following provides step-by-step instructions on how to configure VMware Workstation 8 for Windows 7 installation.

C-1. Download and Install VMware Workstation 8

1. Download VMware Workstation 8 from the following website: http://downloads.vmware.com/d/info/desktop_end_user_computing/vmware_workstation/8_0. This site also provides instructions regarding obtaining a license key.
2. Execute the downloaded file and install by following the onscreen instructions.

C-2. Create and Configure the Windows 7 Installation

1. Open VMware Workstation 8, select "Create a New Virtual Machine" (Figure 59).

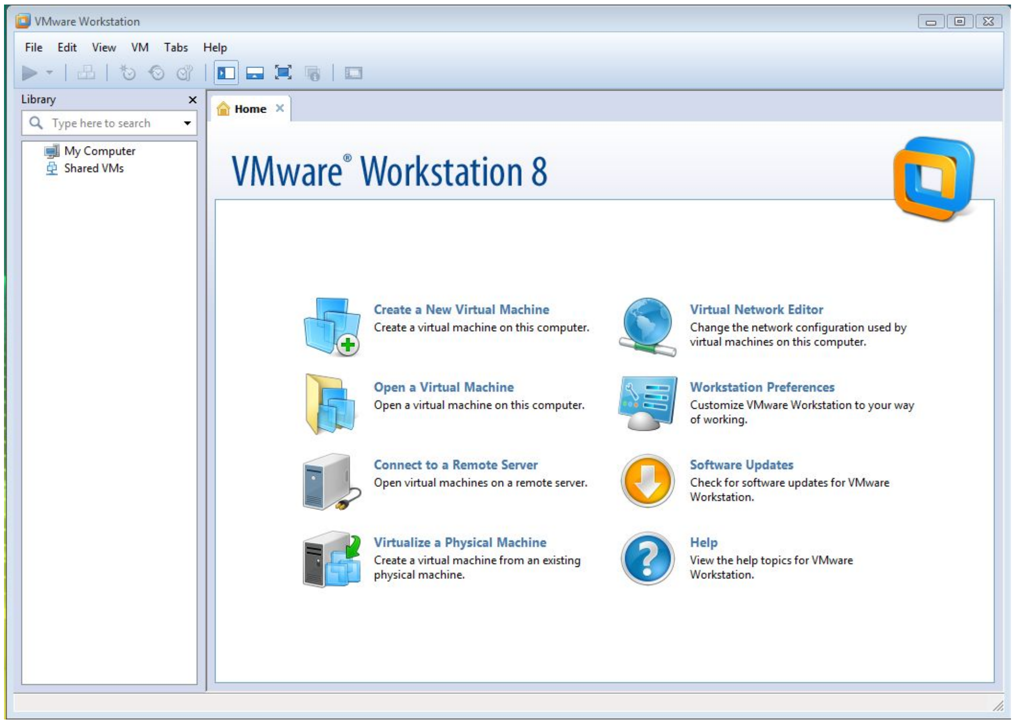
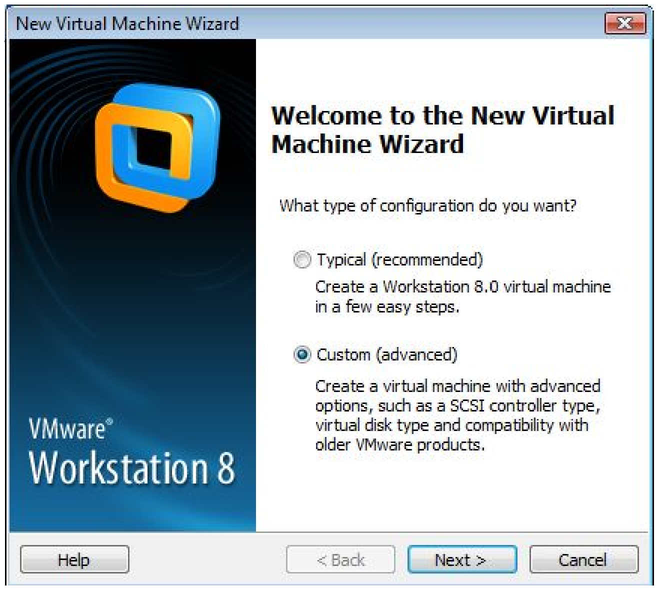

VMware Workstation
File Edit View VM Tabs Help
Library
Type here to search
My Computer
Shared VMs
Home
VMware® Workstation 8
Create a New Virtual Machine
Create a virtual machine on this computer.
Virtual Network Editor
Change the network configuration used by virtual machines on this computer.
Open a Virtual Machine
Open a virtual machine on this computer.
Workstation Preferences
Customize VMware Workstation to your way of working.
Connect to a Remote Server
Open virtual machines on a remote server.
Software Updates
Check for software updates for VMware Workstation.
Virtualize a Physical Machine
Create a virtual machine from an existing physical machine.
Help
View the help topics for VMware Workstation.

Figure 59. Select "Create a New Virtual Machine"

2. Select “Custom” and click “Next” (Figure 60).


New Virtual Machine Wizard

VMware® Workstation 8

Welcome to the New Virtual Machine Wizard

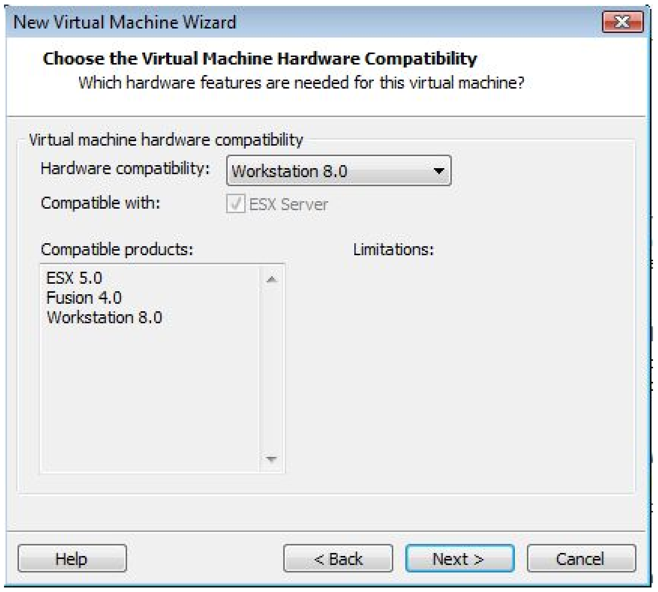
What type of configuration do you want?

◯ Typical (recommended)
Create a Workstation 8.0 virtual machine in a few easy steps.

● Custom (advanced)
Create a virtual machine with advanced options, such as a SCSI controller type, virtual disk type and compatibility with older VMware products.

Figure 60. Select “Custom” and Click “Next”

3. Use the “Workstation 8.0” hardware compatibility settings and click “Next” (Figure 61).


New Virtual Machine Wizard

Choose the Virtual Machine Hardware Compatibility
Which hardware features are needed for this virtual machine?

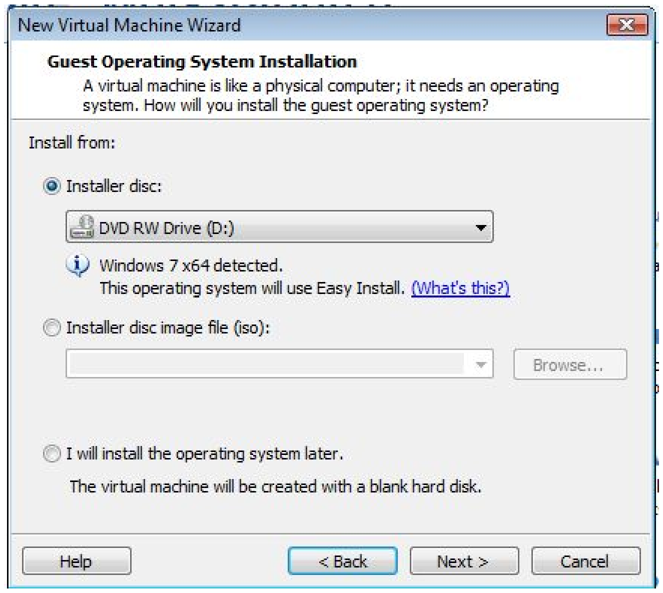
Virtual machine hardware compatibility
Hardware compatibility: Workstation 8.0
Compatible with: ✓ ESX Server

Compatible products:
ESX 5.0
Fusion 4.0
Workstation 8.0

Limitations:

Figure 61. Select “Workstation 8.0” and Click “Next”

4. Check that the install from location that matches the location of the guest OS and click “Next” (Figure 62).



New Virtual Machine Wizard

Guest Operating System Installation

A virtual machine is like a physical computer; it needs an operating system. How will you install the guest operating system?

Install from:

(●) Installer disc:

DVD RW Drive (D:)

Windows 7 x64 detected.
This operating system will use Easy Install. (What's this?)

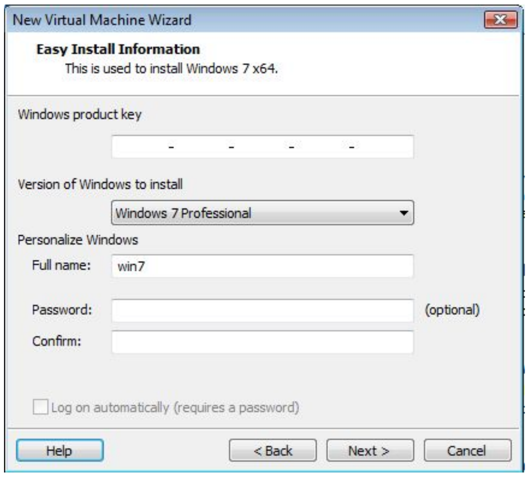
( ) Installer disc image file (iso):

( ) I will install the operating system later.

The virtual machine will be created with a blank hard disk.

Figure 62. Check Install From Location and Click “Next”

5. Fill in the guest OS product key and desired computer name and click “Next”. Note: for Windows installations, if you do not enter the guest product key here, Windows will still install (Figure 63).



New Virtual Machine Wizard

Easy Install Information

This is used to install Windows 7 x64.

Windows product key: - - - -

Version of Windows to install: Windows 7 Professional

Personalize Windows

Full name: win7

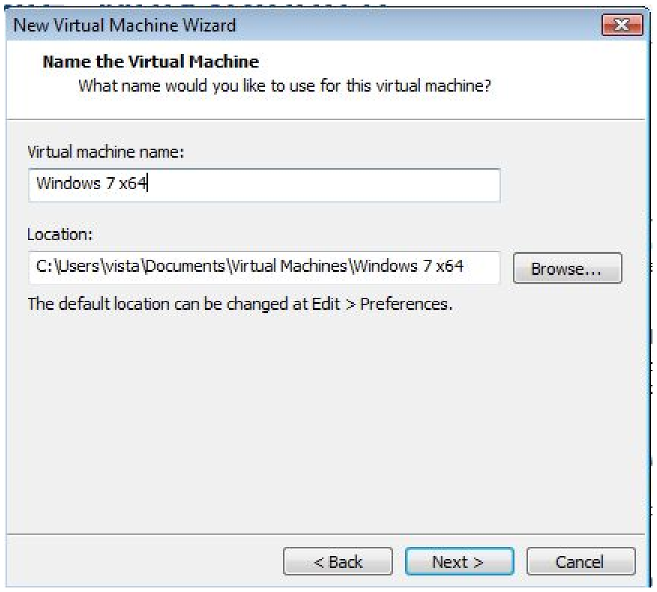
Password: (optional)

Confirm:

[ ] Log on automatically (requires a password)

Figure 63. Fill in and Click “Next”

6. Enter the desired name of the virtual machine and click “Next” (Figure 64).


New Virtual Machine Wizard
Name the Virtual Machine
What name would you like to use for this virtual machine?
Browse...
< Back
Next >
Cancel

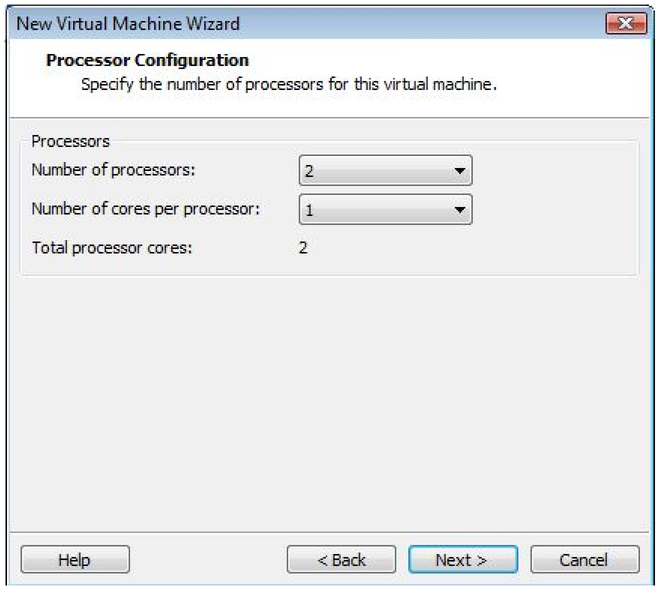
Virtual machine name: Windows 7 x64

Location: C:\Users\vista\Documents\Virtual Machines\Windows 7 x64

The default location can be changed at Edit > Preferences.

Figure 64. Name the Virtual Machine

7. If your host machine has more than one processor, set the number of processors to 1 and number of cores per processor to 2. You can also use 2 processors with 1 core per processor. Click “Next”. NOTE: The HyperScan and Cloaker test frameworks require two cores or two processors to work correctly (Figure 65).


New Virtual Machine Wizard

Processor Configuration

Specify the number of processors for this virtual machine.

Processors

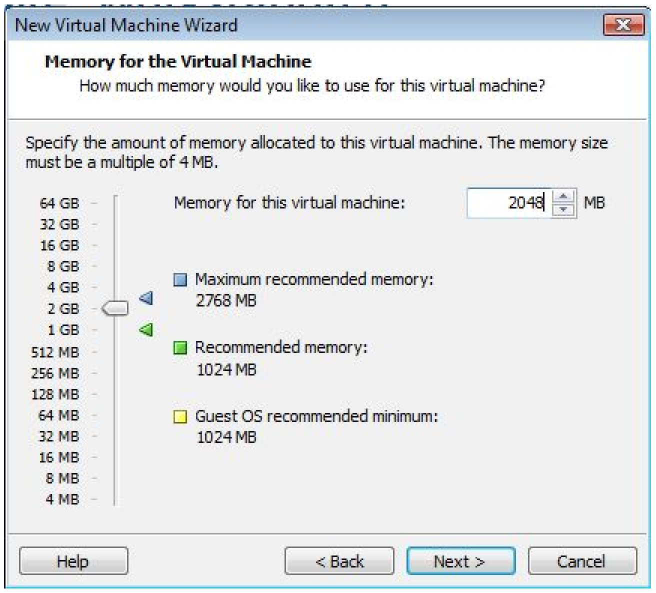
Number of processors: 2

Number of cores per processor: 1

Total processor cores: 2

Figure 65. Processor Configuration

8. Set the memory for the virtual machine to at least the minimum required for the guest OS and click “Next”. For 64-bit Windows 7 the minimum required is 2048 MB (Figure 66).


New Virtual Machine Wizard

Memory for the Virtual Machine

How much memory would you like to use for this virtual machine?

Specify the amount of memory allocated to this virtual machine. The memory size must be a multiple of 4 MB.

Memory for this virtual machine: 2048 MB

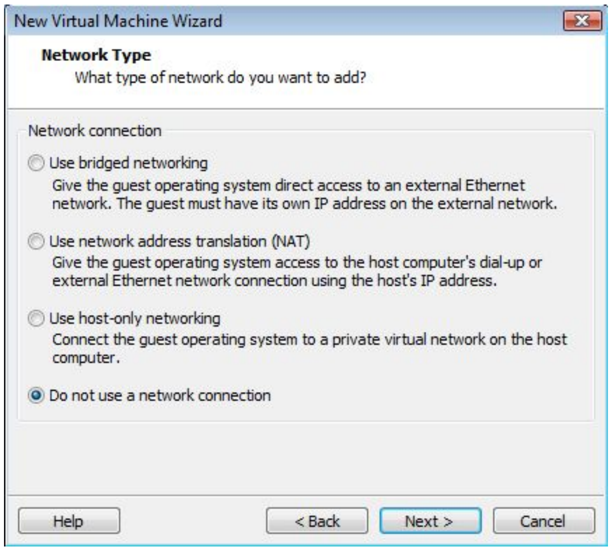
Maximum recommended memory: 2768 MB

Recommended memory: 1024 MB

Guest OS recommended minimum: 1024 MB

Figure 66. Memory Configuration

9. For network type, select "Do not use a network connection" and click "Next" (Figure 67).


New Virtual Machine Wizard

Network Type

What type of network do you want to add?

Network connection

( ) Use bridged networking
Give the guest operating system direct access to an external Ethernet network. The guest must have its own IP address on the external network.

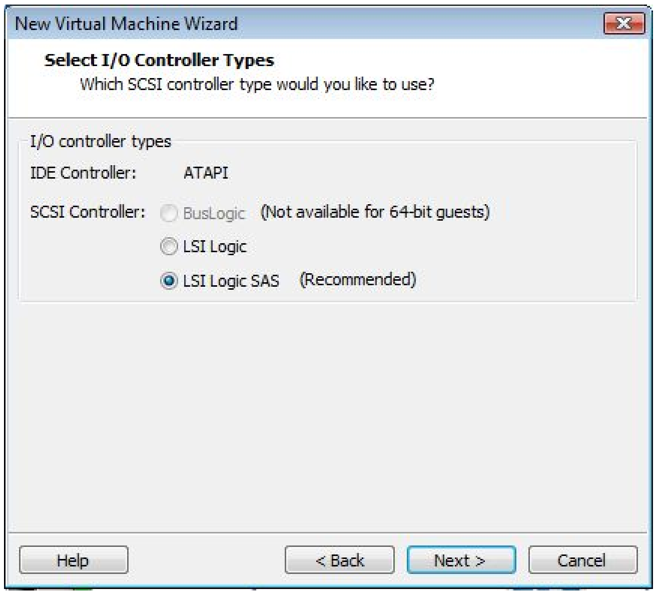
( ) Use network address translation (NAT)
Give the guest operating system access to the host computer's dial-up or external Ethernet network connection using the host's IP address.

( ) Use host-only networking
Connect the guest operating system to a private virtual network on the host computer.

[✓ Do not use a network connection]

Figure 67. Network Configuration

10. Use the recommended setting for the I/O Controller type and click "Next" (Figure 68).


New Virtual Machine Wizard

Select I/O Controller Types

Which SCSI controller type would you like to use?

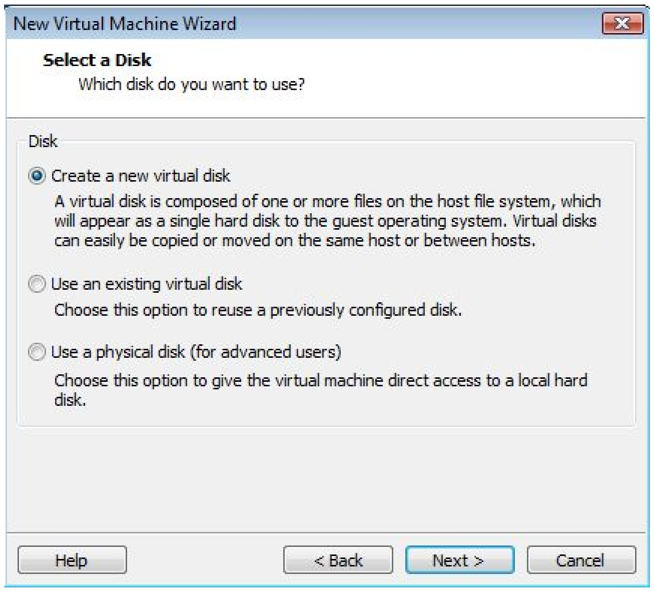
I/O controller types

IDE Controller: ATAPI

SCSI Controller: ( ) BusLogic (Not available for 64-bit guests)
( ) LSI Logic
[✓ LSI Logic SAS] (Recommended)

Figure 68. I/O Controller Configuration

11. Select “Create a new virtual disk” and click “Next” (Figure 69).


New Virtual Machine Wizard

Select a Disk
Which disk do you want to use?

Disk

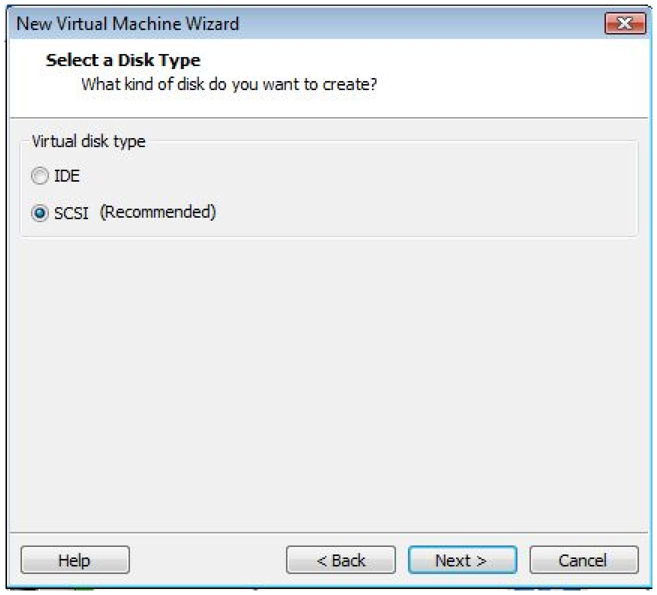
[✓ Create a new virtual disk]
A virtual disk is composed of one or more files on the host file system, which will appear as a single hard disk to the guest operating system. Virtual disks can easily be copied or moved on the same host or between hosts.

Use an existing virtual disk
Choose this option to reuse a previously configured disk.

Use a physical disk (for advanced users)
Choose this option to give the virtual machine direct access to a local hard disk.

Figure 69. Create a New Virtual Disk

12. Select the SCSI virtual disk type and click “Next” (Figure 70).


New Virtual Machine Wizard

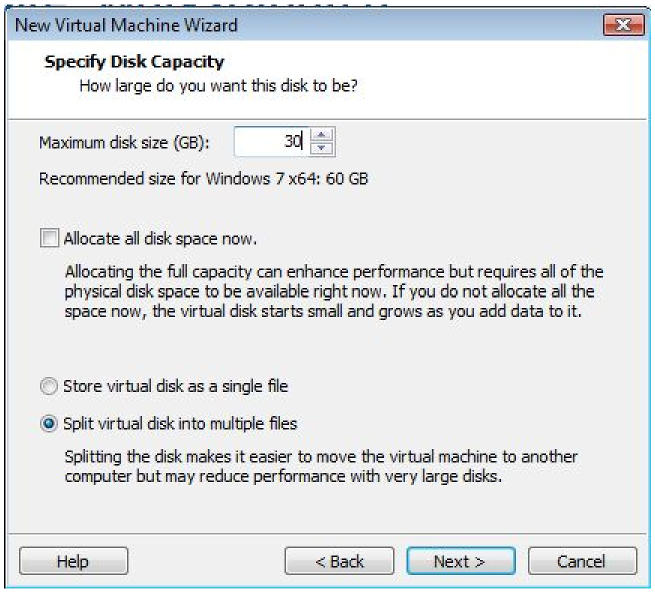
Select a Disk Type
What kind of disk do you want to create?

Virtual disk type

IDE
[✓ SCSI (Recommended)]

Figure 70. Select a Disk Type

13. Allocate 30 GB of disk space for the guest OS, select "Split virtual disk into multiple files" and click "Next" (Figure 71).



New Virtual Machine Wizard

Specify Disk Capacity
How large do you want this disk to be?

Maximum disk size (GB): 30

Recommended size for Windows 7 x64: 60 GB

☐ Allocate all disk space now.

Allocating the full capacity can enhance performance but requires all of the physical disk space to be available right now. If you do not allocate all the space now, the virtual disk starts small and grows as you add data to it.

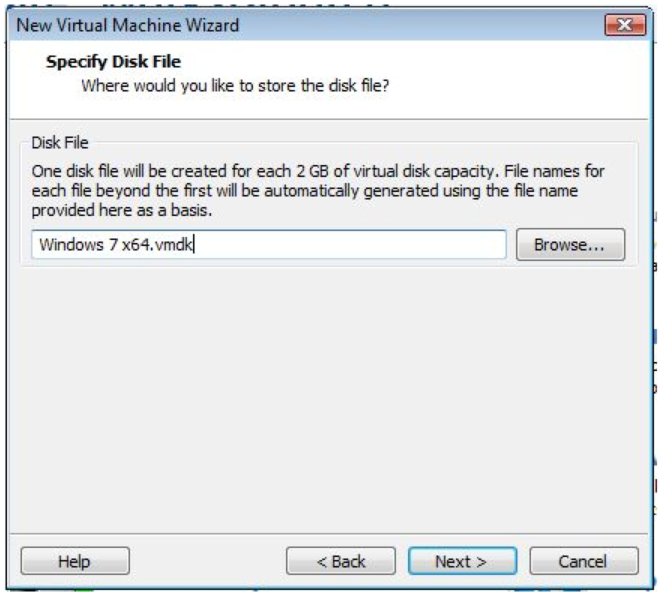
○ Store virtual disk as a single file

● Split virtual disk into multiple files

Splitting the disk makes it easier to move the virtual machine to another computer but may reduce performance with very large disks.

Figure 71. Specify Disk Capacity

14. Keep the default name for the disk file and click "Next" (Figure 72).



New Virtual Machine Wizard

Specify Disk File
Where would you like to store the disk file?

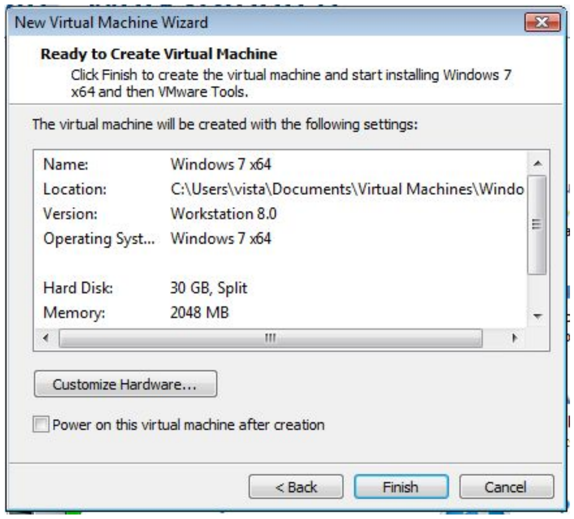
Disk File

One disk file will be created for each 2 GB of virtual disk capacity. File names for each file beyond the first will be automatically generated using the file name provided here as a basis.

Windows 7 x64.vmdk

Figure 72. Specify the Disk File

15. Review the installation settings, click “Customize Hardware” and click “Finish” (Figure 73).


New Virtual Machine Wizard

Ready to Create Virtual Machine
Click Finish to create the virtual machine and start installing Windows 7 x64 and then VMware Tools.

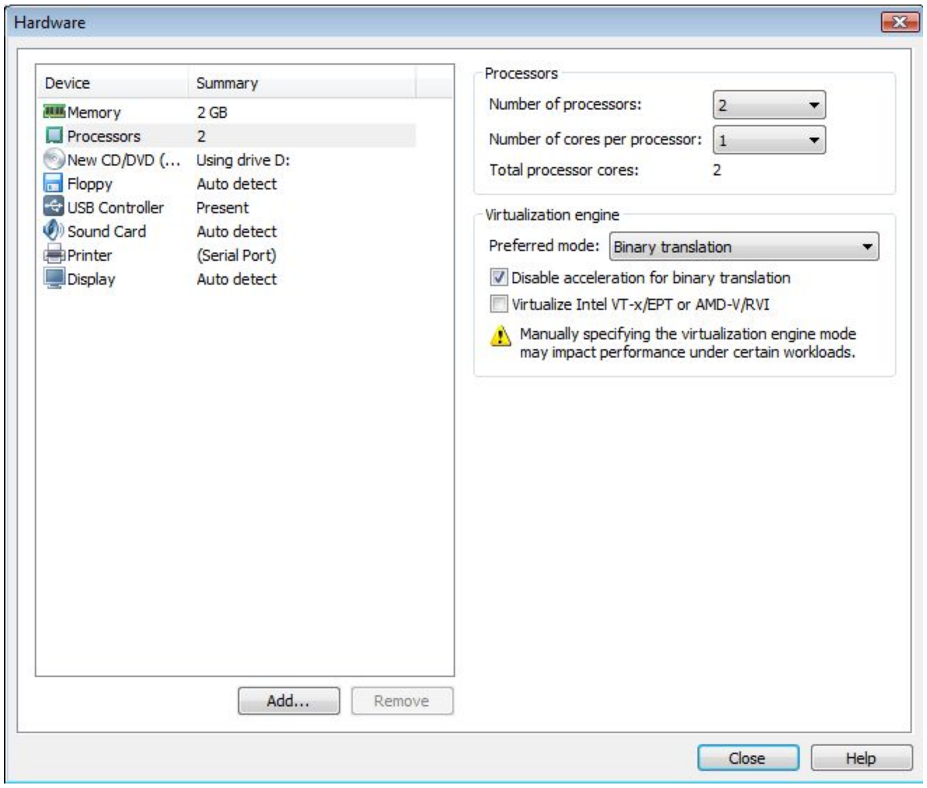
The virtual machine will be created with the following settings:

Name:	Windows 7 x64
Location:	C:\Users\vista\Documents\Virtual Machines\Windo
Version:	Workstation 8.0
Operating Syst...	Windows 7 x64
Hard Disk:	30 GB, Split
Memory:	2048 MB

Figure 73. Select “Customize Hardware”

16. Click on “Processors” and within the “Virtualization engine” field and do one of the following:

- Set up a software-only Full Virtualization hypervisor by selecting “Binary Translation” and checking the “Disable acceleration for binary translation” box (Figure 74).



Device	Summary
Memory	2 GB
Processors	2
New CD/DVD (...	Using drive D:
Floppy	Auto detect
USB Controller	Present
Sound Card	Auto detect
Printer	(Serial Port)
Display	Auto detect

Processors

Number of processors: 2

Number of cores per processor: 1

Total processor cores: 2

Virtualization engine

Preferred mode: Binary translation

[✓] Disable acceleration for binary translation

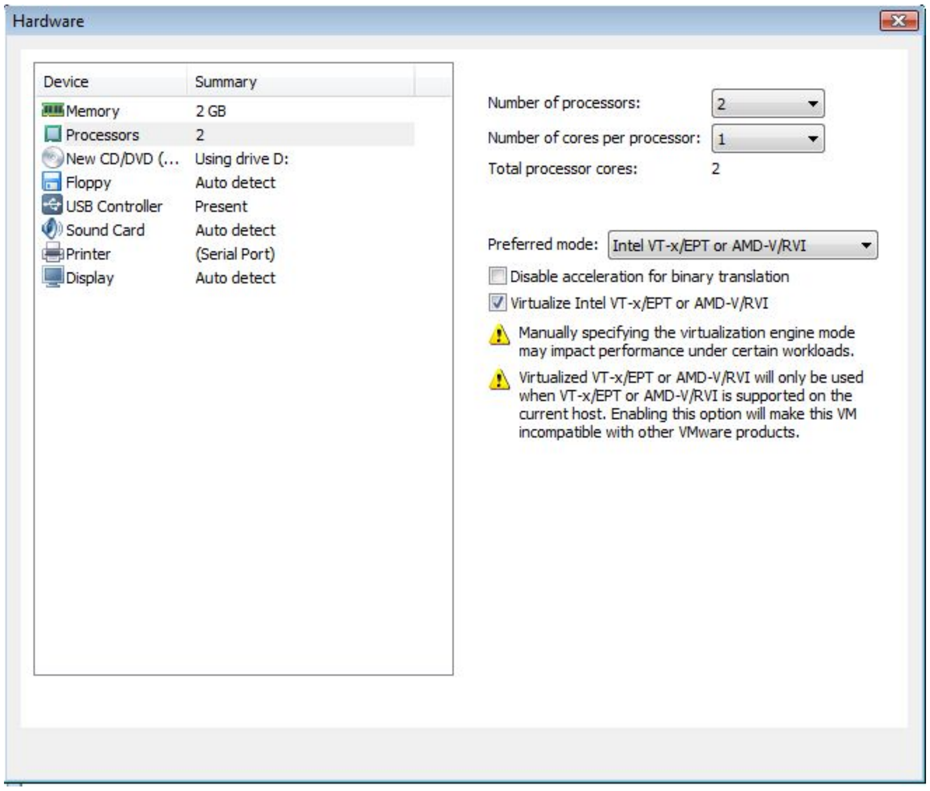
[ ] Virtualize Intel VT-x/EPT or AMD-V/RVI

Manually specifying the virtualization engine mode may impact performance under certain workloads.

Figure 74. Full Virtualization using Binary Translation Configuration

- Set up a Hardware-assisted Full Virtualization hypervisor by selecting "Intel VT-x/EPT or AMD-V/RVI" and checking the "Virtualize Intel VT-x/EPT or AMD-V RVI" box (Figure 75).

When configured, close the window to return to the installation overview.


Hardware

Device	Summary
Memory	2 GB
Processors	2
New CD/DVD (...	Using drive D:
Floppy	Auto detect
USB Controller	Present
Sound Card	Auto detect
Printer	(Serial Port)
Display	Auto detect

Number of processors: 2

Number of cores per processor: 1

Total processor cores: 2

Preferred mode: Intel VT-x/EPT or AMD-V/RVI

[ ] Disable acceleration for binary translation

[✓] Virtualize Intel VT-x/EPT or AMD-V/RVI

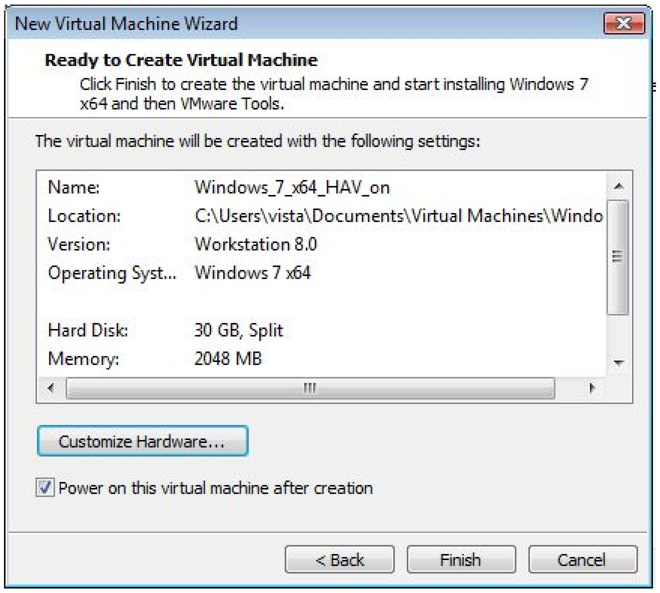
Manually specifying the virtualization engine mode may impact performance under certain workloads.

Virtualized VT-x/EPT or AMD-V/RVI will only be used when VT-x/EPT or AMD-V/RVI is supported on the current host. Enabling this option will make this VM incompatible with other VMware products.

Figure 75. Hardware-assisted Full Virtualization Configuarion

NOTE: Do not simply run experiments with one virtual machine configuration, change the configuration settings, and use the same guest OS for a second set of experiments. Instead, to mitigate any possible configuration discrepancies caused by loading an OS that was created using one virtual machine configuration and using it on a changed virtual machine configuration, each guest OS must be installed within its own custom-configured virtual machine.

17. Click “Finish” to start the virtual machine and begin installing the guest OS (Figure 76).


New Virtual Machine Wizard

Ready to Create Virtual Machine

Click Finish to create the virtual machine and start installing Windows 7 x64 and then VMware Tools.

The virtual machine will be created with the following settings:

Name:	Windows_7_x64_HAV_on
Location:	C:\Users\vista\Documents\Virtual Machines\Windo
Version:	Workstation 8.0
Operating Syst...	Windows 7 x64
Hard Disk:	30 GB, Split
Memory:	2048 MB

☑ Power on this virtual machine after creation

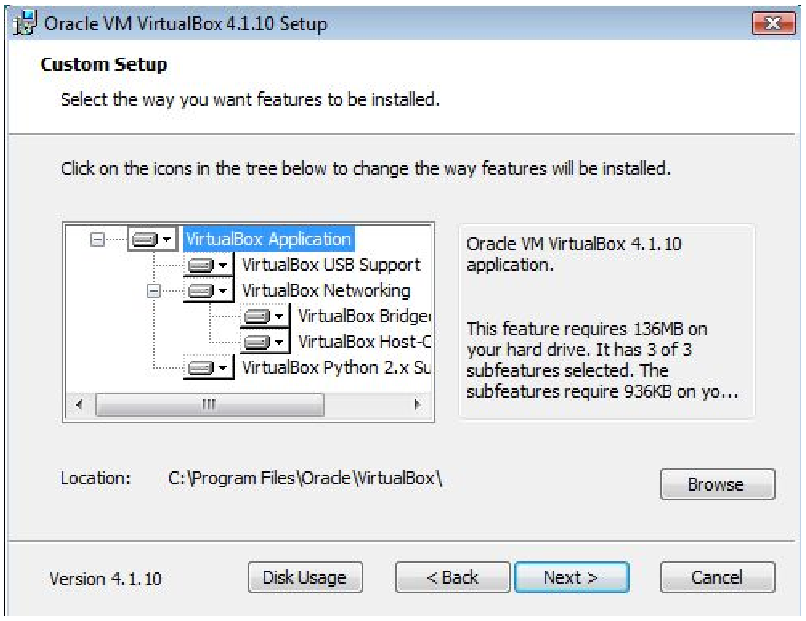
Figure 76. Select “Finish” to Complete the Virtual Machine

Appendix D. VirtualBox Installation and Windows 7 Setup

The following provides step-by-step instructions for how to install VirtualBox on the host OS. Virtual Box version 4.1.10 is used for this installation.

D-1. Download and Install VirtualBox

1. Download VirtualBox 4.1.10 for Windows hosts from the following website: https://www.virtualbox.org/wiki/Downloads. VirtualBox provides extension packs for improved usability however, none are used for experimentation beyond what is installed by a default VirtualBox installation..
2. Within the host machine, locate the downloaded installation file and double click it. When prompted, click next to continue.
3. At the custom setup screen, there is no need to change any settings; click next (Figure 77).


Oracle VM VirtualBox 4.1.10 Setup

Custom Setup

Select the way you want features to be installed.

Click on the icons in the tree below to change the way features will be installed.

VirtualBox Application
VirtualBox USB Support
VirtualBox Networking
VirtualBox Bridge
VirtualBox Host-C
VirtualBox Python 2.x Su

Oracle VM VirtualBox 4.1.10 application.

This feature requires 136MB on your hard drive. It has 3 of 3 subfeatures selected. The subfeatures require 936KB on yo...

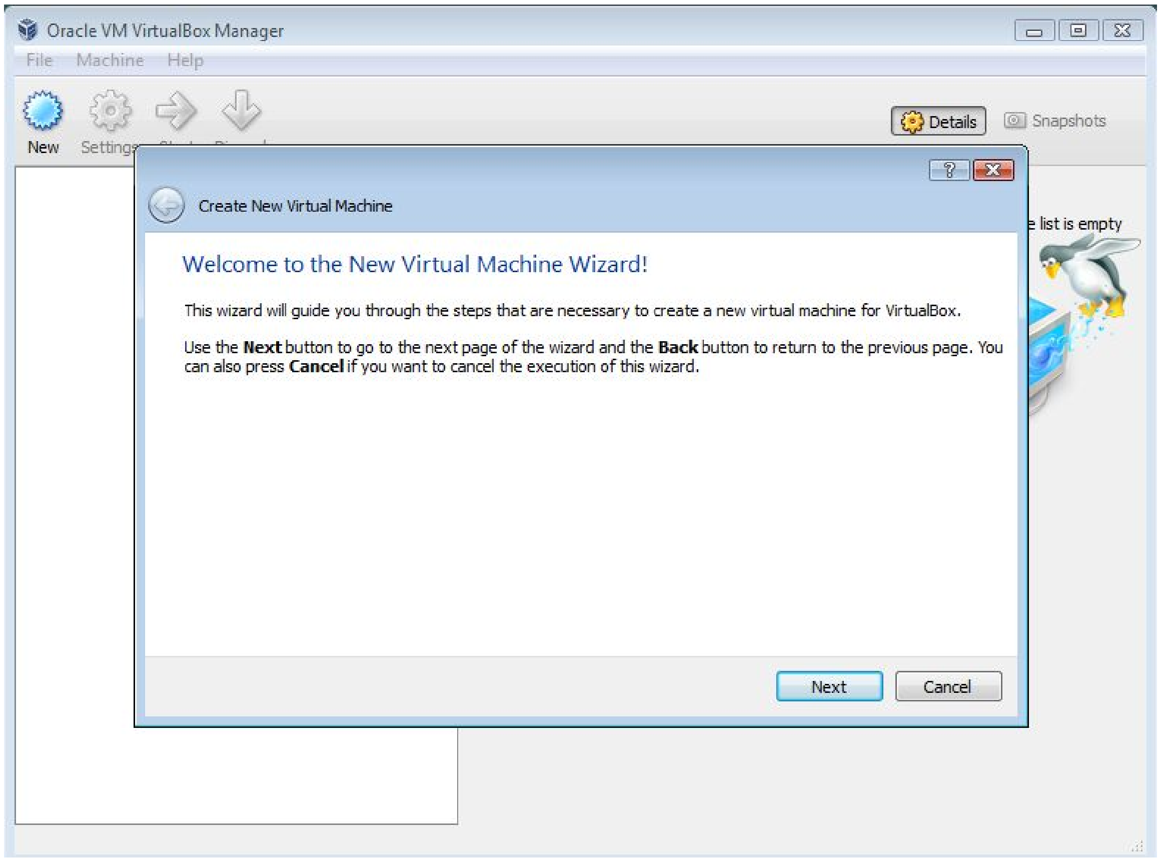
Location: C:\Program Files\Oracle\VirtualBox\

Figure 77. Custom Setup

4. Continue installation, clicking next or continue as prompted, when finished, select "Start Virtual Box when finished" and click finish.

D-2. Create and Configure the Virtual Machine

18. Within VirtualBox, click "New" to create a new Virtual Machine and follow the on-screen prompts (Figure 78).



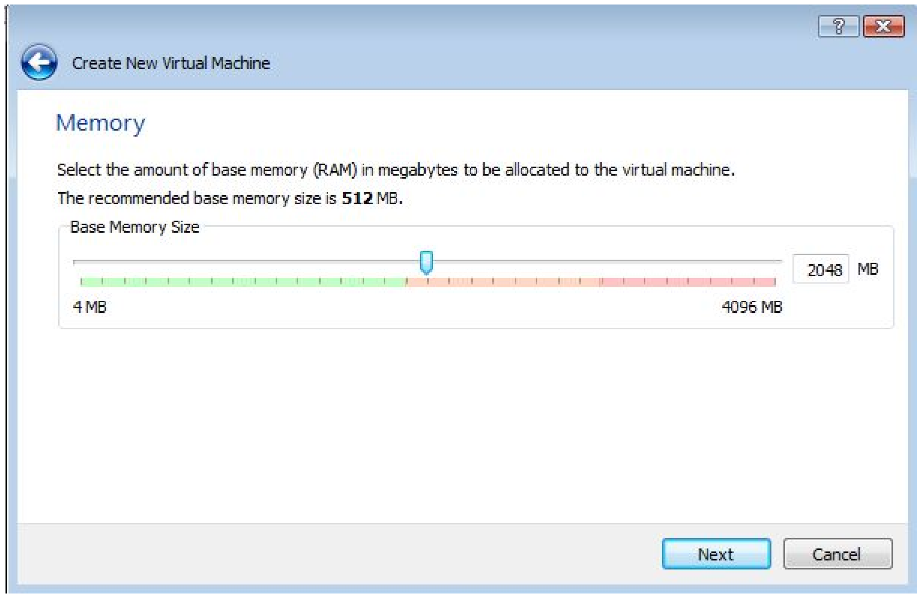
Welcome to the New Virtual Machine Wizard!

This wizard will guide you through the steps that are necessary to create a new virtual machine for VirtualBox.

Use the **Next** button to go to the next page of the wizard and the **Back** button to return to the previous page. You can also press **Cancel** if you want to cancel the execution of this wizard.

Figure 78. Create a New Virtual Machine

19. When prompted for Memory, allocate at least the minimum required for the guest OS, for 64-bit Windows 7 the minimum required is 2048 MB (Figure 79).


Create New Virtual Machine

Memory

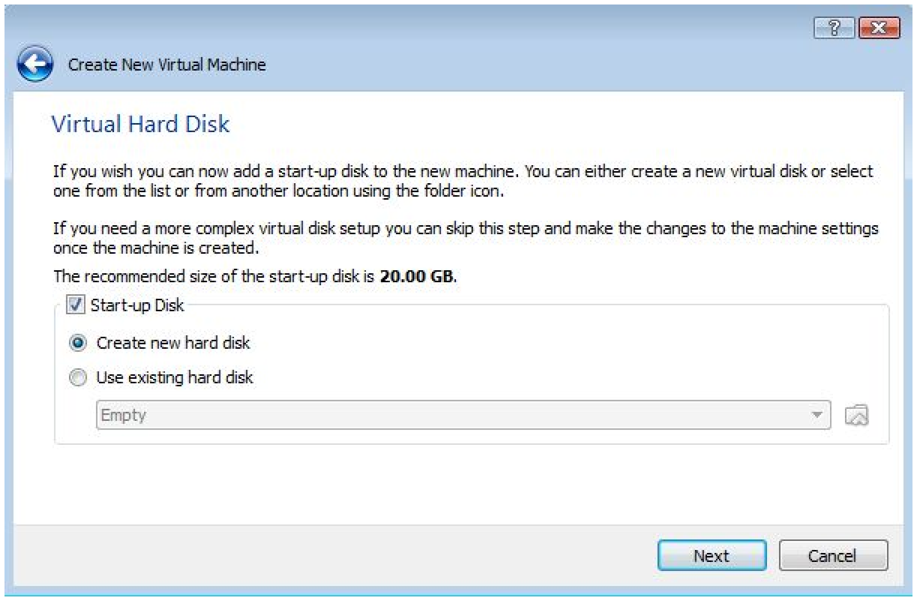
Select the amount of base memory (RAM) in megabytes to be allocated to the virtual machine.
The recommended base memory size is **512** MB.

Base Memory Size: 2048 MB

4 MB — 4096 MB

Figure 79. Memory Allocation

20. When prompted to create a Start-Up Disk, select create new hard disk (Figure 80).


Create New Virtual Machine

Virtual Hard Disk

If you wish you can now add a start-up disk to the new machine. You can either create a new virtual disk or select one from the list or from another location using the folder icon.

If you need a more complex virtual disk setup you can skip this step and make the changes to the machine settings once the machine is created.

The recommended size of the start-up disk is **20.00 GB**.

[✓] Start-up Disk

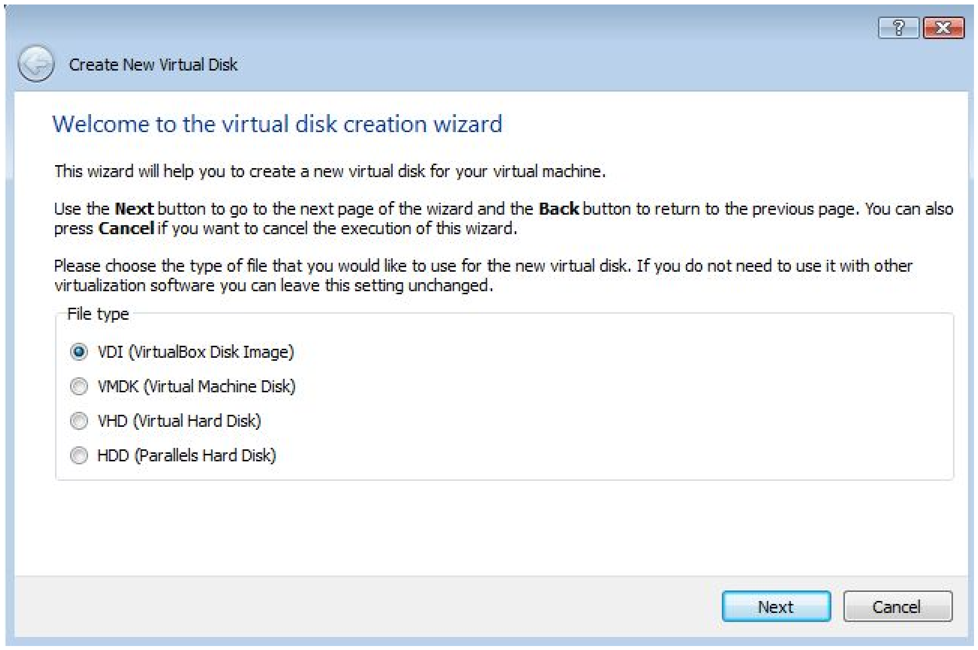
[✓ Create new hard disk]

Use existing hard disk

Empty

Figure 80. Virtual Hard Disk

21. Within the virtual disk creation wizard, select VDI for the file type (Figure 81).



Welcome to the virtual disk creation wizard

This wizard will help you to create a new virtual disk for your virtual machine.

Use the **Next** button to go to the next page of the wizard and the **Back** button to return to the previous page. You can also press **Cancel** if you want to cancel the execution of this wizard.

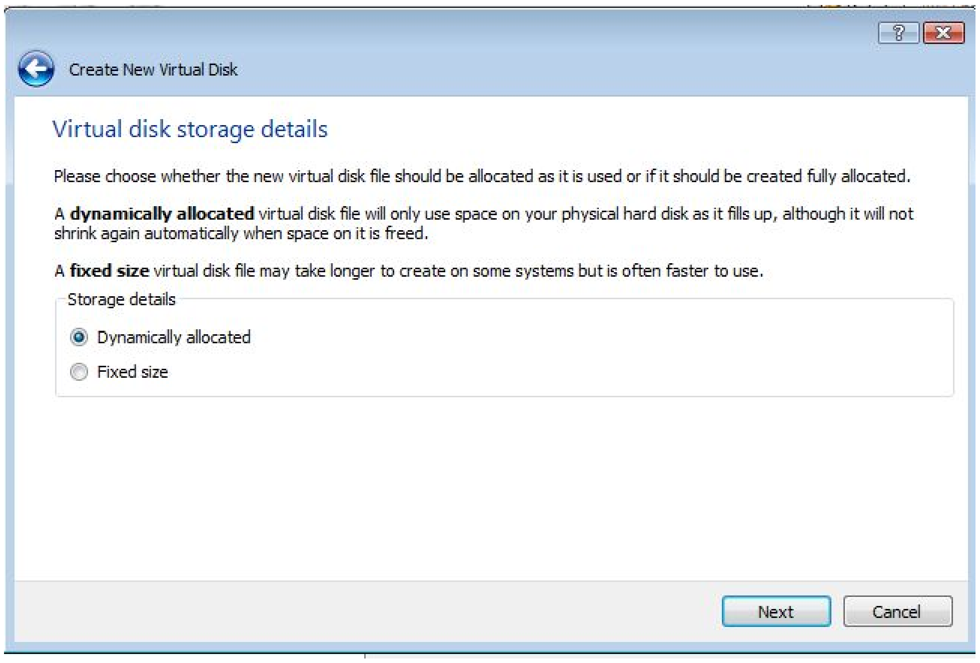
Please choose the type of file that you would like to use for the new virtual disk. If you do not need to use it with other virtualization software you can leave this setting unchanged.

File type

[✓ VDI (VirtualBox Disk Image)]
VMDK (Virtual Machine Disk)
VHD (Virtual Hard Disk)
HDD (Parallels Hard Disk)

Figure 81. Select File Type

22. Select Dynamically Allocated for the Virtual Disk Storage Details (Figure 82)



Virtual disk storage details

Please choose whether the new virtual disk file should be allocated as it is used or if it should be created fully allocated.

A **dynamically allocated** virtual disk file will only use space on your physical hard disk as it fills up, although it will not shrink again automatically when space on it is freed.

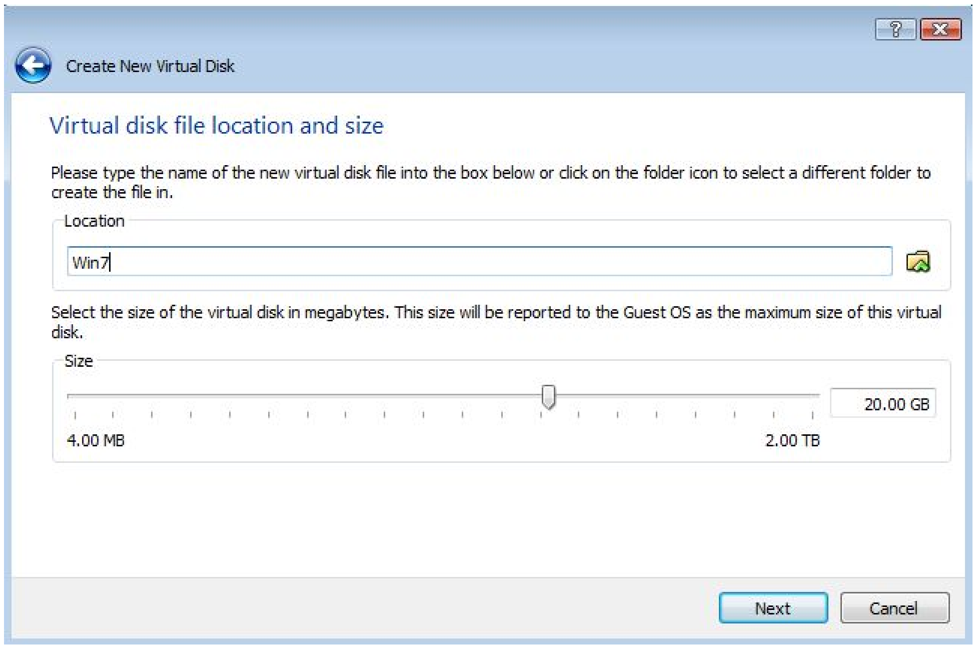
A **fixed size** virtual disk file may take longer to create on some systems but is often faster to use.

Storage details

[✓ Dynamically allocated]
Fixed size

Figure 82. Select Drive Allocation Type

23. For the Virtual disk file location and size, use at least the minimum required for the guest OS, in this case 20 GB for 64-bit Windows 7 (Figure 83).



Create New Virtual Disk

Virtual disk file location and size

Please type the name of the new virtual disk file into the box below or click on the folder icon to select a different folder to create the file in.

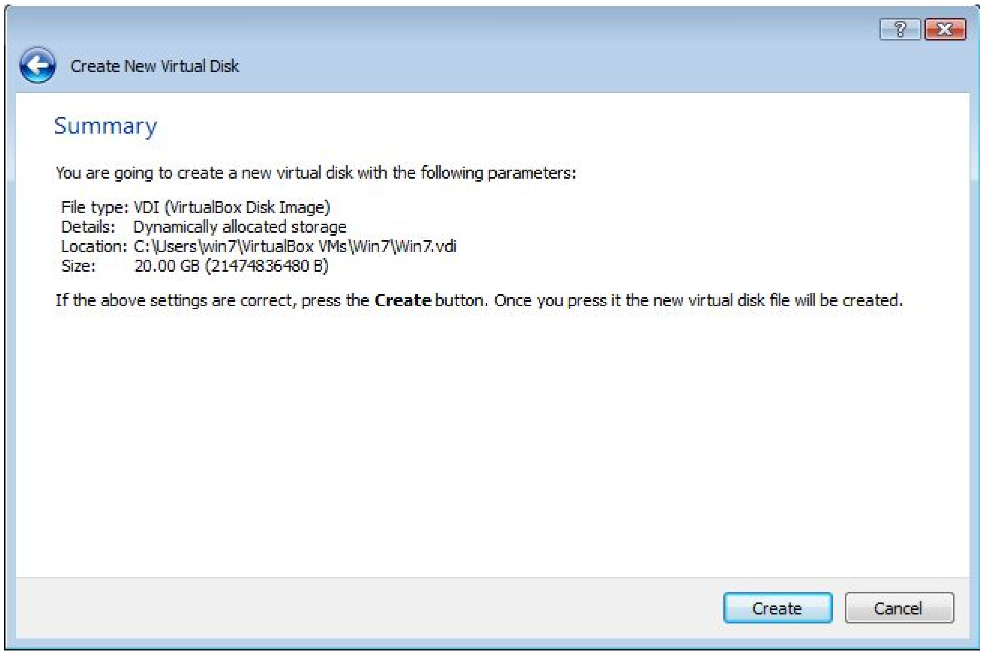
Location: Win7

Select the size of the virtual disk in megabytes. This size will be reported to the Guest OS as the maximum size of this virtual disk.

Size: 20.00 GB

Figure 83. Allocate Virtual Disk Location and Size

24. At the summary window, select “Create” to create your virtual machine (Figure 84).



Summary

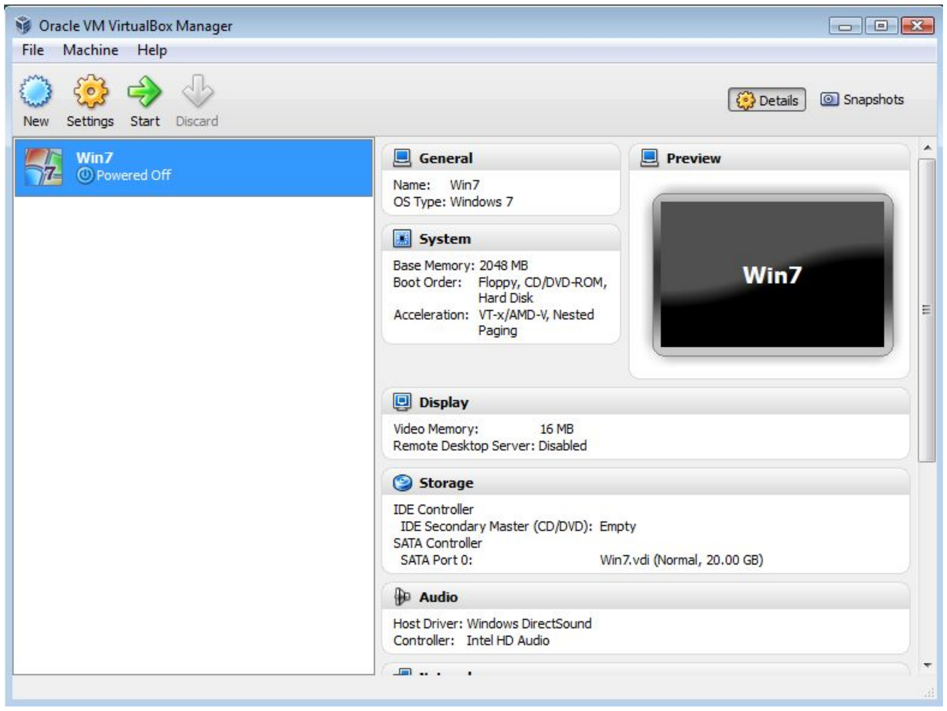
You are going to create a new virtual disk with the following parameters:

File type:	VDI (VirtualBox Disk Image)
Details:	Dynamically allocated storage
Location:	C:\Users\win7\VirtualBox VMs\Win7\Win7.vdi
Size:	20.00 GB (21474836480 B)

If the above settings are correct, press the **Create** button. Once you press it the new virtual disk file will be created.

Figure 84. Virtual Disk Summary Window

25. Double click on your newly created VM to start the virtual machine and start the First Run Wizard. Follow the onscreen instructions to install the OS (Figures 85-86).



General
Name: Win7
OS Type: Windows 7

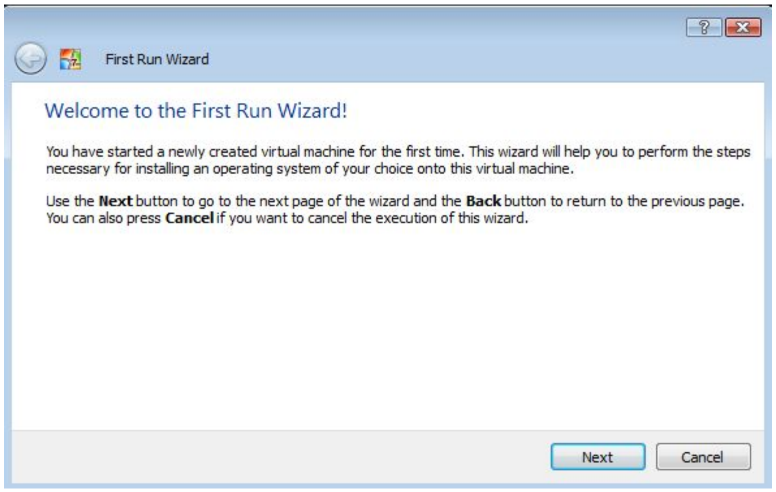
System
Base Memory: 2048 MB
Boot Order: Floppy, CD/DVD-ROM, Hard Disk
Acceleration: VT-x/AMD-V, Nested Paging

Display
Video Memory: 16 MB
Remote Desktop Server: Disabled

Storage
IDE Controller
IDE Secondary Master (CD/DVD): Empty
SATA Controller
SATA Port 0: Win7.vdi (Normal, 20.00 GB)

Audio
Host Driver: Windows DirectSound
Controller: Intel HD Audio

Figure 85. Double Click Win7 to Start the Virtual Machine



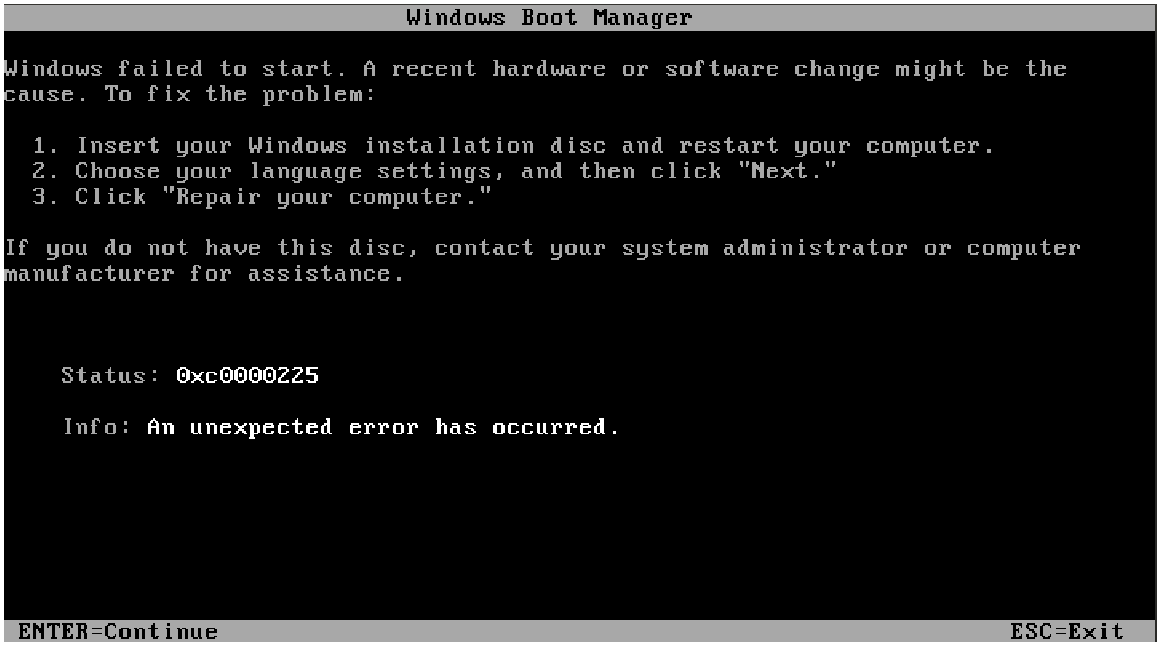
Welcome to the First Run Wizard!

You have started a newly created virtual machine for the first time. This wizard will help you to perform the steps necessary for installing an operating system of your choice onto this virtual machine.

Use the **Next** button to go to the next page of the wizard and the **Back** button to return to the previous page. You can also press **Cancel** if you want to cancel the execution of this wizard.

Figure 86. Welcome to First Run Wizard

26. If you encounter the following error message (Figure 87) within the VirtualBox Manager, click Settings -> System and check "Enable IO APIC".

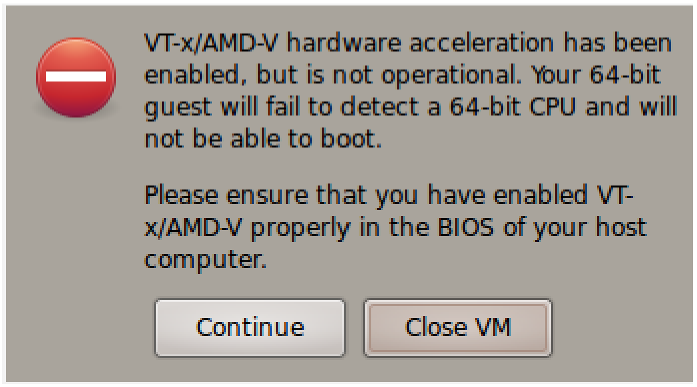


```
Windows Boot Manager

Windows failed to start. A recent hardware or software change might be the
cause. To fix the problem:

  1. Insert your Windows installation disc and restart your computer.
  2. Choose your language settings, and then click "Next."
  3. Click "Repair your computer."

If you do not have this disc, contact your system administrator or computer
manufacturer for assistance.


    Status: 0xc0000225

    Info: An unexpected error has occurred.



ENTER=Continue                                                        ESC=Exit
```

Figure 87. Windows Boot Manager Unexpected Error

Additionally, if you encounter the following error (Figure 88), enter the following command within a command shell and press enter:

```
set VBOX_HWVIRTEX_IGNORE_SVM_IN_U SE=true
```

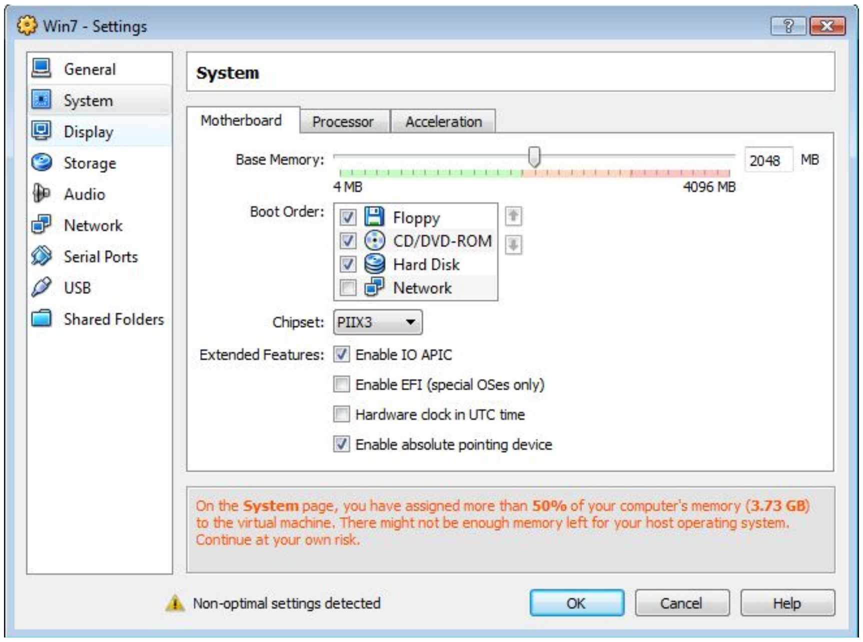


VT-x/AMD-V hardware acceleration has been enabled, but is not operational. Your 64-bit guest will fail to detect a 64-bit CPU and will not be able to boot.

Please ensure that you have enabled VT-x/AMD-V properly in the BIOS of your host computer.

Figure 88. Hardware Acceleration Error Message

Finally, within the processor tab, you may also want to Enable PAE/NX to enable Physical Address Extension of the host CPU depending on your experimental configuration (Figure 89).



Base Memory: 2048 MB (4 MB – 4096 MB)

Boot Order: [✓] Floppy, [✓] CD/DVD-ROM, [✓] Hard Disk, [ ] Network

Chipset: PIIX3

Extended Features: [✓] Enable IO APIC; [ ] Enable EFI (special OSes only); [ ] Hardware clock in UTC time; [✓] Enable absolute pointing device

On the **System** page, you have assigned more than **50%** of your computer's memory (**3.73 GB**) to the virtual machine. There might not be enough memory left for your host operating system. Continue at your own risk.

Non-optimal settings detected

Figure 89. Enable PAE/NX

Appendix E. QEMU Setup and Windows 7 Installation

The following provides step-by-step instructions for how to install QEMU on a Windows system followed by installation of Windows 7 within the emulated environment. QEMU user documentation can be accessed here: http://qemu.weilnetz.de/qemu-doc.html.

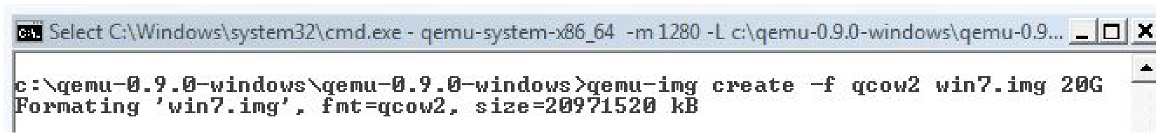
E-1. Setup QEMU

1. Download QEMU from http://www.h7.dion.ne.jp/~qemu-win/. For this example, the file named qemu-0.9.0-windows.zip is used.
2. Unzip QEMU to your C:\ drive. There is no requirement to install QEMU.
3. Obtain the latest BIOS configuration file by downloading the Bochs x86 PC emulator v. 2.5.1 from http://sourceforge.net/projects/bochs/files/bochs/2.5.1/. The file is named "Bochs-2.5.1-msvc-src.zip". Unzip Bochs and locate the file named "BIOS-bochs-latest" in the `bochs-2.5.1\bios` folder. This file will replace the bios.bin file within QEMU. Copy the file from Bochs to `C:\qemu-0.9.0-windows\qemu-0.9.0-windows` and rename it bios.bin. This will overwrite the original bios.bin file and replace it with a newer version that supports 64bit operating systems.

E-2. Create Blank Disk Image and Install Windows 7

1. Open a command window and navigate to the unzipped QEMU folder.
2. Create a blank qcow2-formatted, 20 GB disk image using the following command (Figure 90):

```
qemu-img create –f qcow2 win7.img 20G
```



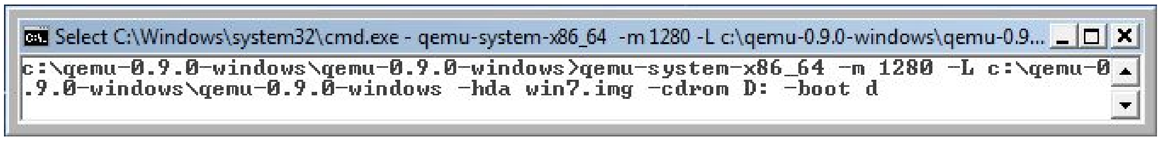
```
Select C:\Windows\system32\cmd.exe - qemu-system-x86_64 -m 1280 -L c:\qemu-0.9.0-windows\qemu-0.9...
c:\qemu-0.9.0-windows\qemu-0.9.0-windows>qemu-img create -f qcow2 win7.img 20G
Formating 'win7.img', fmt=qcow2, size=20971520 kB
```

Figure 90. Create the Blank Disk Image

3. Insert the Windows 7 installation CD

4. Boot the virtual machine off the Windows 7 Installation Disk using the following command:

   ```
   qemu-system-x86_64 –m 1280 –L c:\qemu-0.9.0-
   windows\qemu-0.9.0-windows –hda win7.img –cdrom D: -
   boot d
   ```



```
Select C:\Windows\system32\cmd.exe - qemu-system-x86_64 -m 1280 -L c:\qemu-0.9.0-windows\qemu-0.9...
c:\qemu-0.9.0-windows\qemu-0.9.0-windows>qemu-system-x86_64 -m 1280 -L c:\qemu-0
.9.0-windows\qemu-0.9.0-windows -hda win7.img -cdrom D: -boot d
```

Figure 91. Boot the Virtual Machine for Installation of Windows 7

This starts an x86 64bit emulated environment and passes the following arguments:

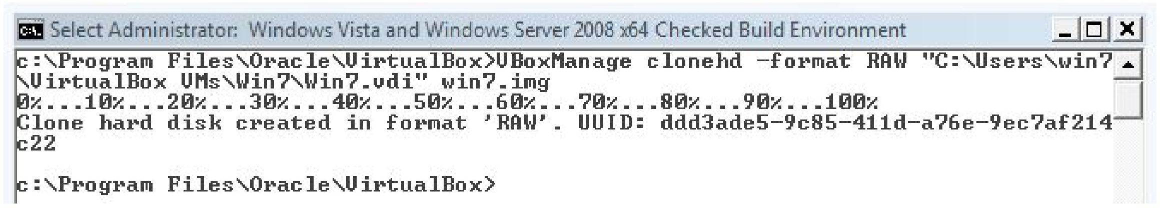
-m	Allocates memory, in this case 1280 Bytes
-L	Sets the directory for the BIOS, VGA BIOS and keymaps.
-hda	Specifies the image file
-cdrom	Designates the designated drive as the guest cd drive.

IMPORTANT: The following notes may be helpful:

- If you encounter a "STOP Error '0x000000A5'" message upon installation of 64-bit Windows 7, verify B1 step 3 was completed and that the –L path points to the location of the replaced bios.bin file.

- If installation halts, the VM can be restarted by pressing alt-tab-2 to access the QEMU monitor and then entering the command `system_reset`. To transition back to the QUI, press alt-tab-1.
- If after being prompted during the windows installation for “Where do you want to install Windows?” you receive an error message of “Windows is unable to install to the selected location. Error: 0x80300024”, delete the win7.img file created earlier and restart at step B-2.
- An alternate way to create and boot a Windows 7 image is to create the windows image using VirtualBox (see Appendix D). Once you have installed Windows 7 in VirtualBox, install any software and make any configuration changes that you will need for experimentation then shut down the Windows 7 virtual machine in VirtualBox. Within a command shell window, navigate to where the VirtualBox VDI image is saved, this should be “C:\Users\<computer name>\VirtualBox VMs\Win7\”. Within this folder, you should also note VBoxManage.exe (if not here, it will likely be found in “Program Files\Oracle\VirtualBox”). You will use the VBoxManage.exe application to convert the Win7.VDI image to a raw .img file that can be booted by QEMU. To do create the raw .img file, enter the following command (Figure 92):

  ```
  VBoxManage clonehd –format RAW <original image - win7.vdi> <destination image - win7.img>
  ```


Select Administrator: Windows Vista and Windows Server 2008 x64 Checked Build Environment

```
c:\Program Files\Oracle\VirtualBox>VBoxManage clonehd -format RAW "C:\Users\win7
\VirtualBox VMs\Win7\Win7.vdi" win7.img
0%...10%...20%...30%...40%...50%...60%...70%...80%...90%...100%
Clone hard disk created in format 'RAW'. UUID: ddd3ade5-9c85-411d-a76e-9ec7af214
c22

c:\Program Files\Oracle\VirtualBox>
```

Figure 92. Clone Hard Disk

Note that both win7.vdi and VBoxManage are in the same directory in this example. Once this command is complete, locate the newly-created win7.img file and copy it to your QEMU folder. Now use the command in step 7 to boot the Windows 7 virtual machine.

5. After Windows 7 is successfully installed, verify that KQemu is not enabled using the following command from the QEMU monitor**:**

```
info kqemu
```

If it is running, use the following command to disable it, placing QEMU in pure emulation mode:

```
-no-kqemu
```

Note: the following command enables KQEMU and places QEMU in Full Virtualization mode:

```
 -kernel-kqemu
```

If attempting to replicate work contained within this thesis, only pure emulation mode (no kqemu) should be used.

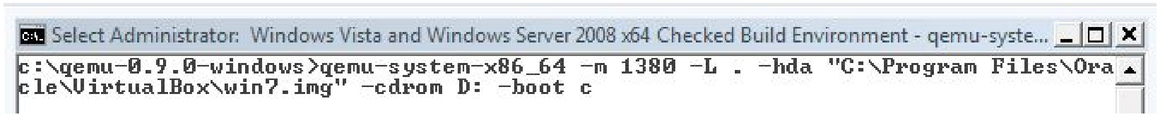
6. Note Following commands:

savevm <name> Save the virtual machine tagged as <name>.

loadvm <name>	Load the virtual machine tagged as <name>From the command line this can be done using: `-loadvm name`
info snapshots	Requests a list of available virtual machine images
quit or **q**	Quits QEMU

7. To start (boot) the Windows 7 virtual machine on a 64 bit system, within a command shell, navigate to the QEMU folder on the C:\ drive and use the following command (Figure 93):

```
qemu-system-x86_64 –m 1380 –L . –hda win7.img –cdrom
D: -boot c
```


Select Administrator: Windows Vista and Windows Server 2008 x64 Checked Build Environment - qemu-syste...

```
c:\qemu-0.9.0-windows>qemu-system-x86_64 -m 1380 -L . -hda "C:\Program Files\Ora
cle\VirtualBox\win7.img" -cdrom D: -boot c
```

Figure 93. Boot the Windows 7 Virtual Machine

Appendix F. BluePill Installation on Windows Vista 64

The following provides step-by-step instructions for how to install BluePill v.0.32 as released by Invisible Things Lab. For installation, you must be running Windows Vista 64 on a processor that supports either Intel VT-x or AMD-V. Additionally, you must enable virtualization within the BIOS.

To install BluePill, the driver signing constraints of Windows Vista must be addressed. Windows Vista 64 requires that all drivers are digitally signed before they are allowed to execute. Within a real-world HAV-R attack scenario, this is one of the challenges which must be overcome for installation within a targeted system. Within an academic or development environment, it is possible to circumvent this requirement through use of test signing. Test-signing uses a test certificate to allow developers to fully test their code to ensure intended operation before obtaining a real certificate [MSN12].

F-1. Enable Test-Signing, Disable Integrity Checks, and Install WinDK

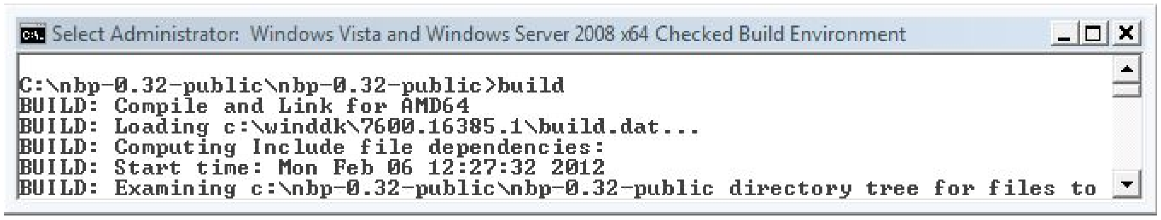
1. Enable Test-Signing, Disable Integrity Checks, and install WinDK as detailed in Appendix B.

F-2. Build the BluePill Driver

1. Copy nbp-0.32-public.zip to your computer and unzip the files. It may be easiest to copy the unzipped files directly onto the c:\ drive. Note that this release provides three components:
    - nbp-0.32-public which contains newbp.sys, the BluePill driver.

- dbgclient which provides a communication channel through use of a driver to enable BluePill to communicate with the target system
- bpknock which is used to verify that BluePill is installed and running.

2. Open an elevated WinDK command window. Click Start > All Programs > Windows Driver Kits > WDK[build number] > Build Environments > Windows Vista and Windows Server 2008 and right click x64 Checked Build Environment and select Run as Administrator. Windows will ask for your permission; click continue.
3. Navigate to the unzipped nbp-0.32-public folder
4. Build newbp.sys by opening the subdirectory labeled nbp-0.32-public and executing the build command as shown in Figure 94. Repeat this process for the dbgclient subdirectory and proceed to the next step.


Select Administrator: Windows Vista and Windows Server 2008 x64 Checked Build Environment

```
C:\nbp-0.32-public\nbp-0.32-public>build
BUILD: Compile and Link for AMD64
BUILD: Loading c:\winddk\7600.16385.1\build.dat...
BUILD: Computing Include file dependencies:
BUILD: Start time: Mon Feb 06 12:27:32 2012
BUILD: Examining c:\nbp-0.32-public\nbp-0.32-public directory tree for files to
```

Figure 94. BluePill Build Example

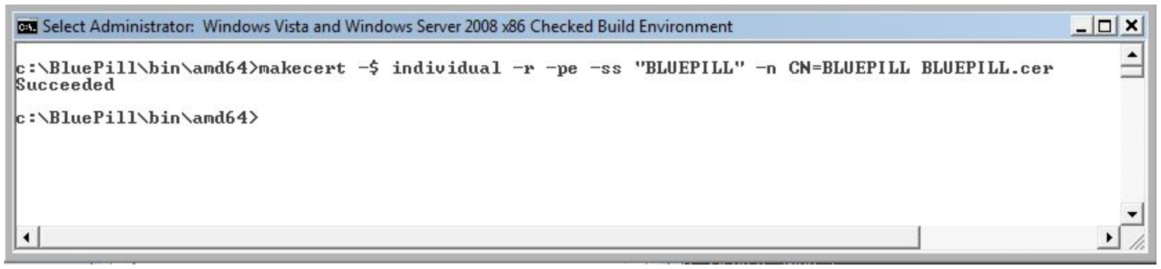
Note: Due to dependencies built into this particular release of BluePill, both dbgclient and nbp-0.32-public must be built and dbgclient.sys must be installed and running newbp.sys is started or newpb.sys will fail.

F-3. Create a Test Certificate

You must associate each BluePill driver with a test certificate. To do this:

1. Open an elevated WinDK command window and enter following command (Figure 95):

   ```
   makecert -$ individual -r -pe -ss "BLUEPILL" -n
   CN="BLUEPILL" BLUEPILL.cer
   ```



Select Administrator: Windows Vista and Windows Server 2008 x86 Checked Build Environment

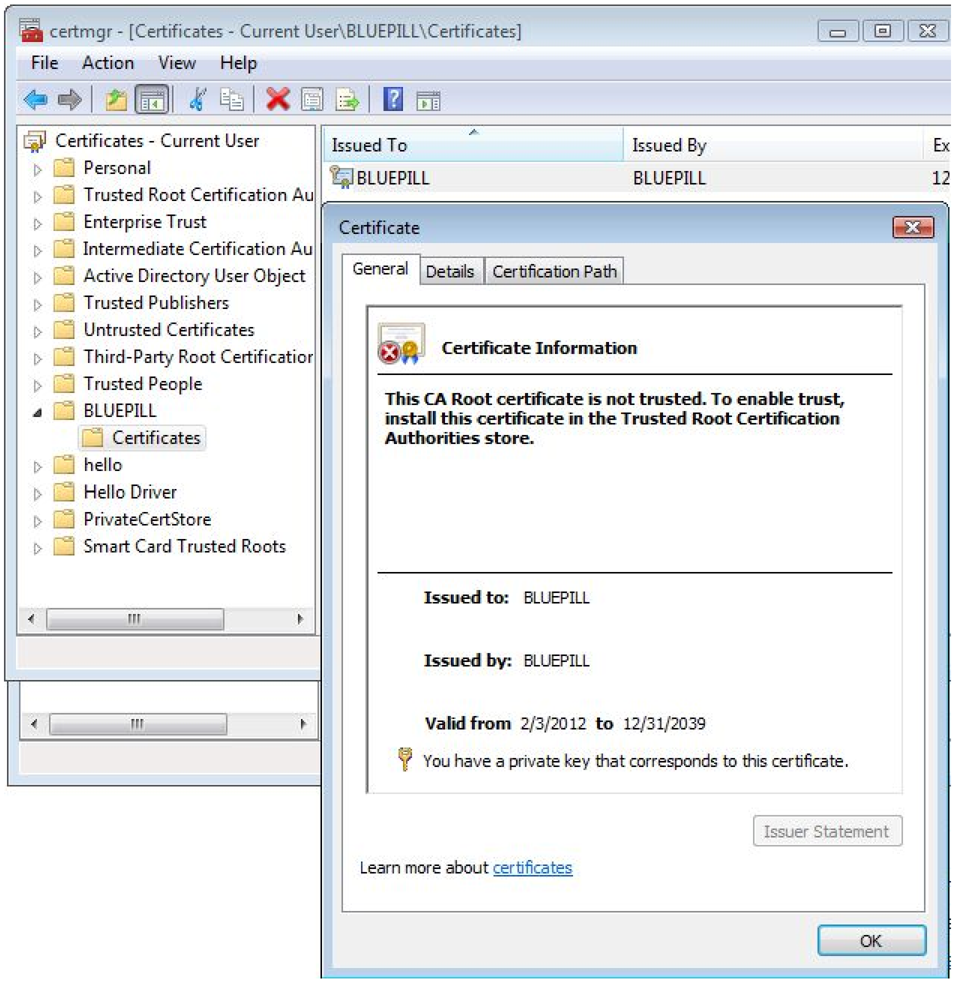
```
c:\BluePill\bin\amd64>makecert -$ individual -r -pe -ss "BLUEPILL" -n CN=BLUEPILL BLUEPILL.cer
Succeeded

c:\BluePill\bin\amd64>
```

Figure 95. Test Certificate Creation, `makecert` Command

This passes makecert the following arguments:

-$	The signing authority of the certificate <individual:commercial>
-r	Creates a self-signed certificate with the same issuer and subject name
-pe	Marks certificate's private key as exportable to the signing machine
-ss	The certificate store name that stores the test certificate, "BLUEPILL"
-n	The certificate subject's name, "BLUEPILL"
BLUEPILL.cer	The certificate's output name

2. Verify that this was successful by referencing the certificate manager. To do this, type `certmgr.msc` in the command window. You can then click on the BLUEPILL folder > Certificates to observe the BluePill certificate which was just created. If you open the certificate by clicking it, you will note that the certificate is not yet trusted (Figure 96).



Issued To	Issued By	Ex
BLUEPILL	BLUEPILL	12

Certificate Information

This CA Root certificate is not trusted. To enable trust, install this certificate in the Trusted Root Certification Authorities store.

Issued to: BLUEPILL

Issued by: BLUEPILL

Valid from 2/3/2012 **to** 12/31/2039

You have a private key that corresponds to this certificate.

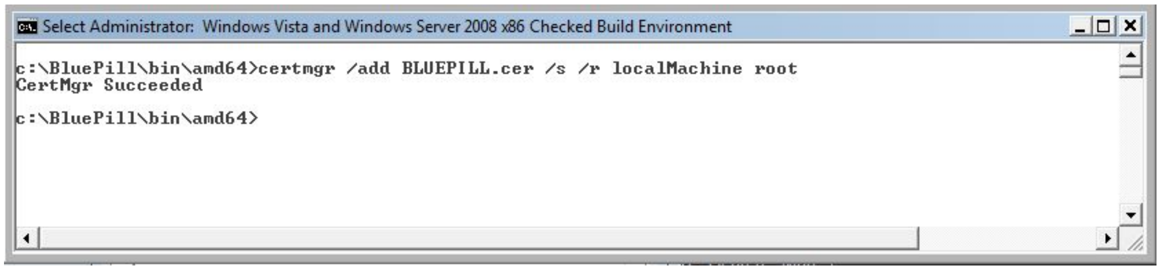
Learn more about certificates

Figure 96. Certificate Manager

F-4. Install the Test Certificate in the Trusted Root Certification Store

Enter the following command to install the test certificate in the Trusted Root Certification Authorities Certificate Store (Figure 97).

```
certmgr /add BLUEPILL.cer /s /r localMachine root
```


Select Administrator: Windows Vista and Windows Server 2008 x86 Checked Build Environment

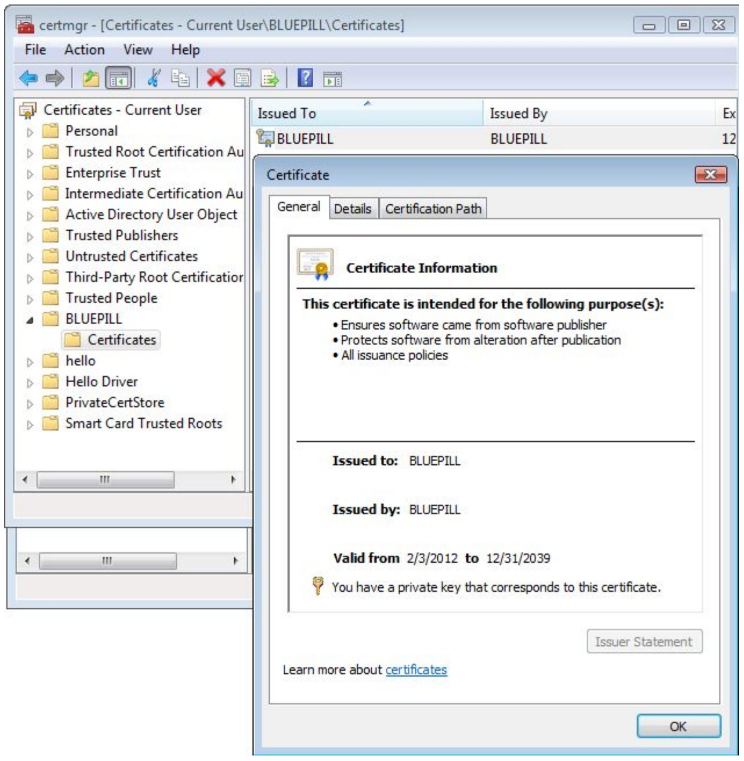
```
c:\BluePill\bin\amd64>certmgr /add BLUEPILL.cer /s /r localMachine root
CertMgr Succeeded

c:\BluePill\bin\amd64>
```

Figure 97. Add Test Cert to Trusted Root Store

This passes certmgr the following arguments:

/add	Adds the certificate to the specified root store; note that the file name containing the certificate is BLUEPILL.cer
/s	Specified that the certificate is to be added to a system store
/r	Specifies the system store location <currentUser:localMachine> as root

Note that, if you refresh the `certmgr.msc,` the certificate is now trusted since you now have a trusted key that corresponds to this certificate (Figure 98).


certmgr - [Certificates - Current User\BLUEPILL\Certificates]

Certificate Information

This certificate is intended for the following purpose(s):
- Ensures software came from software publisher
- Protects software from alteration after publication
- All issuance policies

Issued to: BLUEPILL

Issued by: BLUEPILL

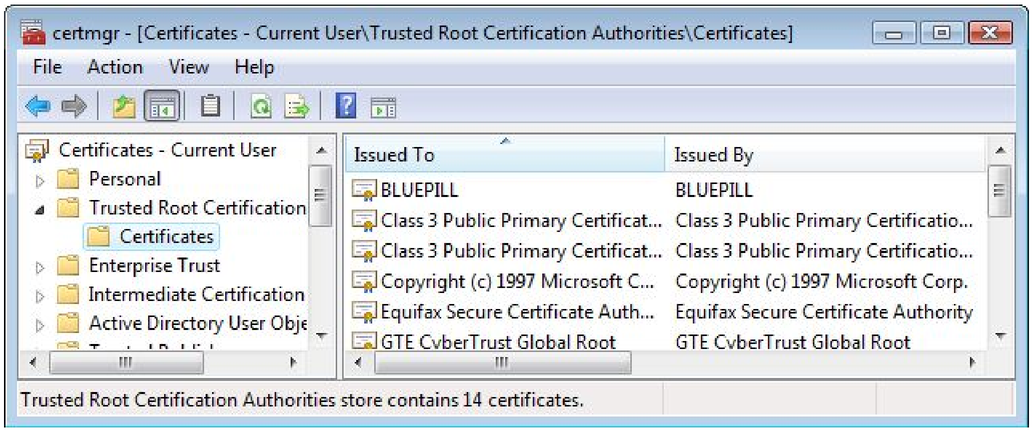
Valid from 2/3/2012 to 12/31/2039

You have a private key that corresponds to this certificate.

Learn more about certificates

Figure 98. Certificate Manager

Also, if you check the Trusted Root Certification Authority folder, BLUEPILL is shown as one of the certificates (Figure 99).


certmgr - [Certificates - Current User\Trusted Root Certification Authorities\Certificates]
File
Action
View
Help
Certificates - Current User
Personal
Trusted Root Certification
Certificates
Enterprise Trust
Intermediate Certification
Active Directory User Obje

Issued To	Issued By
BLUEPILL	BLUEPILL
Class 3 Public Primary Certificat...	Class 3 Public Primary Certificatio...
Class 3 Public Primary Certificat...	Class 3 Public Primary Certificatio...
Copyright (c) 1997 Microsoft C...	Copyright (c) 1997 Microsoft Corp.
Equifax Secure Certificate Auth...	Equifax Secure Certificate Authority
GTE CyberTrust Global Root	GTE CyberTrust Global Root

Trusted Root Certification Authorities store contains 14 certificates.

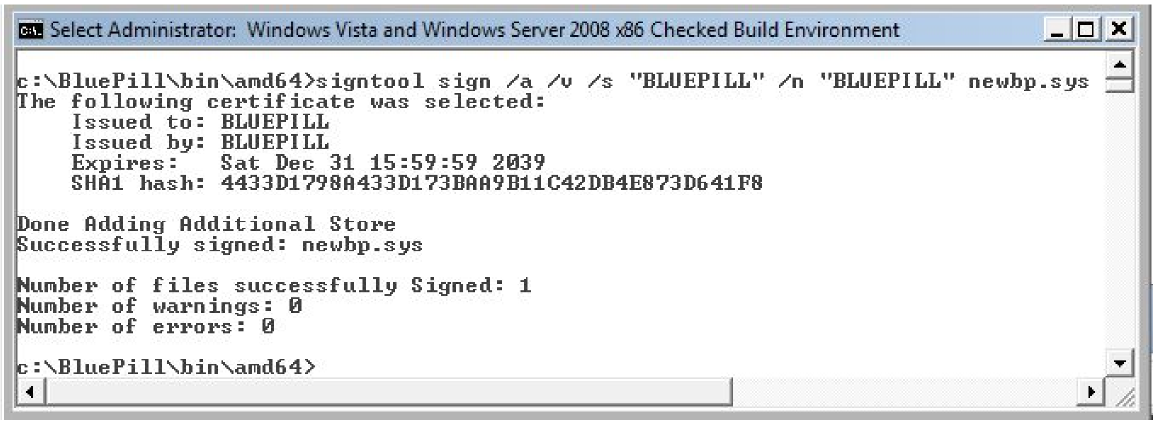
Figure 99. Trusted Root Certification Authority Folder

F-5. Embedded Sign the BluePill newbp.sys Driver

1. Navigate to the folder which contains the newbp.sys driver or prepend newbp.sys with the absolute path to the .sys file.
2. Enter the following command to use the certificate to sign the BluePill driver (Figure 100): `signtool sign /a /v /s “BLUEPILL” /n “BLUEPILL” newbp.sys`

   This passes certmgr the following arguments:

/a	selects the best cert automatically (in case multiple certs were created due to input errors earlier in the process)
/v	Print verbose success and status messages
/s	Specifies the store to open when searching for the certificate


Select Administrator: Windows Vista and Windows Server 2008 x86 Checked Build Environment

```
c:\BluePill\bin\amd64>signtool sign /a /v /s "BLUEPILL" /n "BLUEPILL" newbp.sys
The following certificate was selected:
    Issued to: BLUEPILL
    Issued by: BLUEPILL
    Expires:   Sat Dec 31 15:59:59 2039
    SHA1 hash: 4433D1798A433D173BAA9B11C42DB4E873D641F8

Done Adding Additional Store
Successfully signed: newbp.sys

Number of files successfully Signed: 1
Number of warnings: 0
Number of errors: 0

c:\BluePill\bin\amd64>
```

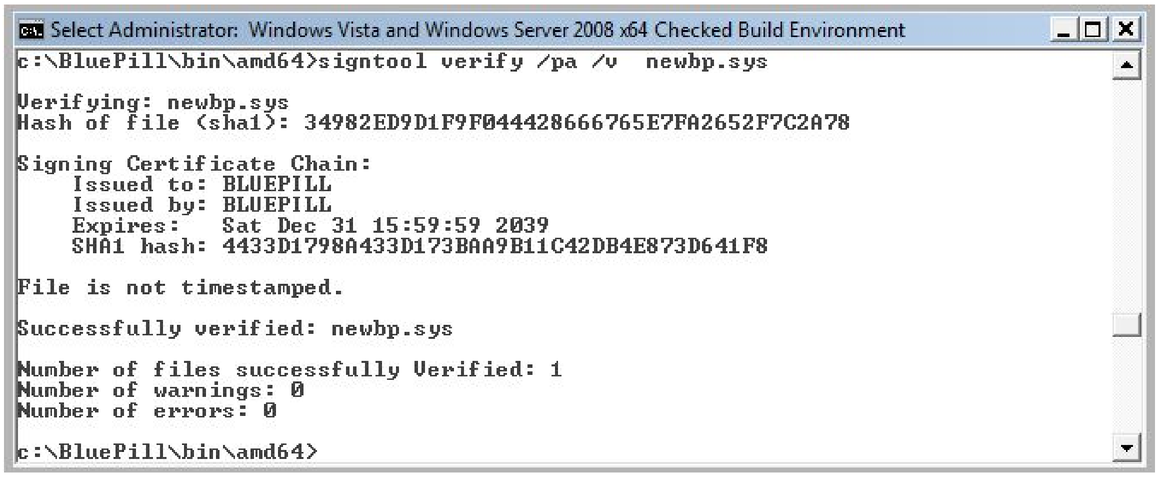
Figure 100. Sign the BluePill Driver

Finally, verify that it is correctly signed using the following command:

```
signtool verify /pa /v newbp.sys
```

This passes signtool the following arguments:

/pa	Use the default authenticode verification policy
/v	Print verbose success and status messages


Select Administrator: Windows Vista and Windows Server 2008 x64 Checked Build Environment

```
c:\BluePill\bin\amd64>signtool verify /pa /v  newbp.sys

Verifying: newbp.sys
Hash of file (sha1): 34982ED9D1F9F044428666765E7FA2652F7C2A78

Signing Certificate Chain:
    Issued to: BLUEPILL
    Issued by: BLUEPILL
    Expires:   Sat Dec 31 15:59:59 2039
    SHA1 hash: 4433D1798A433D173BAA9B11C42DB4E873D641F8

File is not timestamped.

Successfully verified: newbp.sys

Number of files successfully Verified: 1
Number of warnings: 0
Number of errors: 0

c:\BluePill\bin\amd64>
```

Figure 101. Signtool Verification

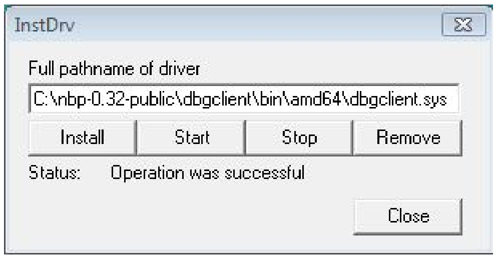
3. Repeat this embedded signing process for dbgclient.sys. Use the following command:

   ```
   signtool sign /a /v /s “BLUEPILL” /n “BLUEPILL”
   dbgclient.sys
   ```

F-6. Start the BluePill Driver

To start the drivers, use InstDrv.exe. To run, simply download InstDrv.exe to your desktop. Right click and select “Open as Administrator”.

1. Start the dbgclient.sys driver by entering the entire path name to the driver and the driver name. Click Install then Start (Figure 102).



InstDrv

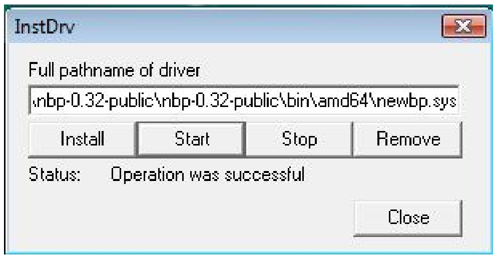
Full pathname of driver

C:\nbp-0.32-public\dbgclient\bin\amd64\dbgclient.sys

Status: Operation was successful

Figure 102. Installing the BluePill `dbgclient.sys` Driver

2. Start the newbp.sys driver by entering the entire path name to the driver and the driver name. Click Install then Start (Figure 104).



InstDrv

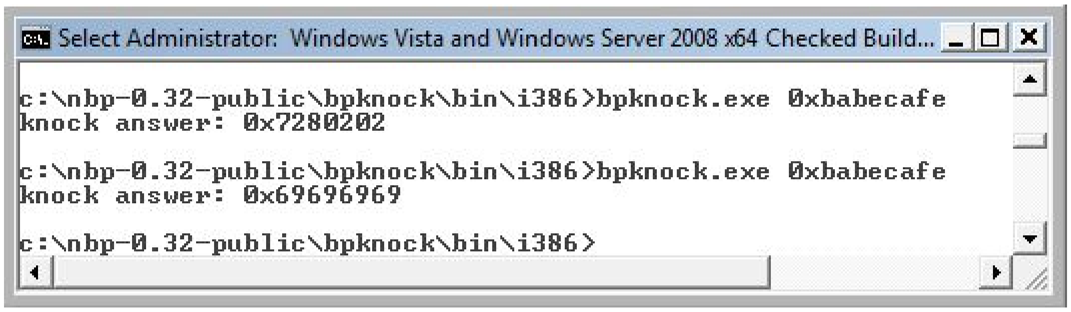
Full pathname of driver

\nbp-0.32-public\nbp-0.32-public\bin\amd64\newbp.sys

Status: Operation was successful

Figure 103. Installing the BluePill `newbp.sys` Driver

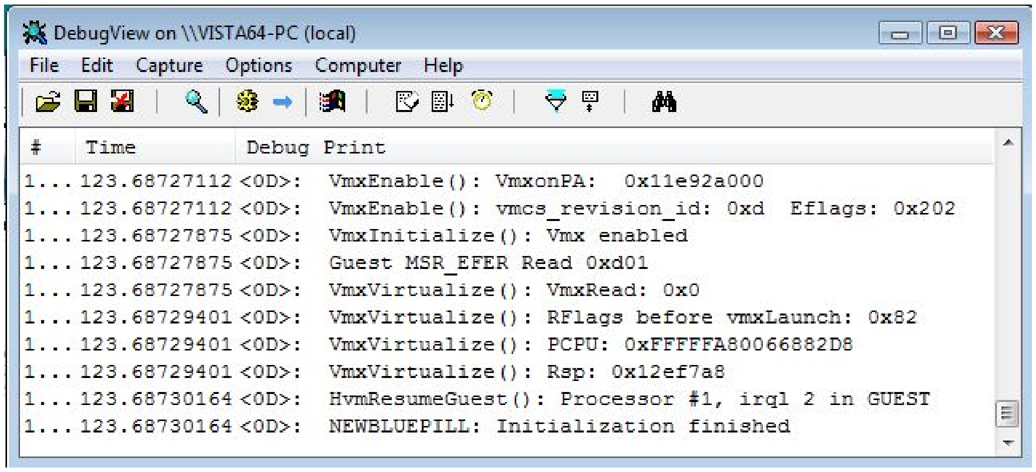
BluePill is now running, and the formerly native OS is running in within a virtualized environment. To verify this, use the bpknock program by simply executing the command `bpknock 0xbabecafe` (see Figure 105).


Select Administrator: Windows Vista and Windows Server 2008 x64 Checked Build...

```
c:\nbp-0.32-public\bpknock\bin\i386>bpknock.exe 0xbabecafe
knock answer: 0x7280202

c:\nbp-0.32-public\bpknock\bin\i386>bpknock.exe 0xbabecafe
knock answer: 0x69696969

c:\nbp-0.32-public\bpknock\bin\i386>
```

Figure 104. `bpknock.exe` Before and After Installation of BluePill

A tool such as DebugView which captures debug statements can also be used to capture messages sent to the debugger upon execution (see Figure 106). Note that you must have DebugView running and capturing before BluePill is installed. If you encounter errors during BluePill installation, DebugView provides insight into debug statements which may be helpful. Note: A common error is forgetting to enable virtualization within the BIOS before BluePill installation.



```
#    Time              Debug Print
1... 123.68727112 <0D>:  VmxEnable(): VmxonPA:  0x11e92a000
1... 123.68727112 <0D>:  VmxEnable(): vmcs_revision_id: 0xd  Eflags: 0x202
1... 123.68727875 <0D>:  VmxInitialize(): Vmx enabled
1... 123.68727875 <0D>:  Guest MSR_EFER Read 0xd01
1... 123.68727875 <0D>:  VmxVirtualize(): VmxRead: 0x0
1... 123.68729401 <0D>:  VmxVirtualize(): RFlags before vmxLaunch: 0x82
1... 123.68729401 <0D>:  VmxVirtualize(): PCPU: 0xFFFFFA80066882D8
1... 123.68729401 <0D>:  VmxVirtualize(): Rsp: 0x12ef7a8
1... 123.68730164 <0D>:  HvmResumeGuest(): Processor #1, irql 2 in GUEST
1... 123.68730164 <0D>:  NEWBLUEPILL: Initialization finished
```

Figure 105. DebugView Showing Successful BluePill Installation

Appendix G. ESX Installation

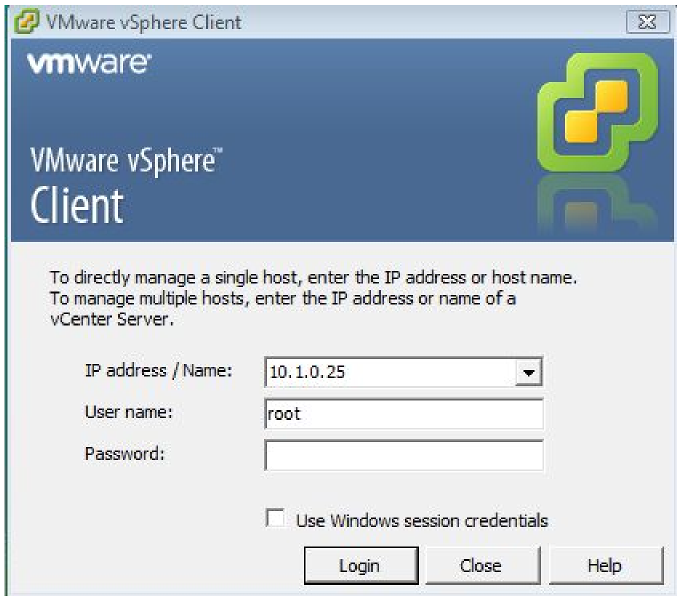
The following provides step-by-step instructions for how to install and configure ESXi 5.0.0 (VMKernel Release Build 623860) for nested virtualization. ESXi creates a thin hypervisor through use of a client/server model where management tools reside within the client in an application called vSphere. The vSphere Installation and Setup guide provided by VMware is located here: http://pubs.vmware.com/vsphere-50/topic/com.vmware.ICbase/PDF/vsphere-esxi-vcenter-server-50-installation-setup-guide.pdf.

G-1. Download VMware ESXi 5.0.0 on Host Machine

1. ESXi is available from https://www.vmware.com/tryvmware. Download the ESXi 5.0 iso and the vSphere client and copy each to a CD.
2. Insert the ESXi CD into the computer which will serve as the host and reboot the machine to install from the CD. Note that you may need to change you BIOS settings
3. On a separate machine which resides on the same network, install the vSphere client.

G-2. Configure the ESXi Host

1. Ensure that the host is running and that ESXi has been installed.
2. Log into the host by starting the vSphere client (Figure 106).



To directly manage a single host, enter the IP address or host name.
To manage multiple hosts, enter the IP address or name of a vCenter Server.

IP address / Name: 10.1.0.25
User name: root
Password:

Use Windows session credentials

Figure 106. Log Into the vSphere Client

3. Enter the license key by doing the following (Figure 107):

    a. Select the 'Configuration' tab

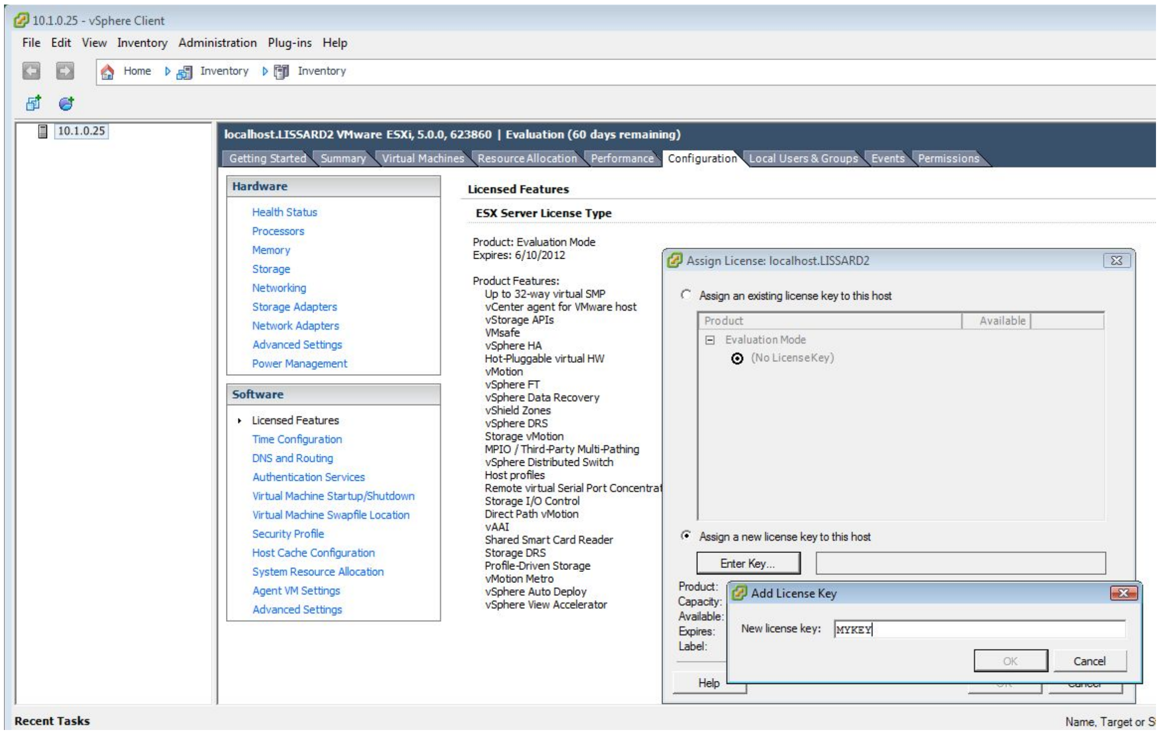
    b. Under 'Software' select 'Licensed Features'

    c. Click on the 'Edit' link at the top right hand corner of the window

    d. Select 'Assign a new license key to this host'

    e. Press the 'Enter Key' button and enter in the license key provided when you downloaded the ISO file

    f. Click 'OK' then 'OK' to save the changes



localhost.LISSARD2 VMware ESXi, 5.0.0, 623860 | Evaluation (60 days remaining)

Licensed Features

ESX Server License Type

Product: Evaluation Mode
Expires: 6/10/2012

Product Features:
Up to 32-way virtual SMP
vCenter agent for VMware host
vStorage APIs
VMsafe
vSphere HA
Hot-Pluggable virtual HW
vMotion
vSphere FT
vSphere Data Recovery
vShield Zones
vSphere DRS
Storage vMotion
MPIO / Third-Party Multi-Pathing
vSphere Distributed Switch
Host profiles
Remote virtual Serial Port Concentrat
Storage I/O Control
Direct Path vMotion
vAAI
Shared Smart Card Reader
Storage DRS
Profile-Driven Storage
vMotion Metro
vSphere Auto Deploy
vSphere View Accelerator

Assign License: localhost.LISSARD2

Assign an existing license key to this host

Product	Available
Evaluation Mode	
(No License Key)	

[✓ Assign a new license key to this host]

Product:
Capacity:
Available:
Expires:
Label:

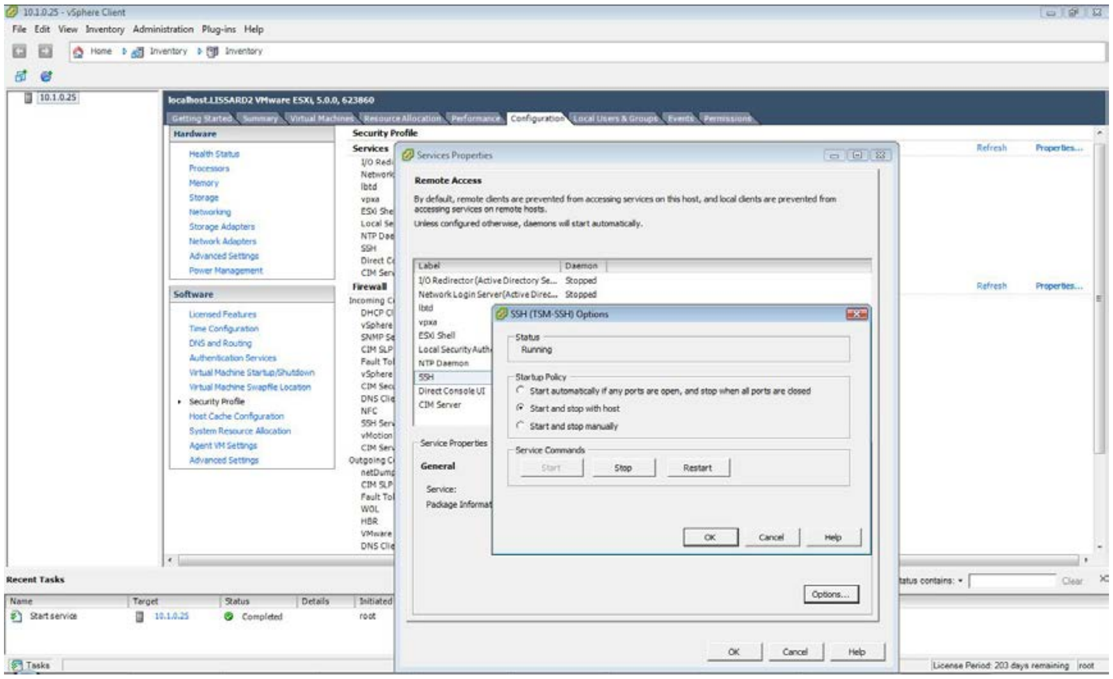
Add License Key

New license key: MYKEY

Figure 107. Enter the vSphere License Key

4. Enable 64-bit nested virtualization by doing the following:

   a. Enable SSH on the host machine by clicking on the Configuration tab, Under “Software” select “Security Profile”, click “Properties” in the far right corner of the Services area, click on SSH, and click the “Options” button. Click “Start” to start SSH and select the option to “Start and stop with host”, then click “Ok” (Figure 108).



localhost.LISSARD2 VMware ESXi, 5.0.0, 623860

Services Properties

Remote Access

By default, remote clients are prevented from accessing services on this host, and local clients are prevented from accessing services on remote hosts.

Unless configured otherwise, daemons will start automatically.

Label	Daemon
I/O Redirector (Active Directory Se...	Stopped
Network Login Server(Active Direc...	Stopped
lbtd	
vpxa	
ESXi Shell	
Local Security Auth	
NTP Daemon	
SSH	
Direct Console UI	
CIM Server	

SSH (TSM-SSH) Options

Status: Running

Startup Policy:
- Start automatically if any ports are open, and stop when all ports are closed
- [✓ Start and stop with host]
- Start and stop manually

Service Commands: Start, Stop, Restart

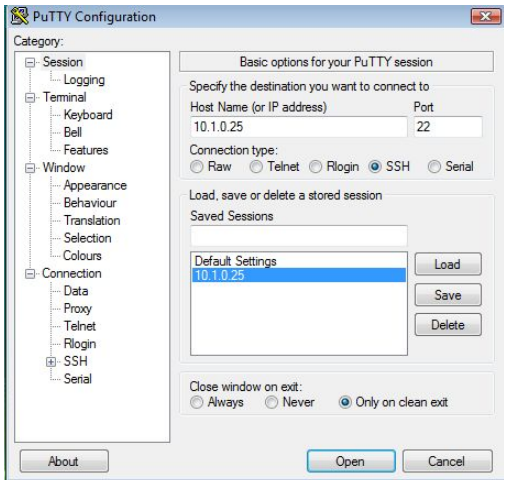
Recent Tasks

Name	Target	Status	Details	Initiated
Start service	10.1.0.25	Completed		root

Figure 108. Enable SSH on the host machine

b. Download PUTTY.exe from http://www.chiark.greenend.org.uk/~sgtatham/putty/download.html. Install on the client machine.

c. SSH into the host machine and add the following line to the /etc/vmware/config file to enable virtualized hardware-assisted virtualization (vhv) (Figures 109-111): `vhv.allow = “TRUE”`



PuTTY Configuration

Basic options for your PuTTY session

Specify the destination you want to connect to

Host Name (or IP address): 10.1.0.25

Port: 22

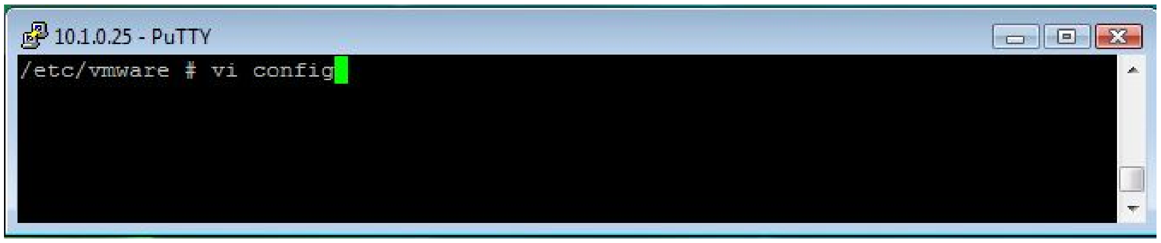
Connection type: Raw Telnet Rlogin [✓ SSH] Serial

Load, save or delete a stored session

Saved Sessions:
- Default Settings
- 10.1.0.25

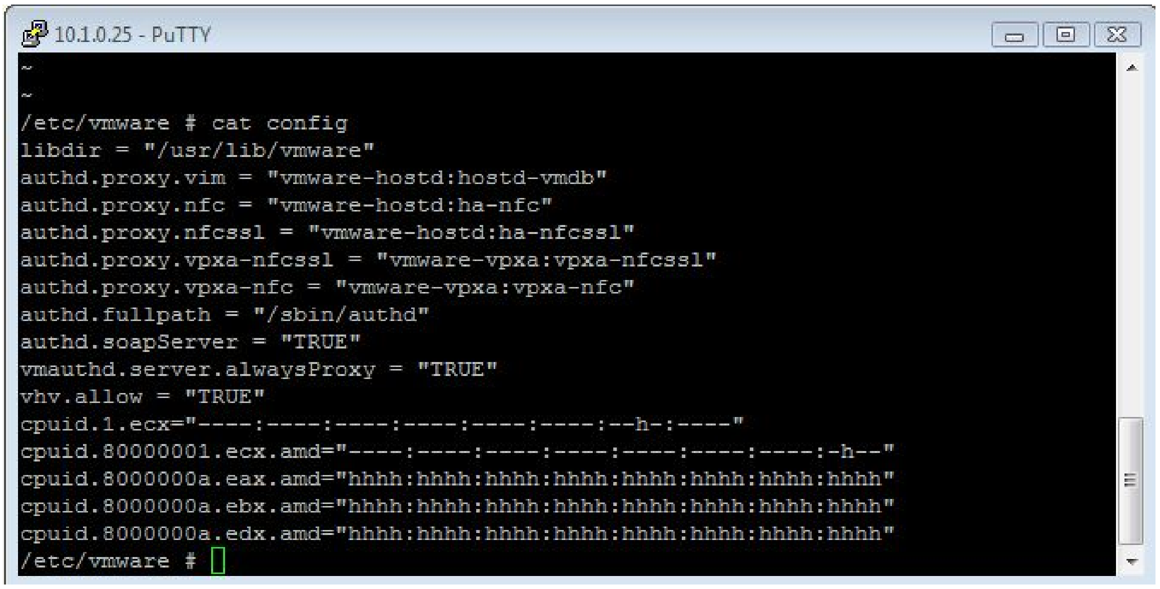
Close window on exit: Always Never [✓ Only on clean exit]

Figure 109. SSH into the Host Machine



```
/etc/vmware # vi config
```

Figure 110. Open the /etc/vmware/config File for Editing



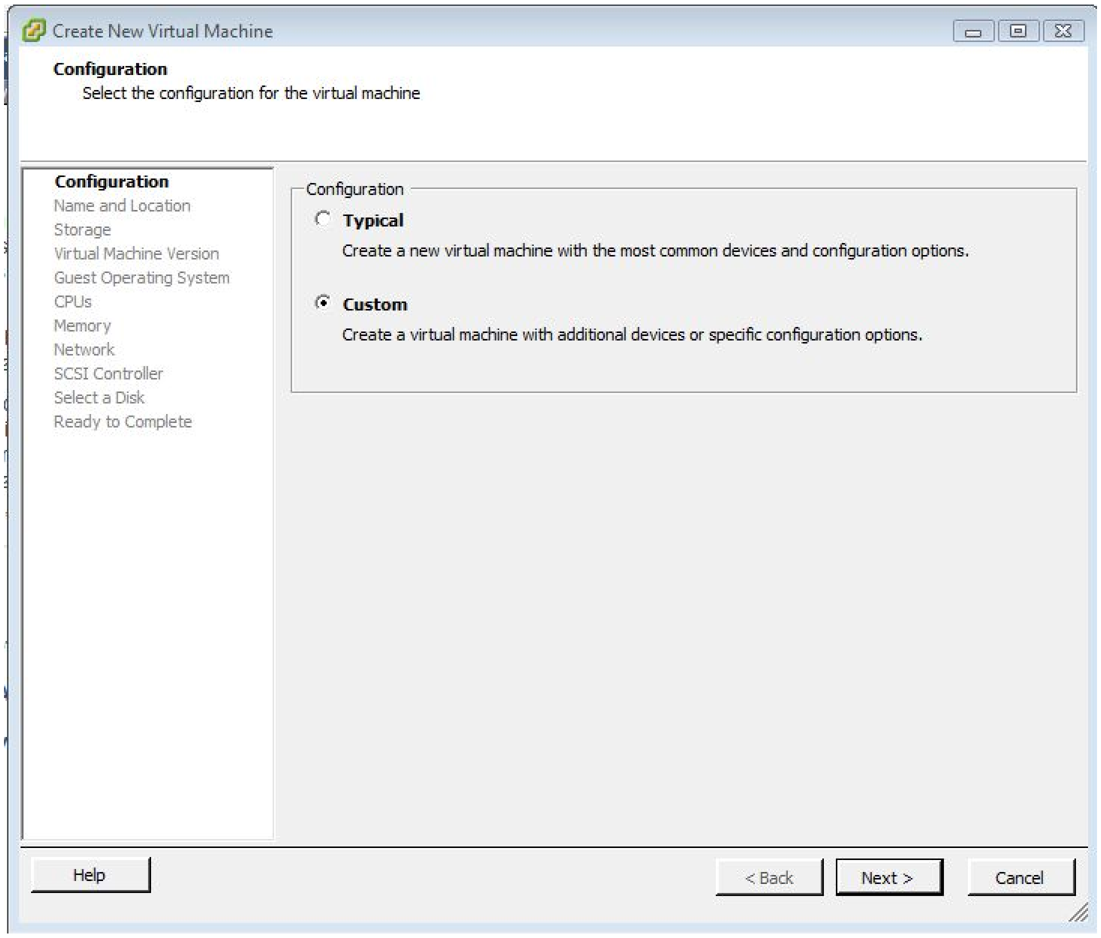
```
~
~
/etc/vmware # cat config
libdir = "/usr/lib/vmware"
authd.proxy.vim = "vmware-hostd:hostd-vmdb"
authd.proxy.nfc = "vmware-hostd:ha-nfc"
authd.proxy.nfcssl = "vmware-hostd:ha-nfcssl"
authd.proxy.vpxa-nfcssl = "vmware-vpxa:vpxa-nfcssl"
authd.proxy.vpxa-nfc = "vmware-vpxa:vpxa-nfc"
authd.fullpath = "/sbin/authd"
authd.soapServer = "TRUE"
vmauthd.server.alwaysProxy = "TRUE"
vhv.allow = "TRUE"
cpuid.1.ecx="----:----:----:----:----:----:--h-:----"
cpuid.80000001.ecx.amd="----:----:----:----:----:----:----:-h--"
cpuid.8000000a.eax.amd="hhhh:hhhh:hhhh:hhhh:hhhh:hhhh:hhhh:hhhh"
cpuid.8000000a.ebx.amd="hhhh:hhhh:hhhh:hhhh:hhhh:hhhh:hhhh:hhhh"
cpuid.8000000a.edx.amd="hhhh:hhhh:hhhh:hhhh:hhhh:hhhh:hhhh:hhhh"
/etc/vmware #
```

Figure 111. Add `vhv.allow = “TRUE”` to the config file

5. Restart the ESXi host.

G-3. Create the Virtual Machine

1. Within vSphere Client, click “File>New>Virtual Machine
2. Select Custom and click “Next” (Figure 112).


Create New Virtual Machine

Configuration
Select the configuration for the virtual machine

Configuration

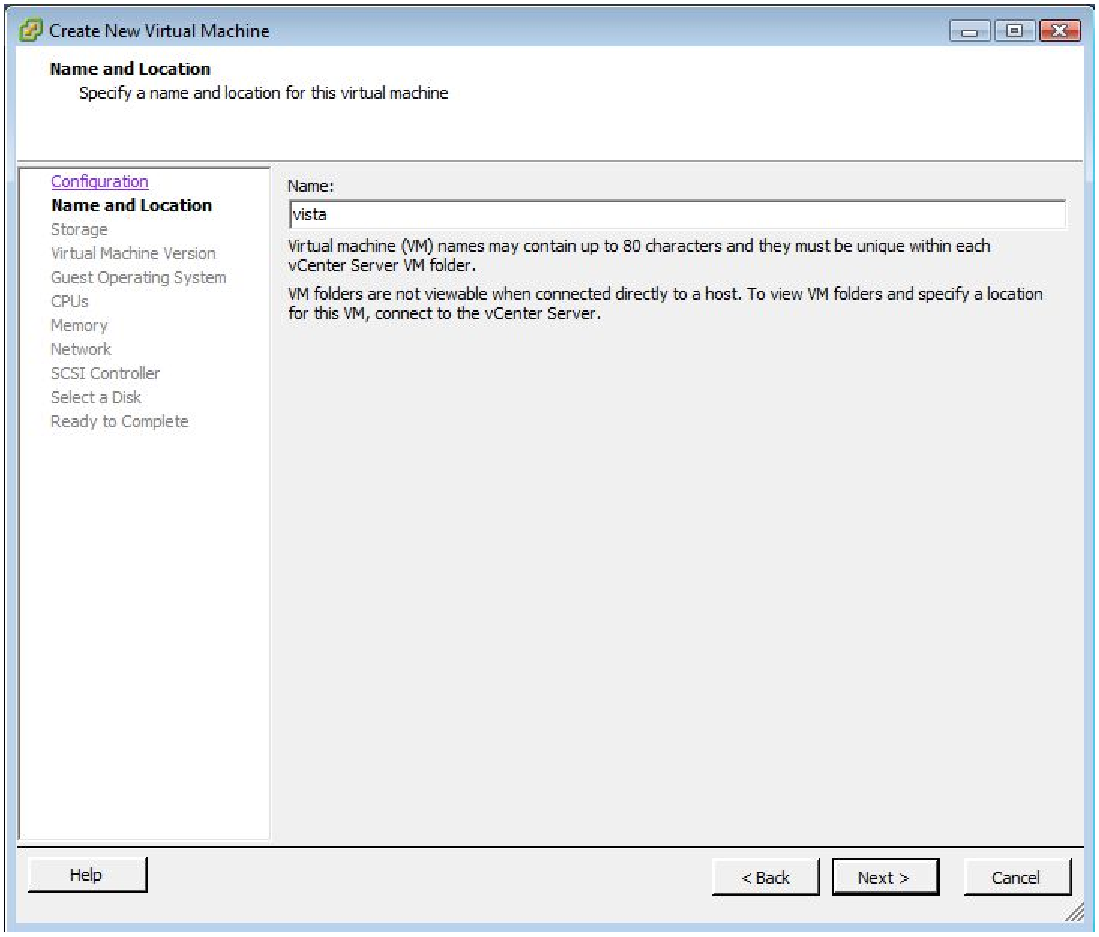
Typical [✓ Custom]

Typical
Create a new virtual machine with the most common devices and configuration options.

Custom
Create a virtual machine with additional devices or specific configuration options.

Figure 112. Select Custom Configuration

3. Enter the name of the VM and click “Next” (Figure 113).



Name and Location

Specify a name and location for this virtual machine

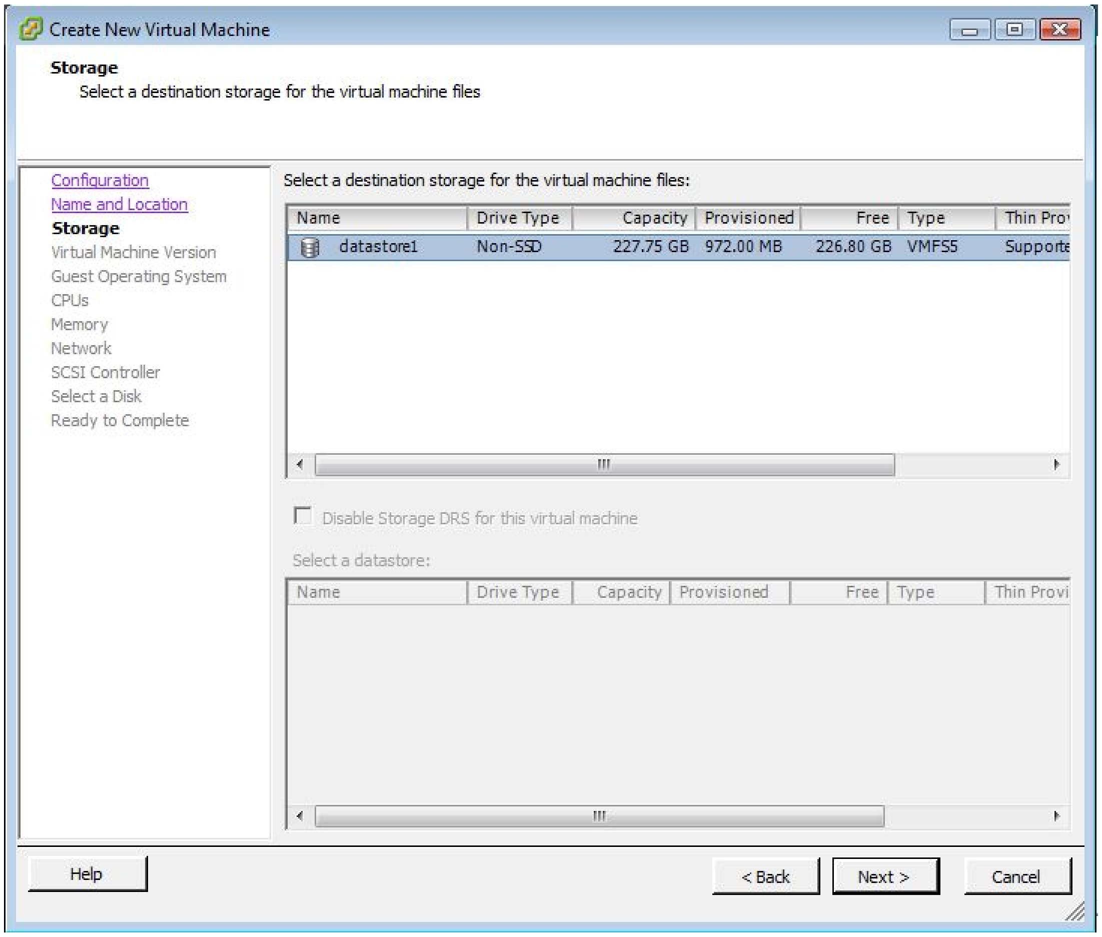
Name: vista

Virtual machine (VM) names may contain up to 80 characters and they must be unique within each vCenter Server VM folder.

VM folders are not viewable when connected directly to a host. To view VM folders and specify a location for this VM, connect to the vCenter Server.

Figure 113. Enter the Name of the VM

4. For Storage, leave the default settings and click "Next" (Figure 114).



Create New Virtual Machine

Storage

Select a destination storage for the virtual machine files

Select a destination storage for the virtual machine files:

Name	Drive Type	Capacity	Provisioned	Free	Type	Thin Prov
datastore1	Non-SSD	227.75 GB	972.00 MB	226.80 GB	VMFS5	Supporte

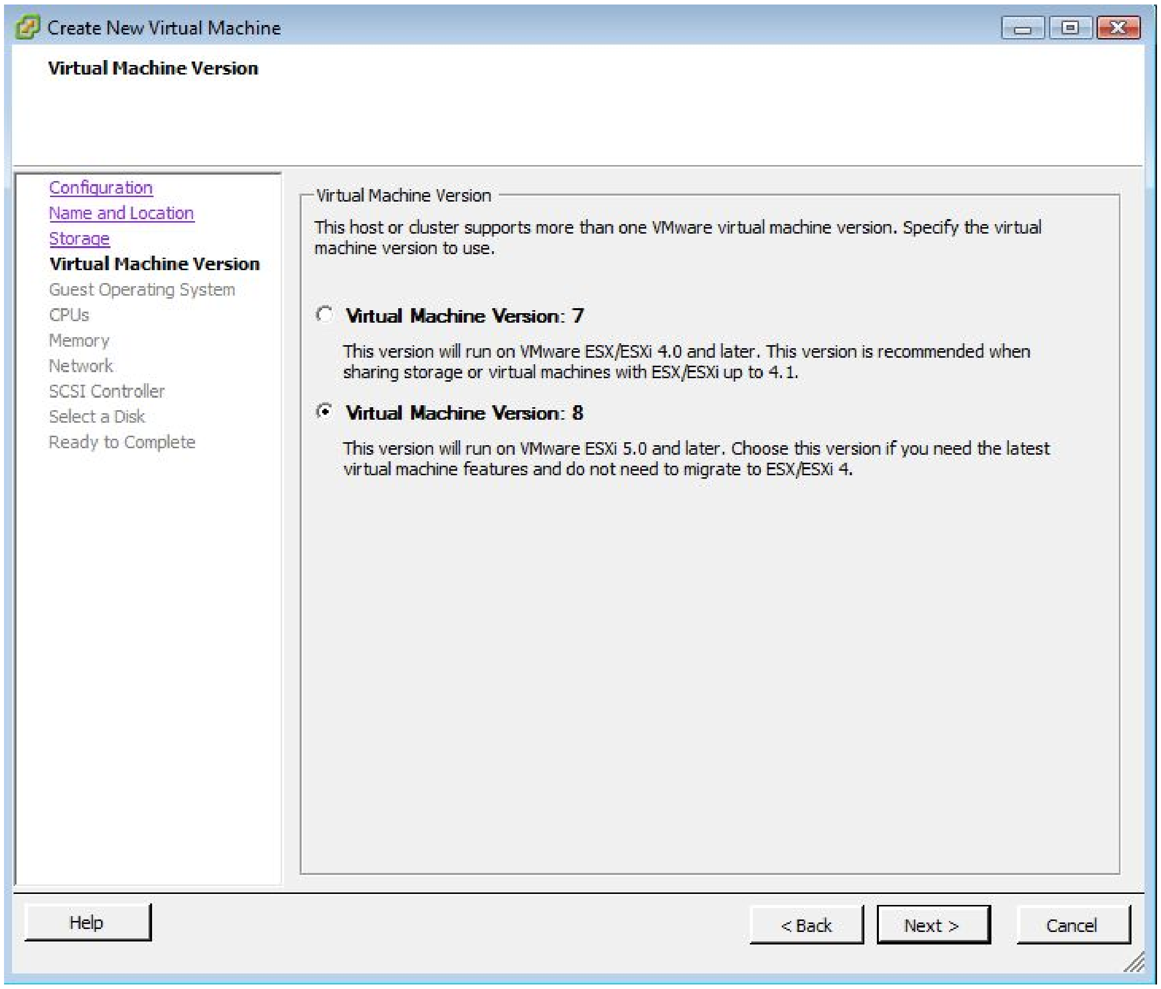
☐ Disable Storage DRS for this virtual machine

Select a datastore:

Name	Drive Type	Capacity	Provisioned	Free	Type	Thin Provi

Figure 114. Storage Settings

5. For Virtual Machine Version, select Virtual Machine Version 8 and click "Next" (Figure 115).



Virtual Machine Version

This host or cluster supports more than one VMware virtual machine version. Specify the virtual machine version to use.

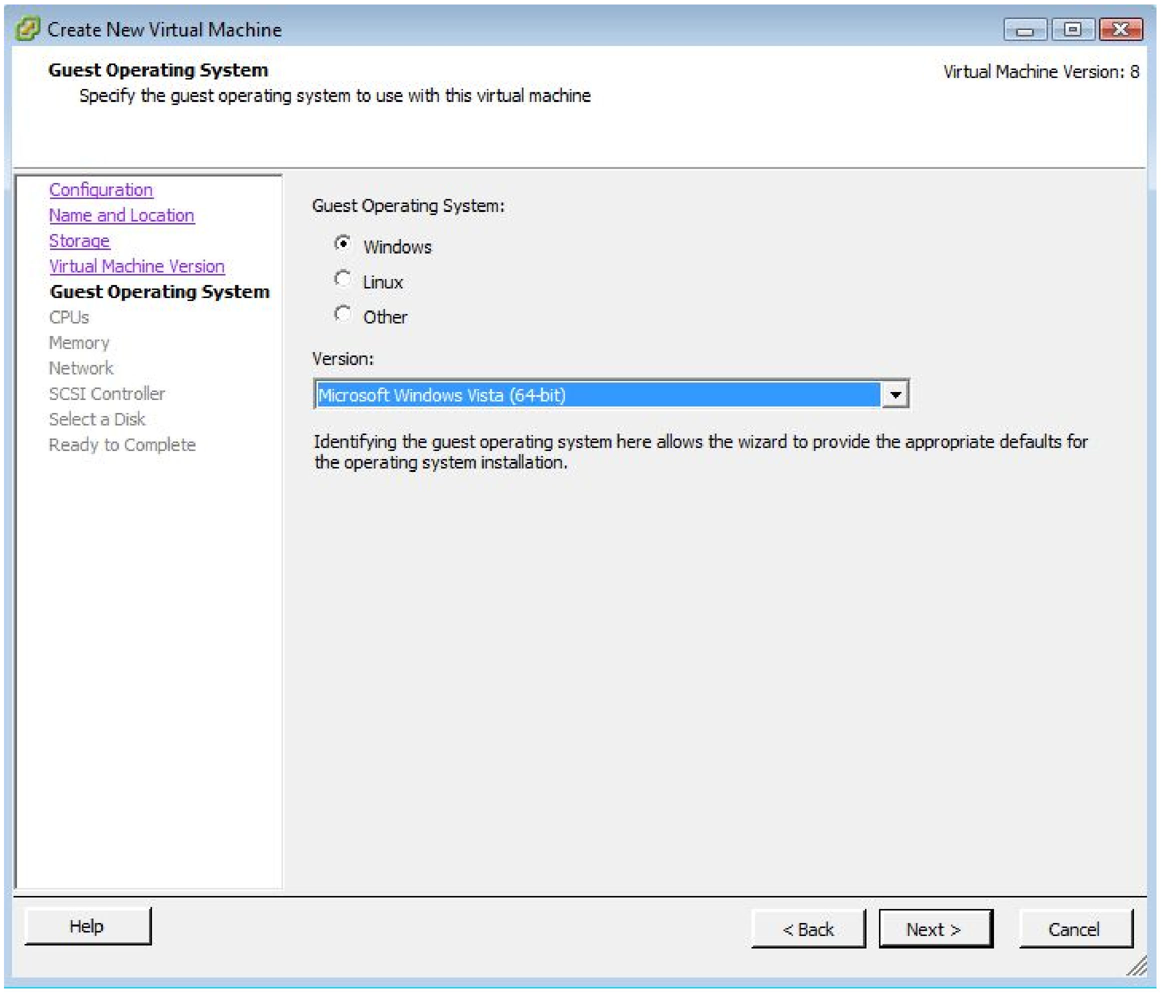
Virtual Machine Version: 7 [✓ Virtual Machine Version: 8]

This version will run on VMware ESX/ESXi 4.0 and later. This version is recommended when sharing storage or virtual machines with ESX/ESXi up to 4.1.

This version will run on VMware ESXi 5.0 and later. Choose this version if you need the latest virtual machine features and do not need to migrate to ESX/ESXi 4.

Figure 115. Select Virtual Machine Version

6. For Guest Operating System, chose the appropriate OS and click “Next” (Figure 116).


Create New Virtual Machine

Guest Operating System
Specify the guest operating system to use with this virtual machine

Virtual Machine Version: 8

Guest Operating System:

[✓ Windows]
Linux
Other

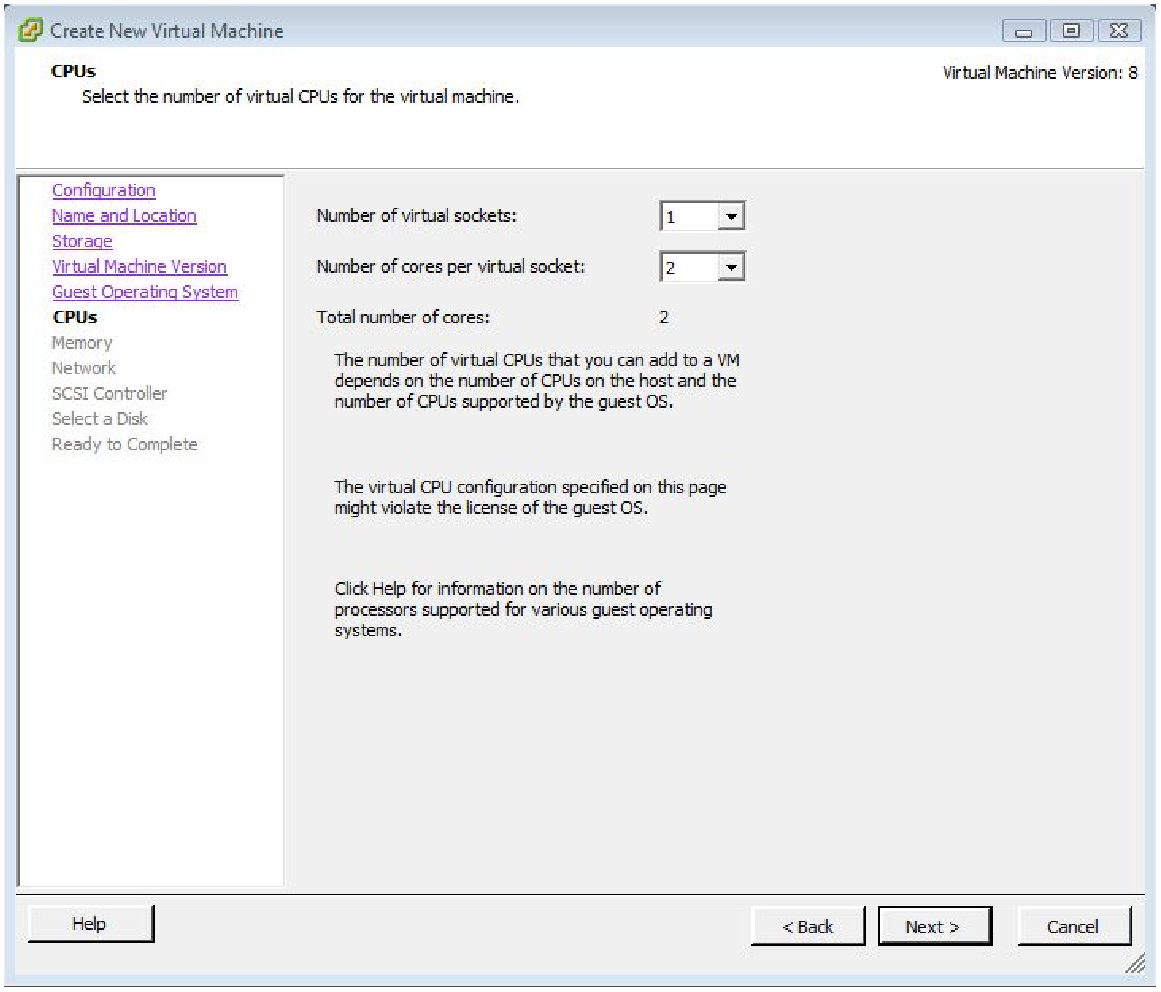
Version:

Microsoft Windows Vista (64-bit)

Identifying the guest operating system here allows the wizard to provide the appropriate defaults for the operating system installation.

Figure 116. Select Guest Operating System

7. For CPUs, select at least 1 virtual socket with 2 cores per virtual socket and click "Next" (Figure 117).



CPUs
Select the number of virtual CPUs for the virtual machine.

Virtual Machine Version: 8

Number of virtual sockets: 1
Number of cores per virtual socket: 2
Total number of cores: 2

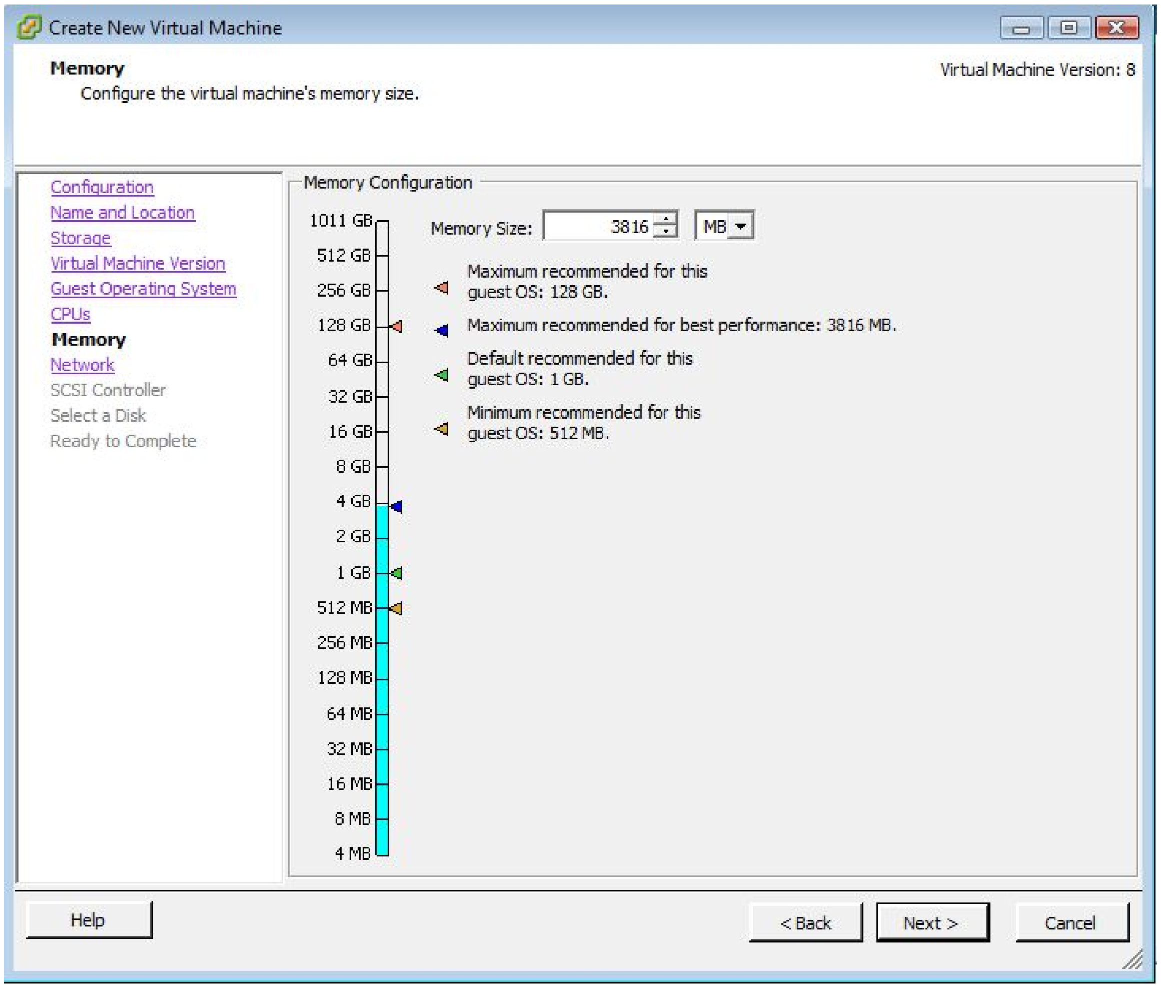
The number of virtual CPUs that you can add to a VM depends on the number of CPUs on the host and the number of CPUs supported by the guest OS.

The virtual CPU configuration specified on this page might violate the license of the guest OS.

Click Help for information on the number of processors supported for various guest operating systems.

Figure 117. CPU Settings

8. For Memory, select the maximum recommended, in this case, 3816 MB, and click "Next" (Figure 118).


Create New Virtual Machine

Memory
Configure the virtual machine's memory size.

Virtual Machine Version: 8

Memory Configuration

Memory Size: 3816 MB

Maximum recommended for this guest OS: 128 GB.

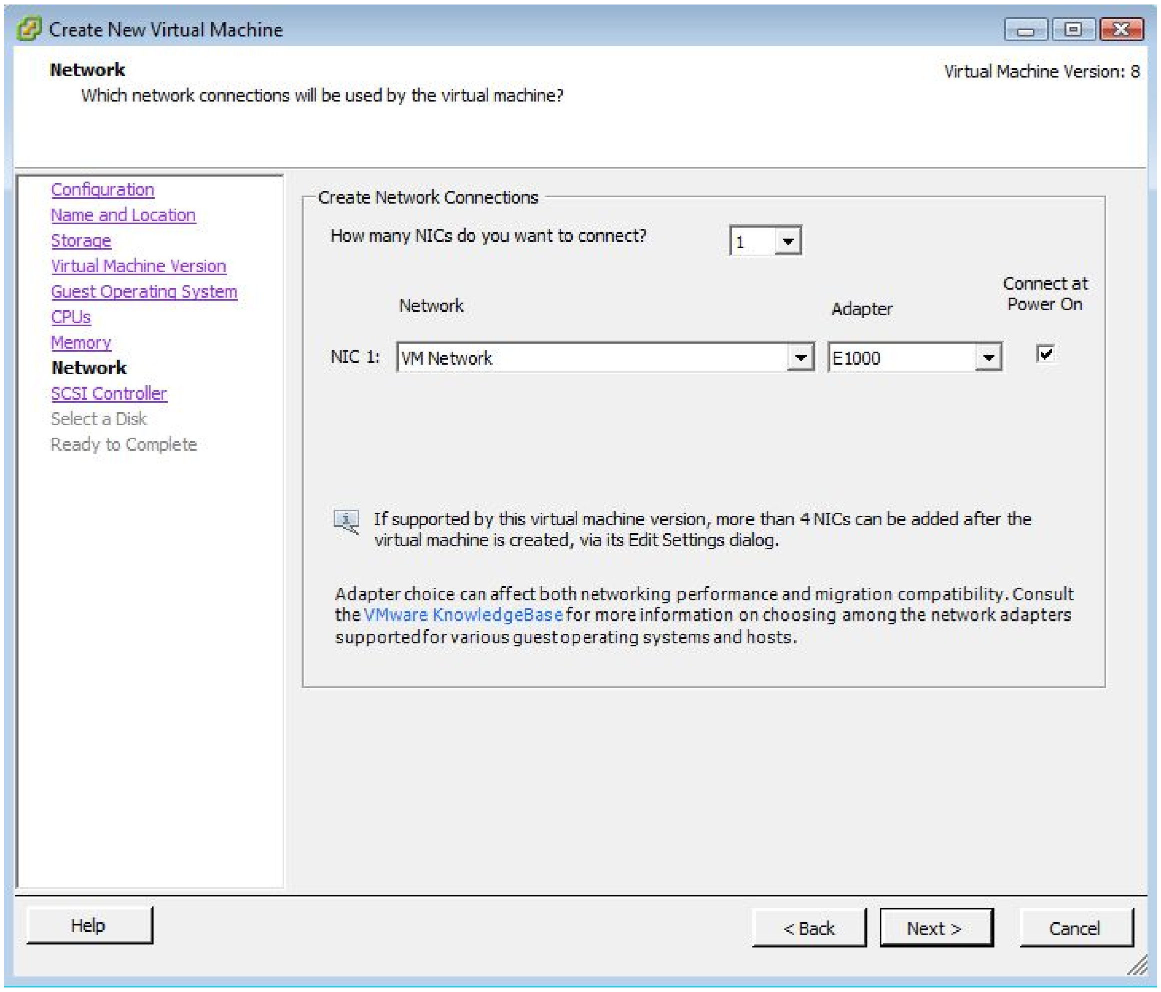
Maximum recommended for best performance: 3816 MB.

Default recommended for this guest OS: 1 GB.

Minimum recommended for this guest OS: 512 MB.

Figure 118. Memory Settings

9. For Network, leave the default settings and click Next (Figure 119).


Create New Virtual Machine

Network
Which network connections will be used by the virtual machine?

Virtual Machine Version: 8

Create Network Connections

How many NICs do you want to connect? 1

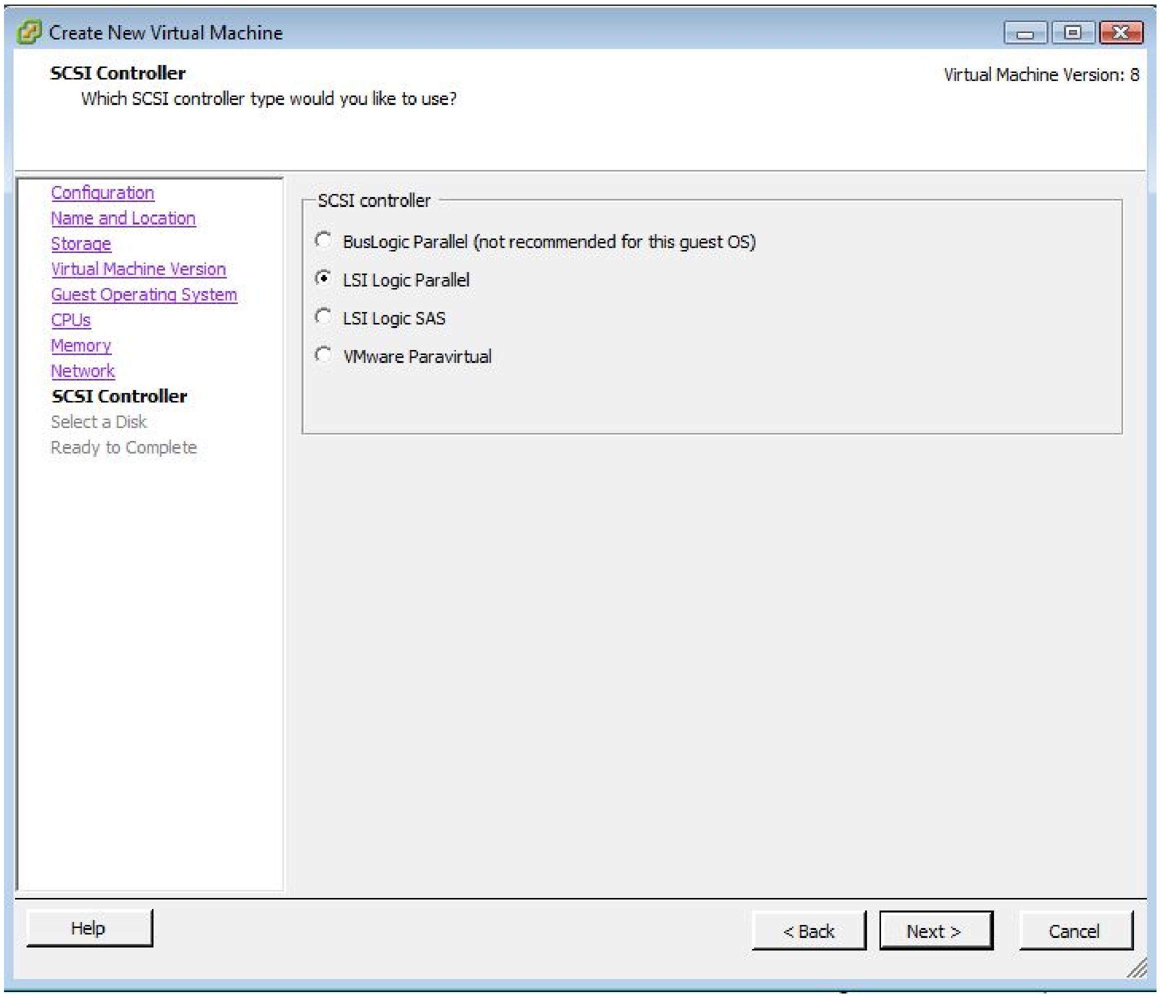
	Network	Adapter	Connect at Power On
NIC 1:	VM Network	E1000	✓

If supported by this virtual machine version, more than 4 NICs can be added after the virtual machine is created, via its Edit Settings dialog.

Adapter choice can affect both networking performance and migration compatibility. Consult the VMware KnowledgeBase for more information on choosing among the network adapters supported for various guest operating systems and hosts.

Figure 119. Network Settings

10. For SCSI Controller, leave the default settings and click “Next” (Figure 120).


Create New Virtual Machine

SCSI Controller
Which SCSI controller type would you like to use?

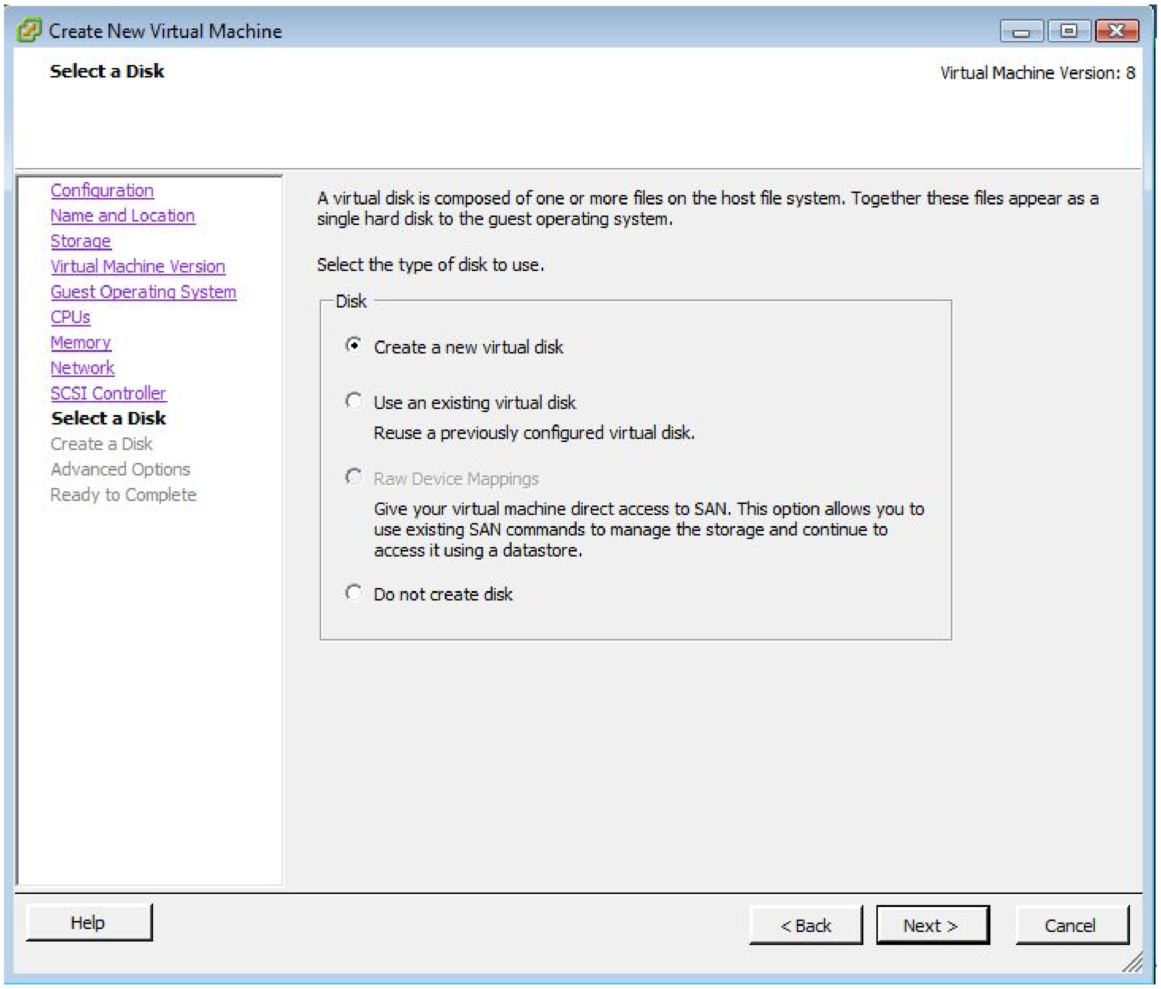
Virtual Machine Version: 8

SCSI controller

- BusLogic Parallel (not recommended for this guest OS)
- [✓ LSI Logic Parallel]
- LSI Logic SAS
- VMware Paravirtual

Figure 120. SCSI Controller Settings

11. For Select a Disk, leave the default settings and click "Next" (Figure 121).


Create New Virtual Machine

Select a Disk

Virtual Machine Version: 8

A virtual disk is composed of one or more files on the host file system. Together these files appear as a single hard disk to the guest operating system.

Select the type of disk to use.

Disk

[✓ Create a new virtual disk]

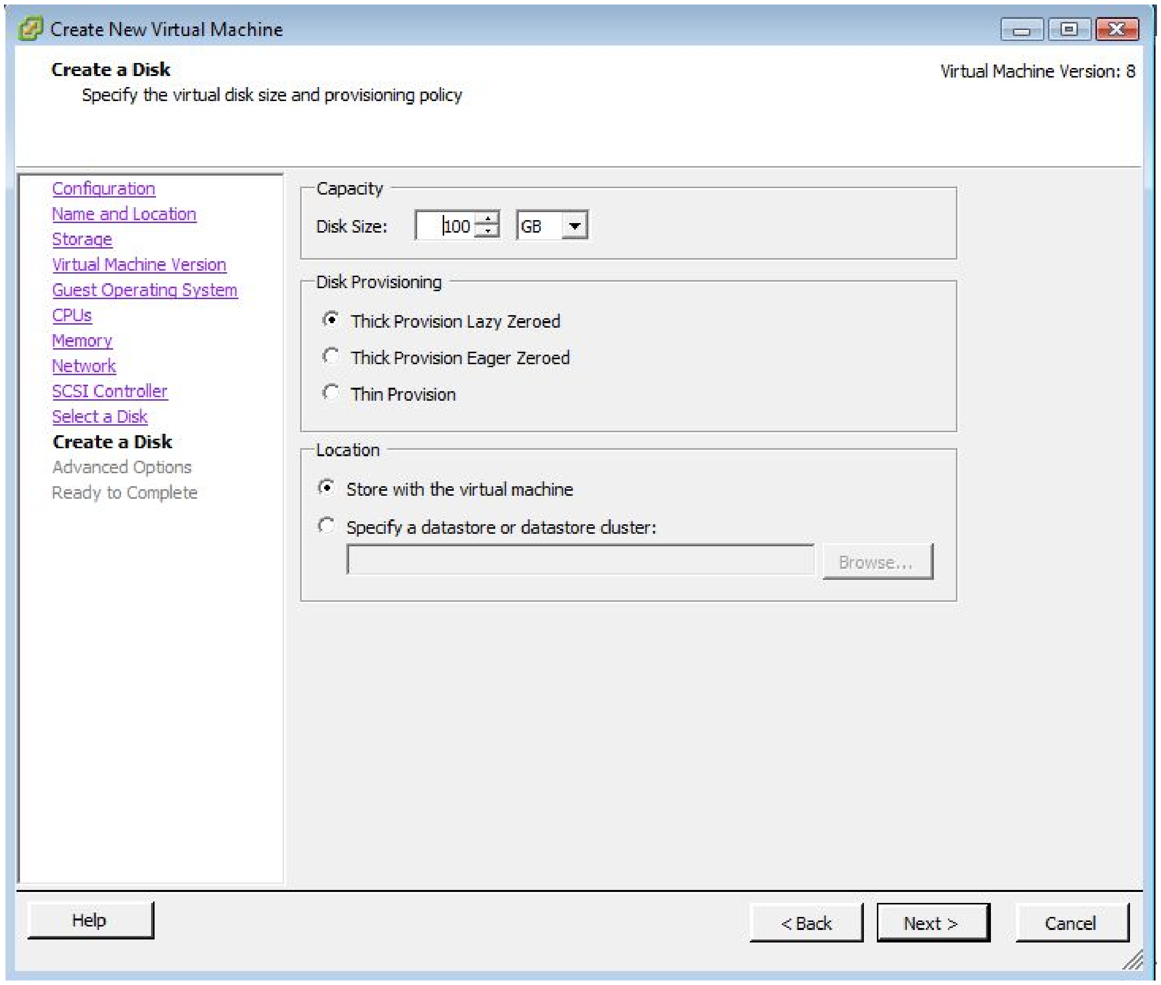
Use an existing virtual disk
Reuse a previously configured virtual disk.

Raw Device Mappings
Give your virtual machine direct access to SAN. This option allows you to use existing SAN commands to manage the storage and continue to access it using a datastore.

Do not create disk

Figure 121. Create a New Virtual Disk

12. For Create a Disk, create a Disk Size of at least 100 GB and leave the remaining settings at their default values. Click Next (Figure 122).


Create New Virtual Machine

Create a Disk
Specify the virtual disk size and provisioning policy

Virtual Machine Version: 8

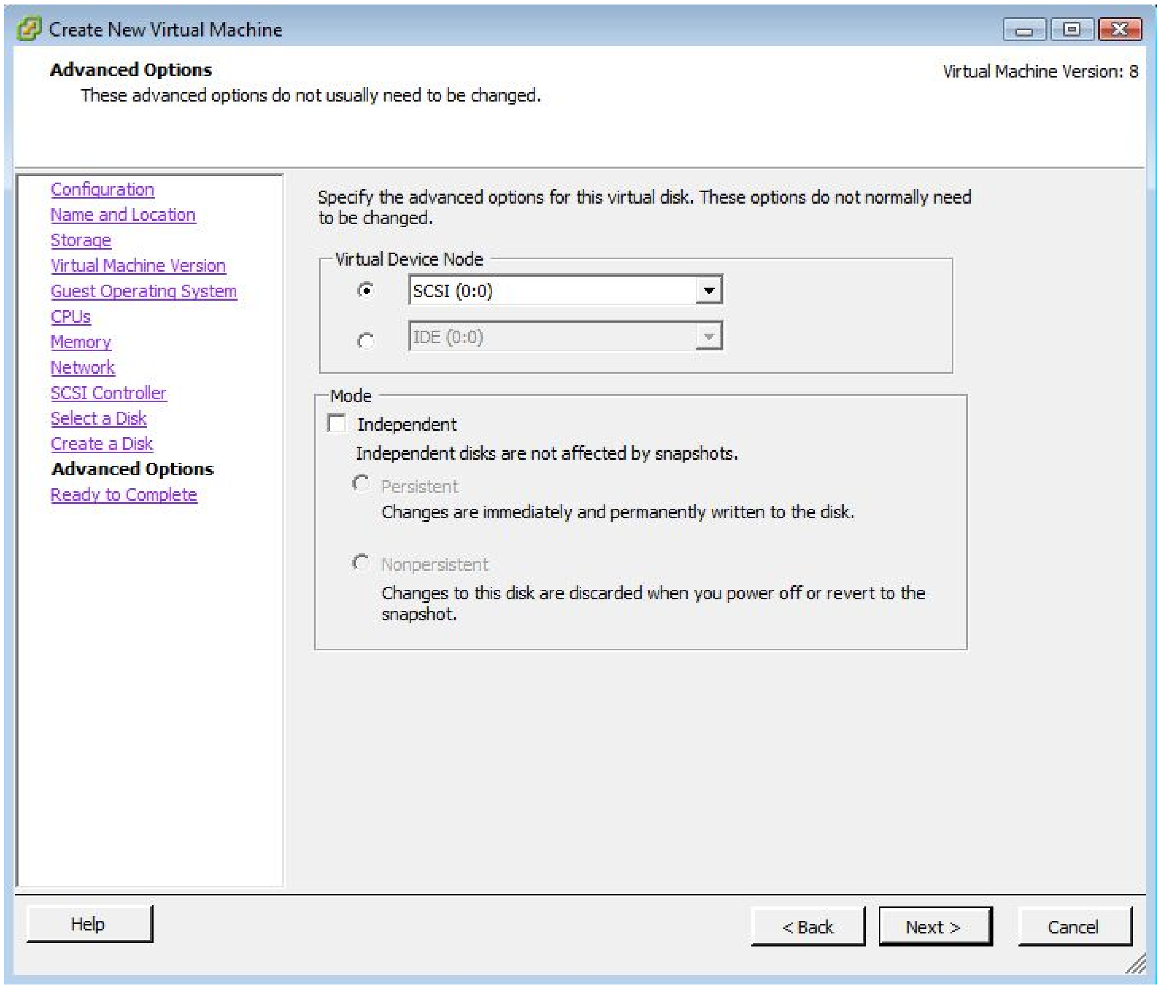
Capacity
Disk Size: 100 GB

Disk Provisioning
[✓ Thick Provision Lazy Zeroed]
Thick Provision Eager Zeroed
Thin Provision

Location
[✓ Store with the virtual machine]
Specify a datastore or datastore cluster:

Figure 122. Disk Configuration Settings

13. For Advanced Options, leave the default settings and click Next (Figure 123).



Create New Virtual Machine

Advanced Options

These advanced options do not usually need to be changed.

Virtual Machine Version: 8

Specify the advanced options for this virtual disk. These options do not normally need to be changed.

Virtual Device Node

- [✓] SCSI (0:0)
- IDE (0:0)

Mode

- [ ] Independent

Independent disks are not affected by snapshots.

- Persistent

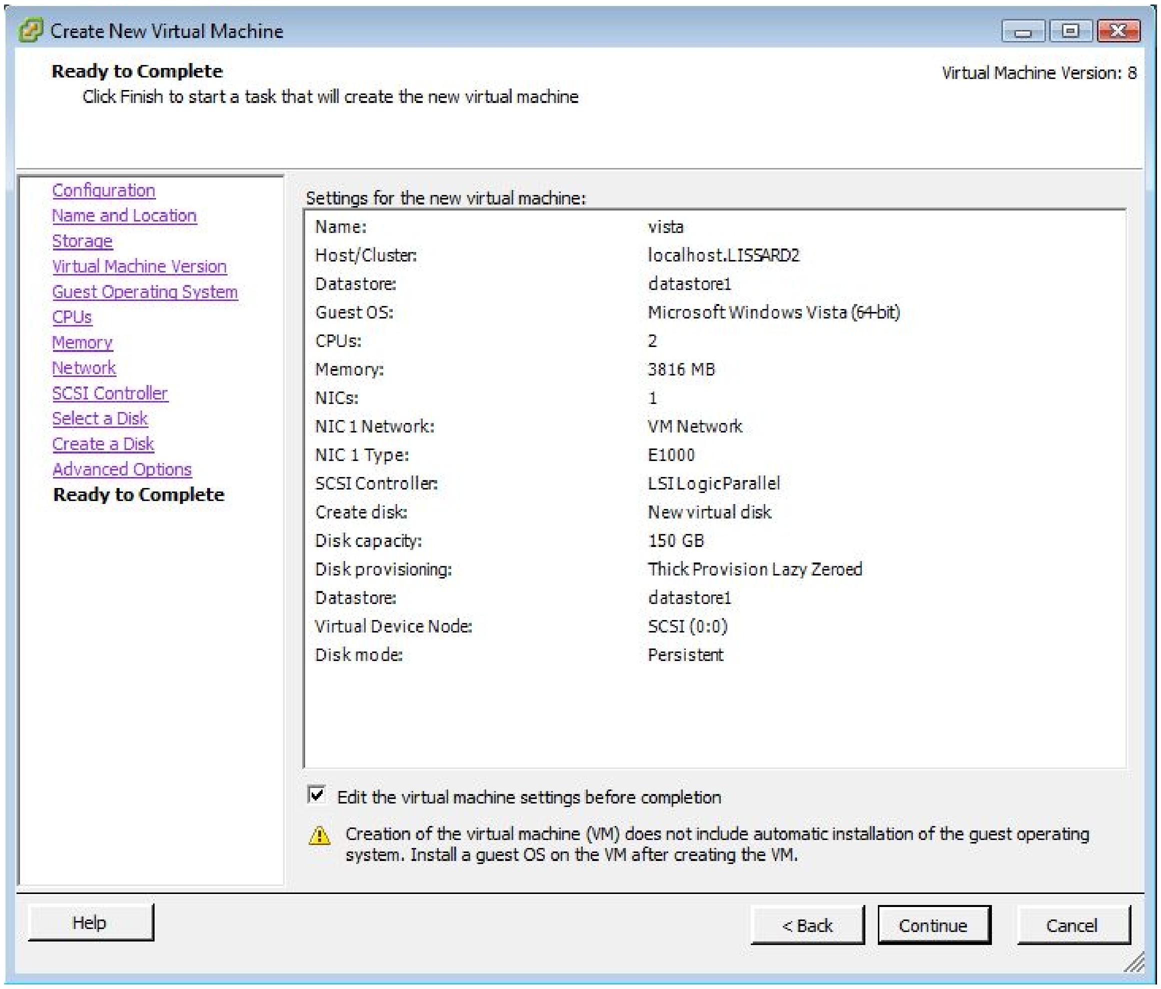
  Changes are immediately and permanently written to the disk.

- Nonpersistent

  Changes to this disk are discarded when you power off or revert to the snapshot.

Figure 123. Advanced Options Left at Default Settings

14. Review the VM settings, select “Edit the virtual machine settings before completion”, and click Continue (Figure 124).



Settings for the new virtual machine:

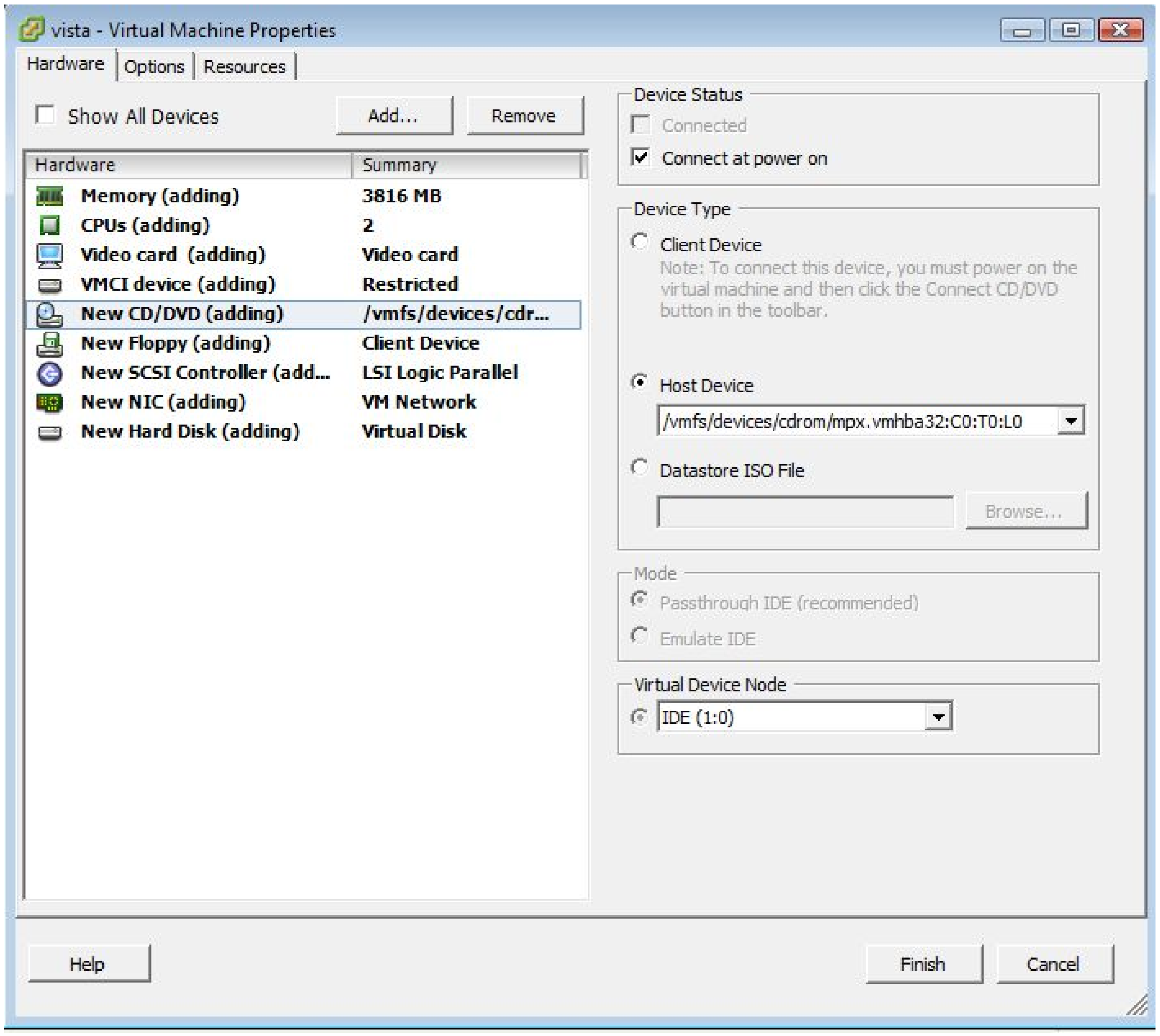
Name:	vista
Host/Cluster:	localhost.LISSARD2
Datastore:	datastore1
Guest OS:	Microsoft Windows Vista (64-bit)
CPUs:	2
Memory:	3816 MB
NICs:	1
NIC 1 Network:	VM Network
NIC 1 Type:	E1000
SCSI Controller:	LSI Logic Parallel
Create disk:	New virtual disk
Disk capacity:	150 GB
Disk provisioning:	Thick Provision Lazy Zeroed
Datastore:	datastore1
Virtual Device Node:	SCSI (0:0)
Disk mode:	Persistent

[✓] Edit the virtual machine settings before completion

Creation of the virtual machine (VM) does not include automatic installation of the guest operating system. Install a guest OS on the VM after creating the VM.

Figure 124. Select the Edit Virtual Machine Settings Before Completion Option

15. Within the Hardware tab, select New CD/DVD (adding), and under “Device Type, select “Host Device”. Under Device Status, select “Connect at power on” (Figure 125).


vista - Virtual Machine Properties

Hardware | Options | Resources

☐ Show All Devices

Hardware	Summary
Memory (adding)	3816 MB
CPUs (adding)	2
Video card (adding)	Video card
VMCI device (adding)	Restricted
New CD/DVD (adding)	/vmfs/devices/cdr...
New Floppy (adding)	Client Device
New SCSI Controller (add...	LSI Logic Parallel
New NIC (adding)	VM Network
New Hard Disk (adding)	Virtual Disk

Device Status
☐ Connected
☑ Connect at power on

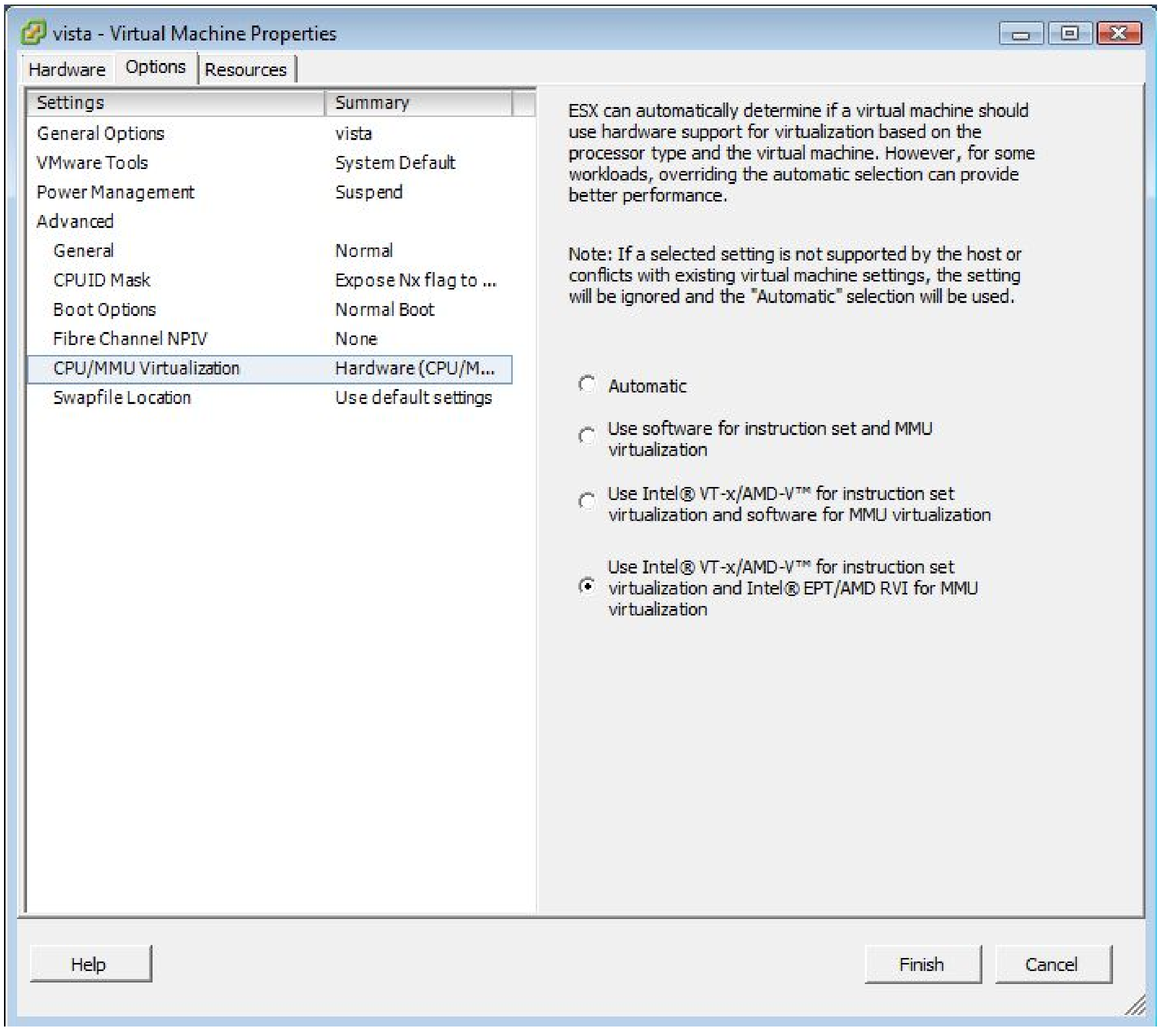
Device Type
○ Client Device
Note: To connect this device, you must power on the virtual machine and then click the Connect CD/DVD button in the toolbar.
● Host Device
/vmfs/devices/cdrom/mpx.vmhba32:C0:T0:L0
○ Datastore ISO File

Mode
● Passthrough IDE (recommended)
○ Emulate IDE

Virtual Device Node
IDE (1:0)

Figure 125. Edit the Hardware Tab

16. Within the “Options” tab, click CPU/MMU Virtualization and select “Use Intel VT-x/AMD-V for instruction set virtualization and Intel EPT/AMD RVI for MMU virtualization” and select “Finish” (Figure 126).



Settings	Summary
General Options	vista
VMware Tools	System Default
Power Management	Suspend
Advanced	
General	Normal
CPUID Mask	Expose Nx flag to ...
Boot Options	Normal Boot
Fibre Channel NPIV	None
CPU/MMU Virtualization	Hardware (CPU/M...
Swapfile Location	Use default settings

ESX can automatically determine if a virtual machine should use hardware support for virtualization based on the processor type and the virtual machine. However, for some workloads, overriding the automatic selection can provide better performance.

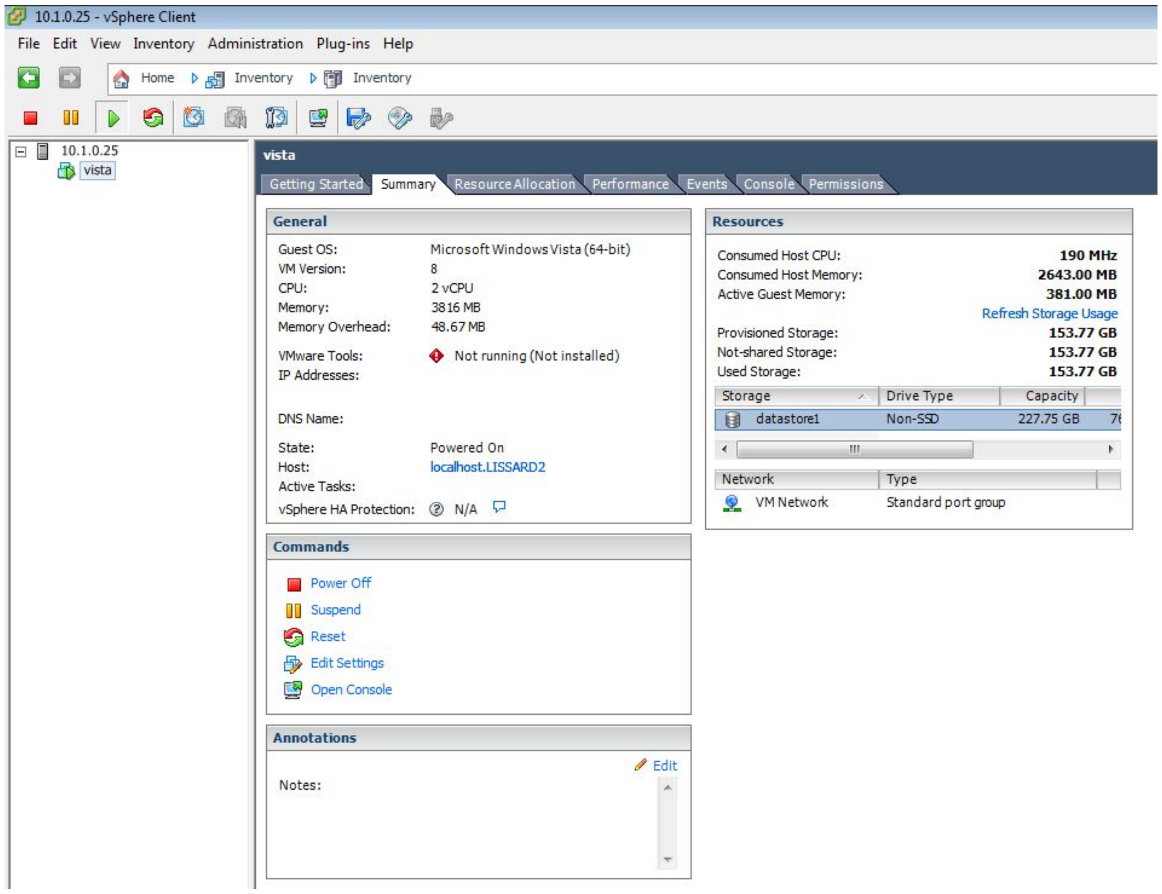
Note: If a selected setting is not supported by the host or conflicts with existing virtual machine settings, the setting will be ignored and the "Automatic" selection will be used.

- Automatic
- Use software for instruction set and MMU virtualization
- Use Intel® VT-x/AMD-V™ for instruction set virtualization and software for MMU virtualization
- [✓ Use Intel® VT-x/AMD-V™ for instruction set virtualization and Intel® EPT/AMD RVI for MMU virtualization]

Figure 126. Edit the CPU/MMU Virtualization Tab

G-4. Append the OS.vmx File to Enable Nested Virtualization

1. Within vSphere, click on the Summary tab and, under resources, right click on the hard disk icon in the "Storage" area and select "Browse Datastore" (Figure 127).


10.1.0.25 - vSphere Client
File Edit View Inventory Administration Plug-ins Help
Home Inventory Inventory
10.1.0.25
vista
vista
Getting Started Summary Resource Allocation Performance Events Console Permissions

General

Guest OS:	Microsoft Windows Vista (64-bit)
VM Version:	8
CPU:	2 vCPU
Memory:	3816 MB
Memory Overhead:	48.67 MB
VMware Tools:	Not running (Not installed)
IP Addresses:	
DNS Name:	
State:	Powered On
Host:	localhost.LISSARD2
Active Tasks:	
vSphere HA Protection:	N/A

Resources

Consumed Host CPU:	190 MHz
Consumed Host Memory:	2643.00 MB
Active Guest Memory:	381.00 MB
	Refresh Storage Usage
Provisioned Storage:	153.77 GB
Not-shared Storage:	153.77 GB
Used Storage:	153.77 GB

Storage	Drive Type	Capacity
datastore1	Non-SSD	227.75 GB

Network	Type
VM Network	Standard port group

Commands

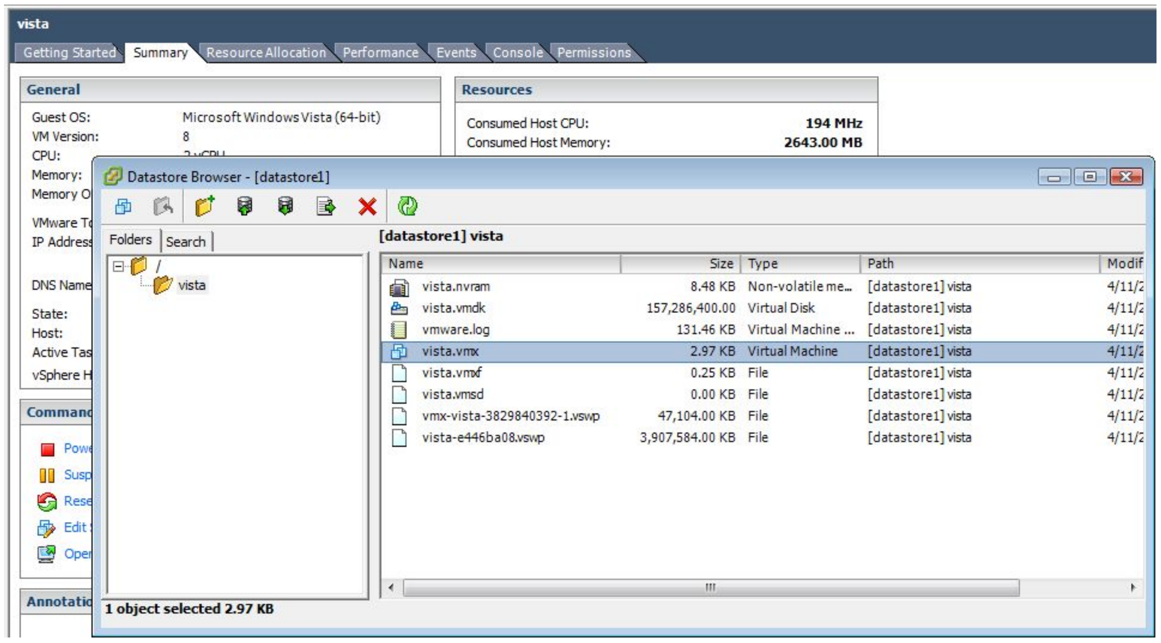
Power Off
Suspend
Reset
Edit Settings
Open Console

Annotations

Edit
Notes:

Figure 127. Locating the Data Store

2. Download the OS.vmx folder to your client machine by right clicking on the file and selecting Download (Figure 128).



vista
Getting Started Summary Resource Allocation Performance Events Console Permissions
Datastore Browser - [datastore1]
Folders Search
vista

General

Guest OS: Microsoft Windows Vista (64-bit)
VM Version: 8

Resources

Consumed Host CPU: 194 MHz
Consumed Host Memory: 2643.00 MB

[datastore1] vista

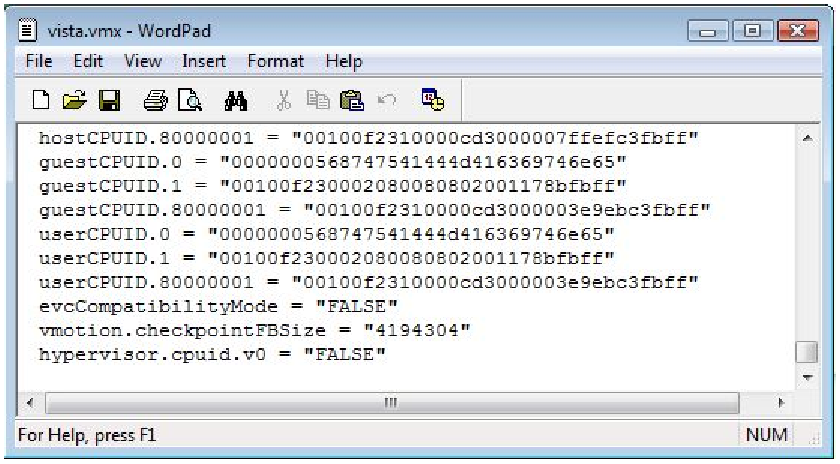
Name	Size	Type	Path	Modif
vista.nvram	8.48 KB	Non-volatile me...	[datastore1] vista	4/11/2
vista.vmdk	157,286,400.00	Virtual Disk	[datastore1] vista	4/11/2
vmware.log	131.46 KB	Virtual Machine ...	[datastore1] vista	4/11/2
vista.vmx	2.97 KB	Virtual Machine	[datastore1] vista	4/11/2
vista.vmxf	0.25 KB	File	[datastore1] vista	4/11/2
vista.vmsd	0.00 KB	File	[datastore1] vista	4/11/2
vmx-vista-3829840392-1.vswp	47,104.00 KB	File	[datastore1] vista	4/11/2
vista-e446ba08.vswp	3,907,584.00 KB	File	[datastore1] vista	4/11/2

1 object selected 2.97 KB

Figure 128. Download the OS.vmx Folder

3. Open the file in a text editor and append the following:

`hypervisor.cpuid.v0 = “FALSE”`



```
hostCPUID.80000001 = "00100f2310000cd3000007ffefc3fbff"
guestCPUID.0 = "0000000568747541444d416369746e65"
guestCPUID.1 = "00100f230002080080802001178bfbff"
guestCPUID.80000001 = "00100f2310000cd3000003e9ebc3fbff"
userCPUID.0 = "0000000568747541444d416369746e65"
userCPUID.1 = "00100f230002080080802001178bfbff"
userCPUID.80000001 = "00100f2310000cd3000003e9ebc3fbff"
evcCompatibilityMode = "FALSE"
vmotion.checkpointFBSize = "4194304"
hypervisor.cpuid.v0 = "FALSE"
```

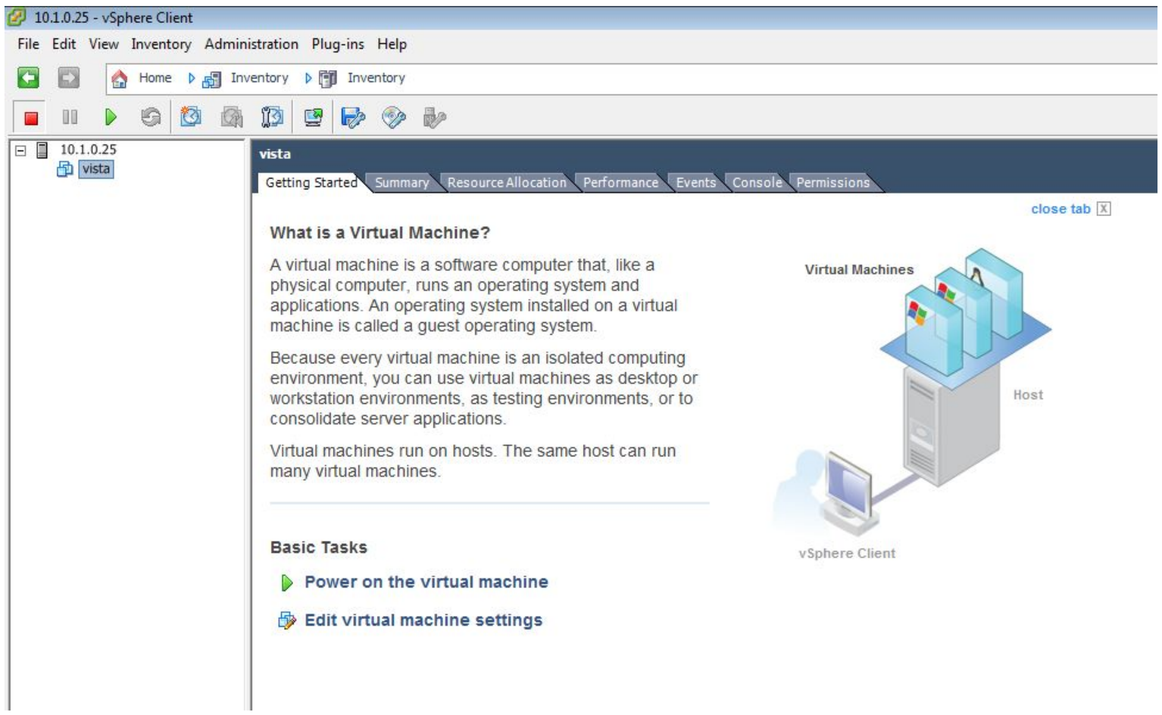
Figure 129. Append the .vmx Folder

This indicates to the Guest OS that the CPU is not virtualized.

4. Upload the modified OS.vmx file back to the host by selecting the upload button and uploading the file from the client.
5. Close the Datastore Browser.

G-5. Install the Guest OS (64-bit Windows Vista Business)

1. Insert the OS install CD into the host machine CD-ROM
2. Within vSphere, click on the VM and, with the Getting Started tab, click Power on the Virtual Machine (Figure 130).


10.1.0.25 - vSphere Client
File Edit View Inventory Administration Plug-ins Help
Home Inventory Inventory
10.1.0.25
vista
vista
Getting Started Summary Resource Allocation Performance Events Console Permissions
close tab
Virtual Machines
Host
vSphere Client

What is a Virtual Machine?

A virtual machine is a software computer that, like a physical computer, runs an operating system and applications. An operating system installed on a virtual machine is called a guest operating system.

Because every virtual machine is an isolated computing environment, you can use virtual machines as desktop or workstation environments, as testing environments, or to consolidate server applications.

Virtual machines run on hosts. The same host can run many virtual machines.

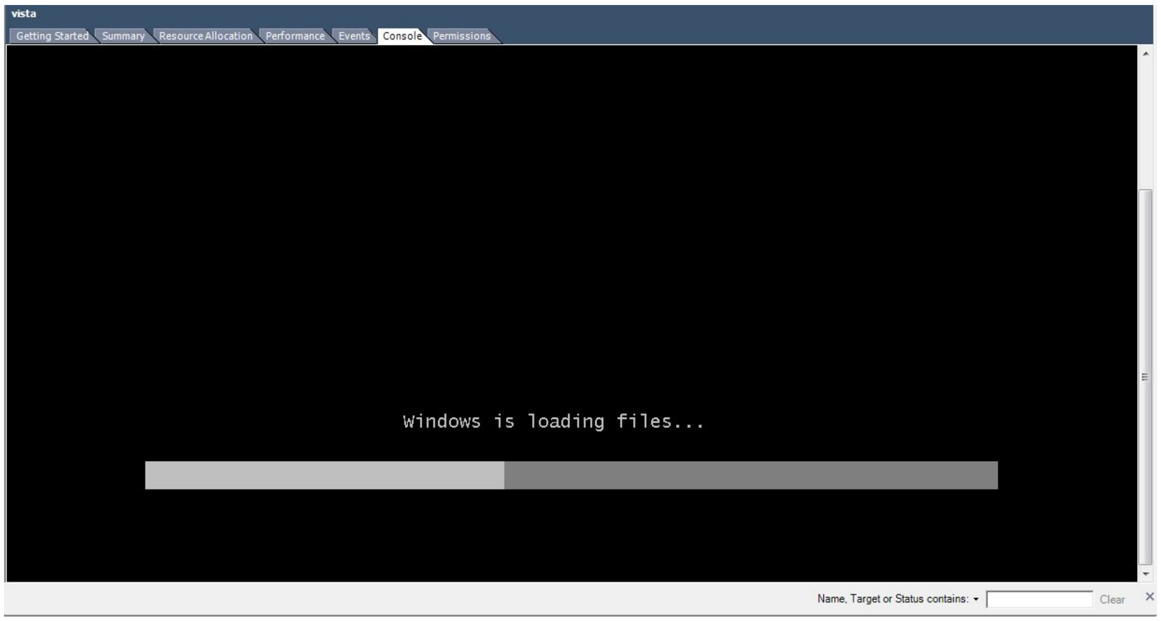
Basic Tasks

Power on the virtual machine

Edit virtual machine settings

Figure 130. Power on the Virtual Machine

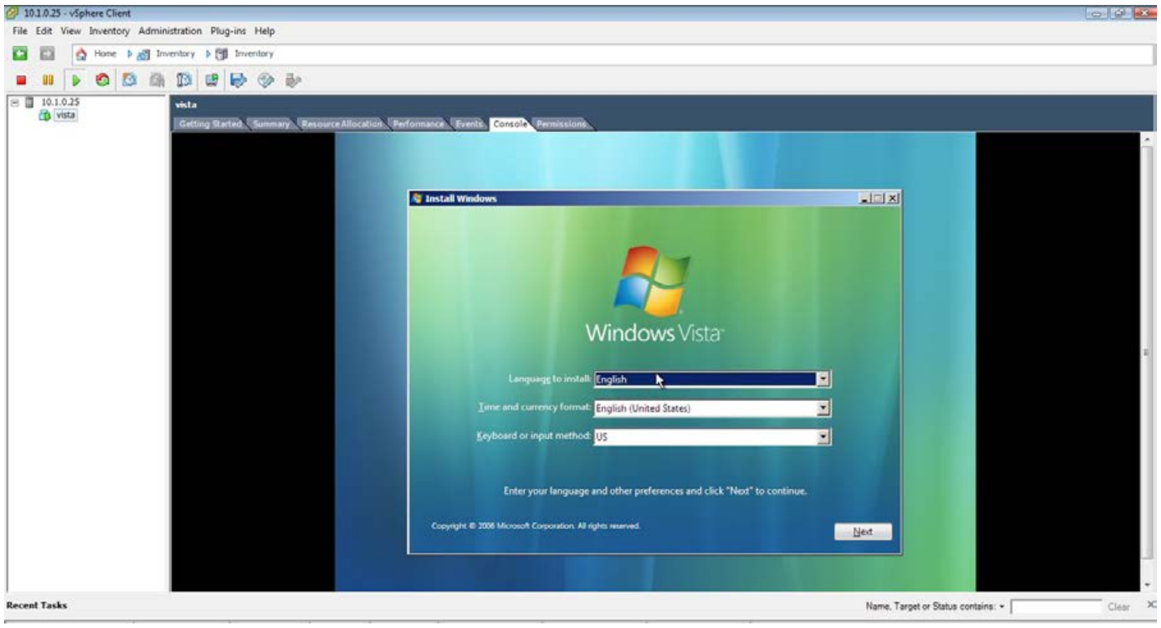
3. Select the Console tab to observe the installation (Figure 131).



```
Windows is loading files...
```

Figure 131. Select the Console Tab to View the Installation

4. Follow the onscreen instructions to install the OS (Figure 132).



Language to install: English

Time and currency format: English (United States)

Keyboard or input method: US

Enter your language and other preferences and click "Next" to continue.

Copyright © 2006 Microsoft Corporation. All rights reserved.

Figure 132. Windows Installation Screen

Appendix H. Statistical Analysis

The following quantile quantile (QQ) plots and density plots characterize the data gathered by HyperScan. Within the QQ plots, the closeness of the line formed by the data points to a theoretical diagonal line from the bottom left to the top right corner of the box corresponds to the relative normality of the data. Observations of the subsequent QQ plots below reveal that the data is generally not normally distributed. This is supported by the corresponding density plots which reveal a preponderance of skewed, long-tailed data with outliers. This supports the claim that the data is relatively non-parametric.

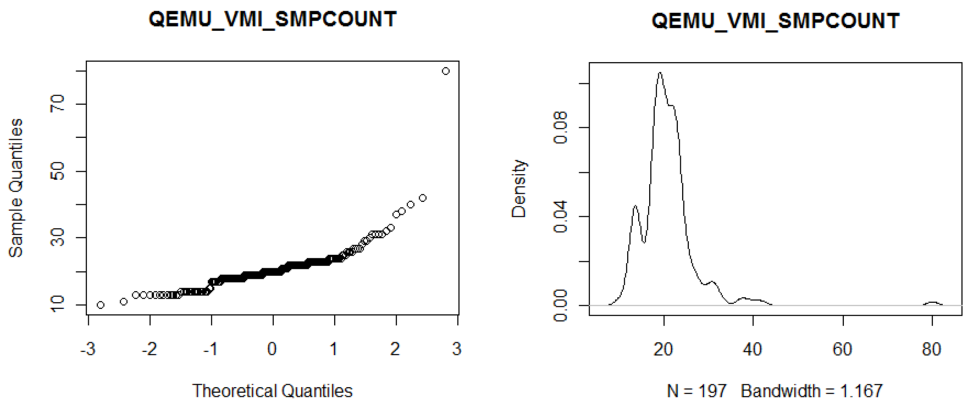


Figure 133. QQ Plot and Density Plot: QEMU_VMI_SMPCOUNT

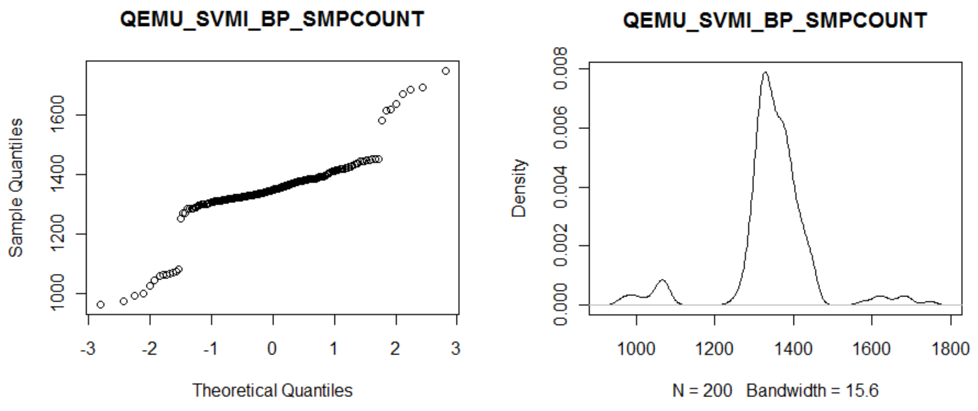


Figure 134. QQ Plot and Density Plot: QEMU_SVMI_BP_SMPCOUNT

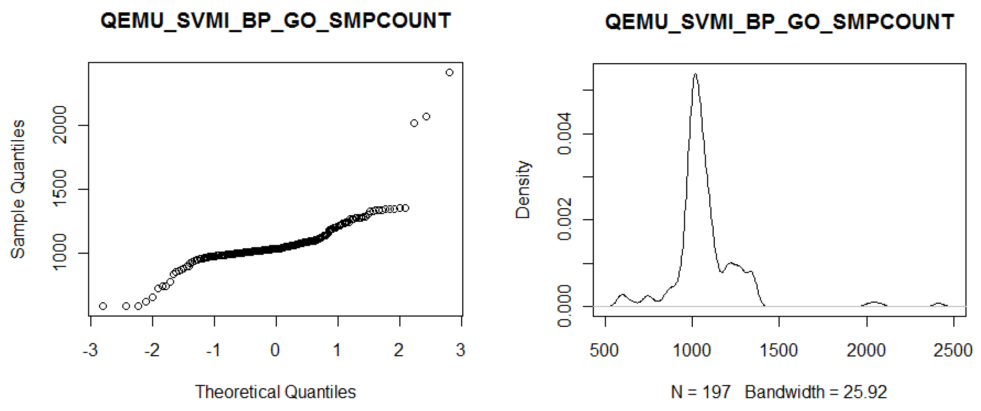


Figure 135. QQ Plot and Density Plot: QEMU_SVMI_BP_SMPCOUNT

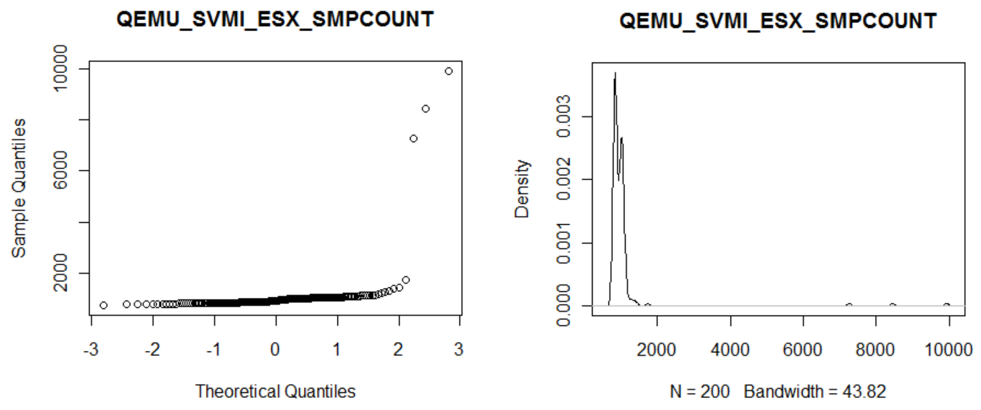


Figure 136. QQ Plot and Density Plot: QEMU_SVMI_BP_SMPCOUNT

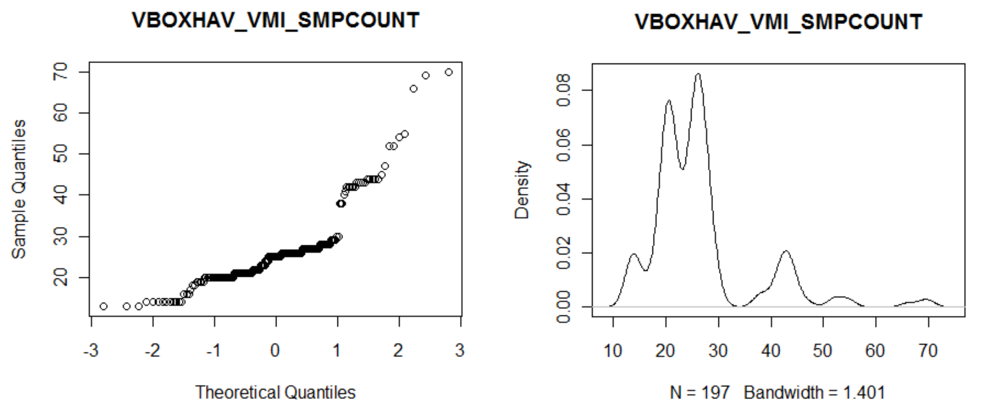


Figure 137. QQ Plot and Density Plot: VBOXHAV_VMI_SMPCOUNT

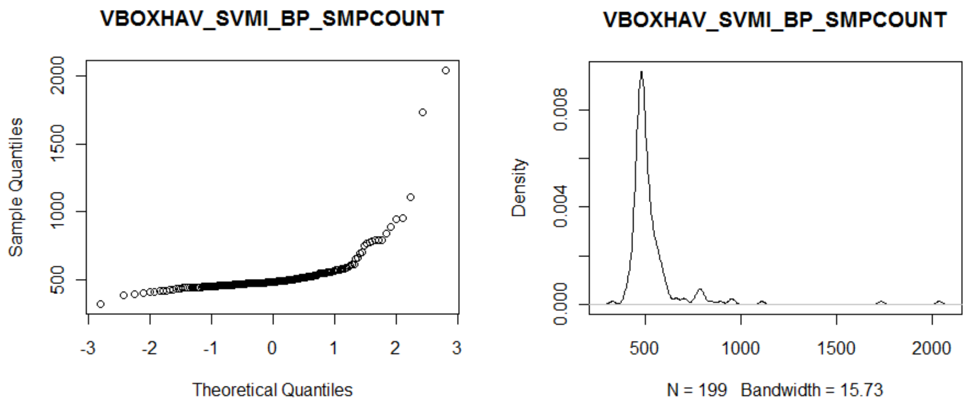


Figure 138. QQ Plot and Density Plot: VBOXHAV_SVMI_BP_SMPCOUNT

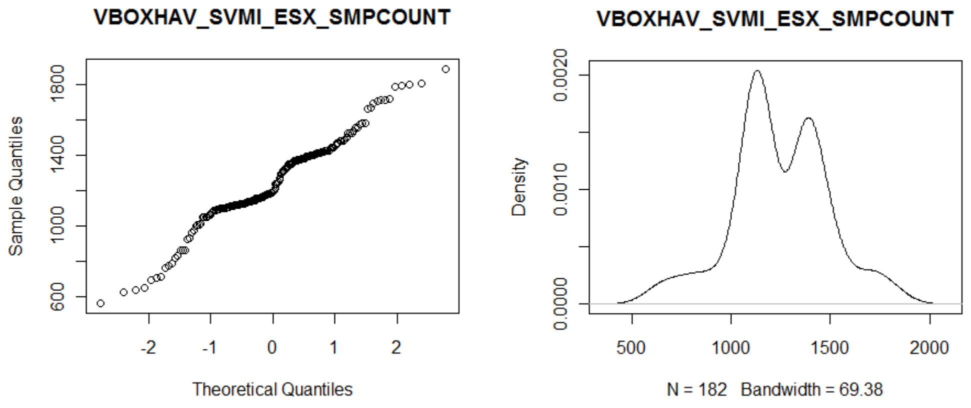


Figure 139. QQ Plot and Density Plot: VBOX_SVMI_ESX_SMPCOUNT

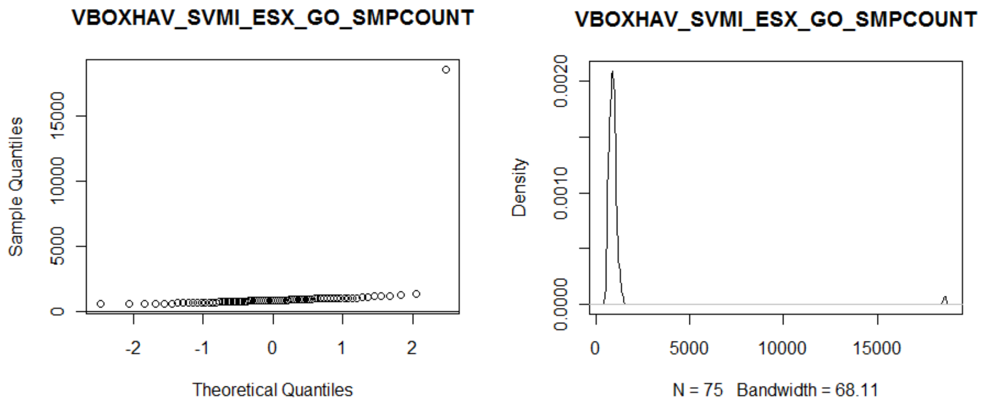


Figure 140. QQ Plot and Density Plot: VBOXHAV_SVMI_ESX_GO_SMPCOUNT

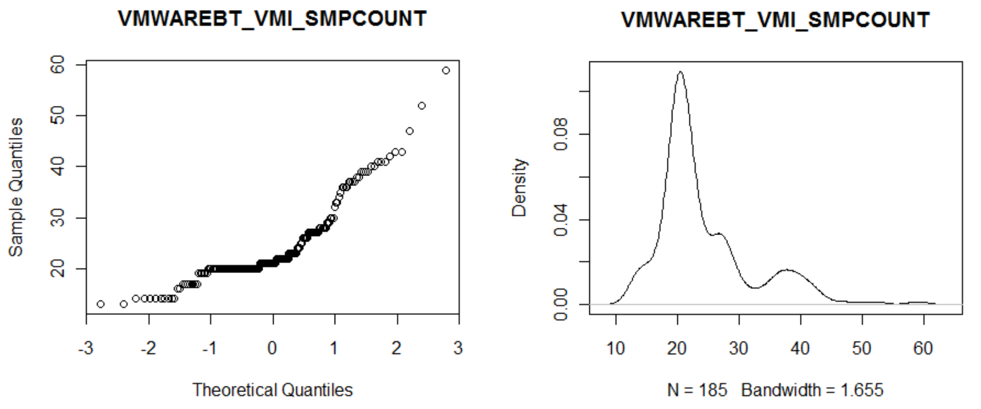


Figure 141. QQ Plot and Density Plot: VMWAREBT_VMI_SMPCOUNT

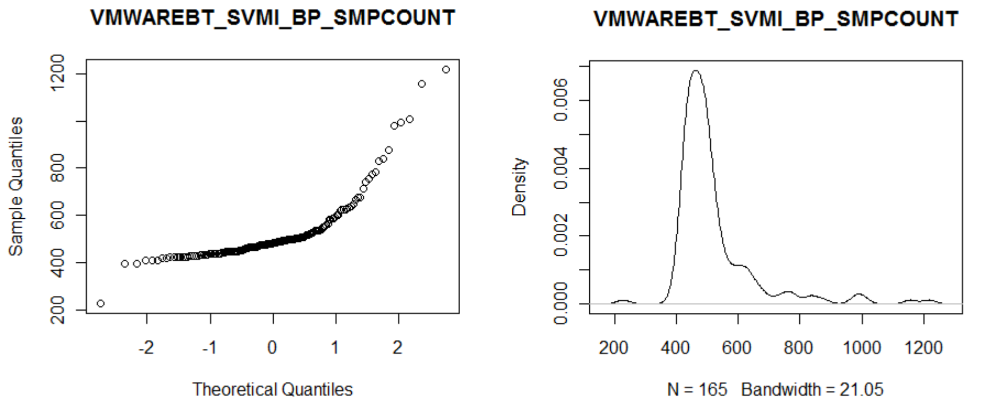


Figure 142. QQ Plot and Density Plot: VMWARE_SVMI_BP_SMPCOUNT

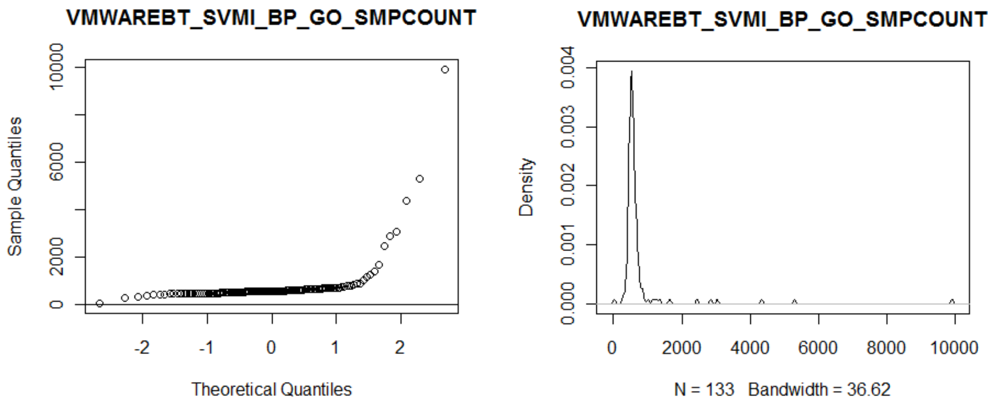


Figure 143. QQ Plot and Density Plot: VMWAREBT_SVMI_BP_GO_SMPCOUNT

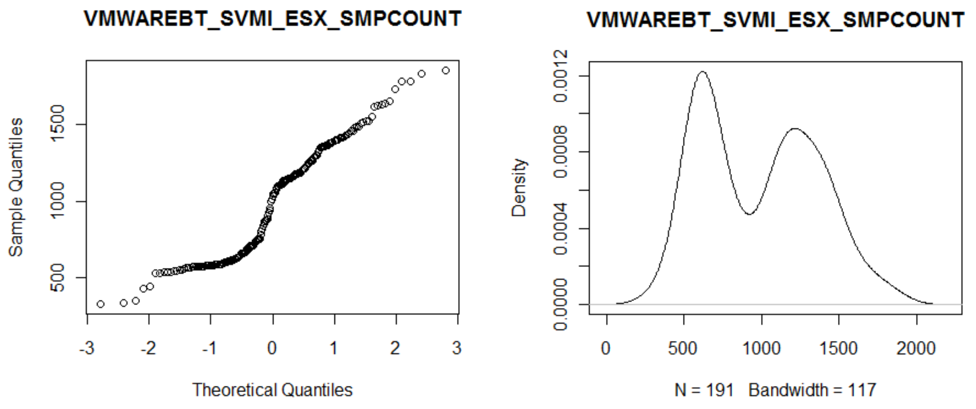


Figure 144. QQ Plot and Density Plot: VMWAREBT_SVMI_ESX_SMPCOUNT

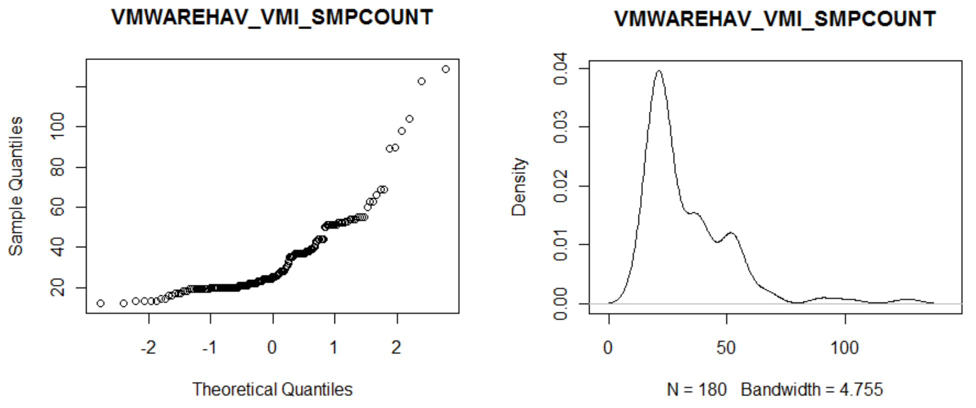


Figure 145. QQ Plot and Density Plot: VMWAREHAV_VMI_SMPCOUNT

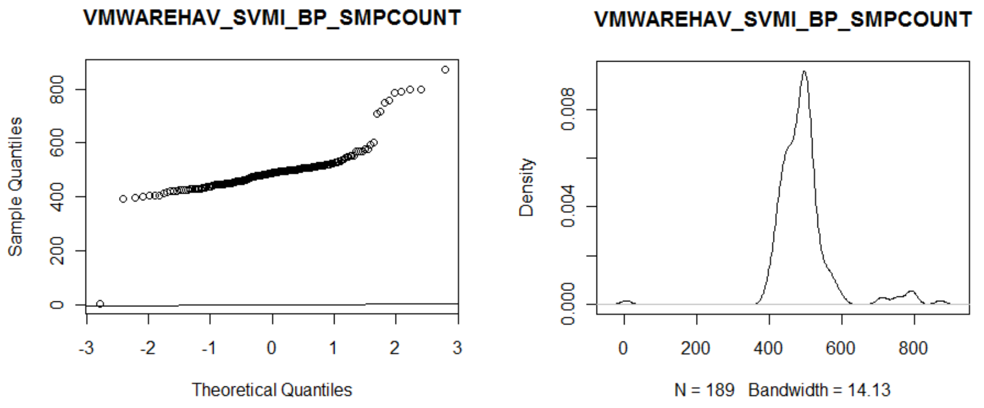


Figure 146. QQ Plot and Density Plot: VMWAREHAV_SVMI_BP_SMPCOUNT

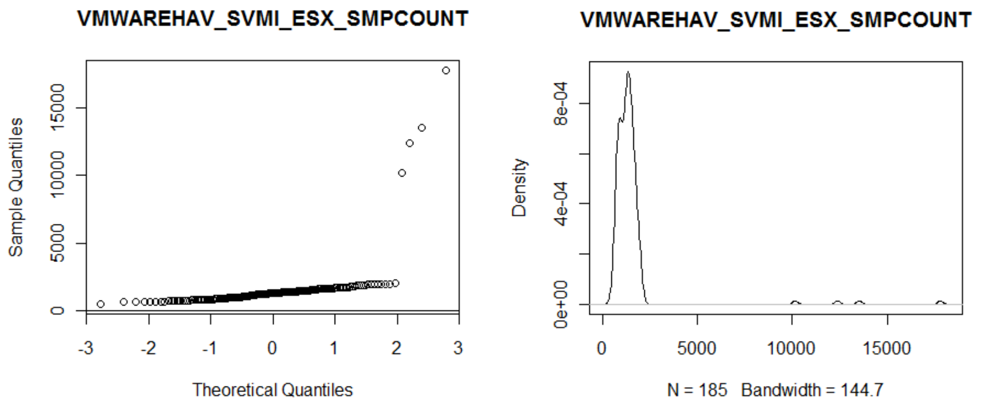


Figure 147. QQ Plot and Density Plot: VMWAREHAV_SVMI_ESX_SMPCOUNT

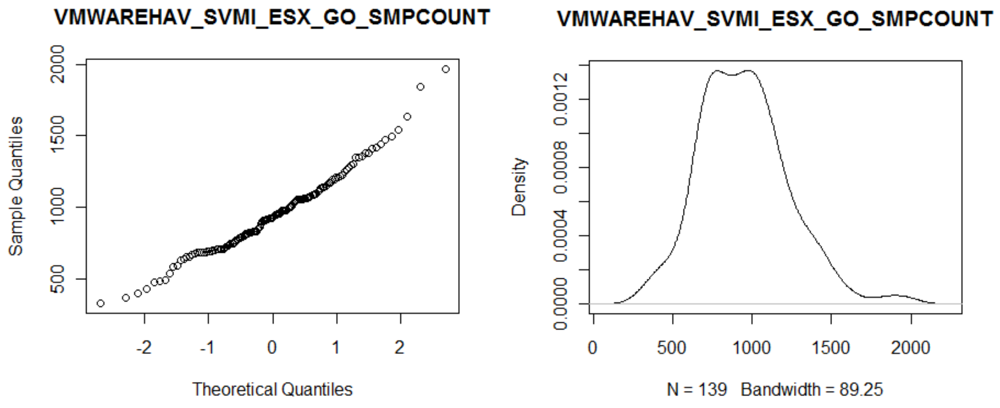


Figure 148. QQ Plot and Density Plot: VMWAREHAV_SVMI_ESX_GO_SMPCOUNT

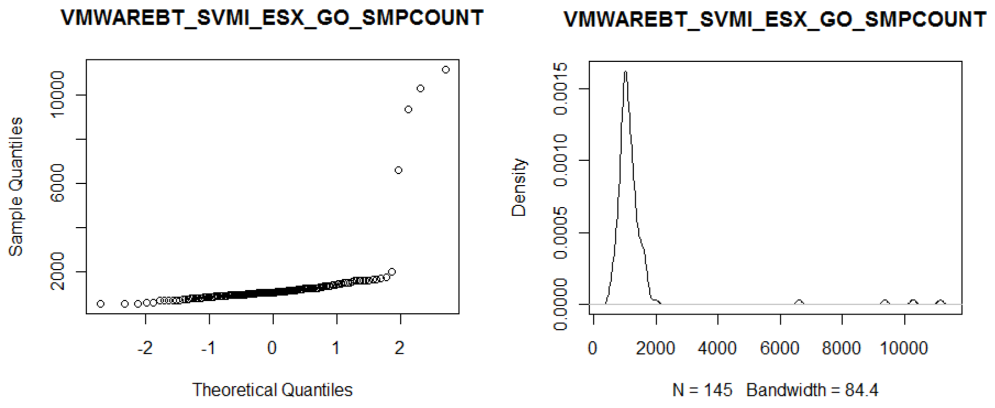


Figure 149. QQ Plot and Density Plot: VMWAREBT_SVMI_ESX_GO_SMPCOUNT

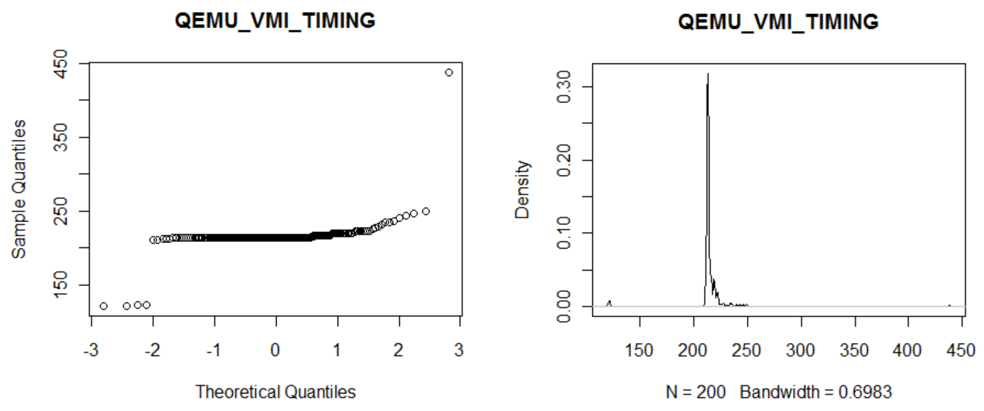


Figure 150. QQ Plot and Density Plot: QEMU_VMI_TIMING

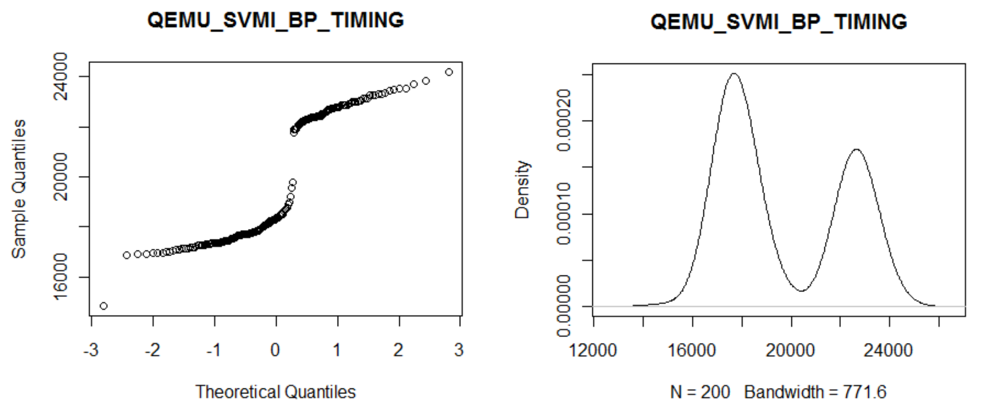


Figure 151. QQ Plot and Density Plot: QEMU_SVMI_BP_TIMING

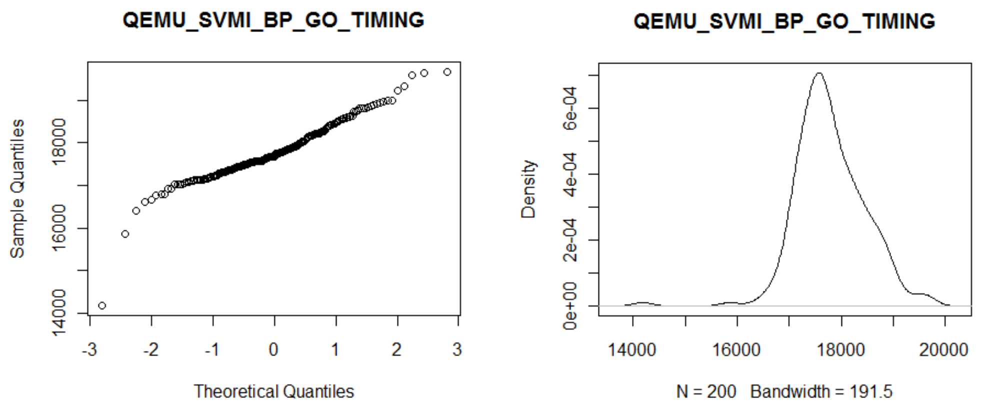


Figure 152. QQ Plot and Density Plot: QEMU_SVMI_BP_GO_TIMING

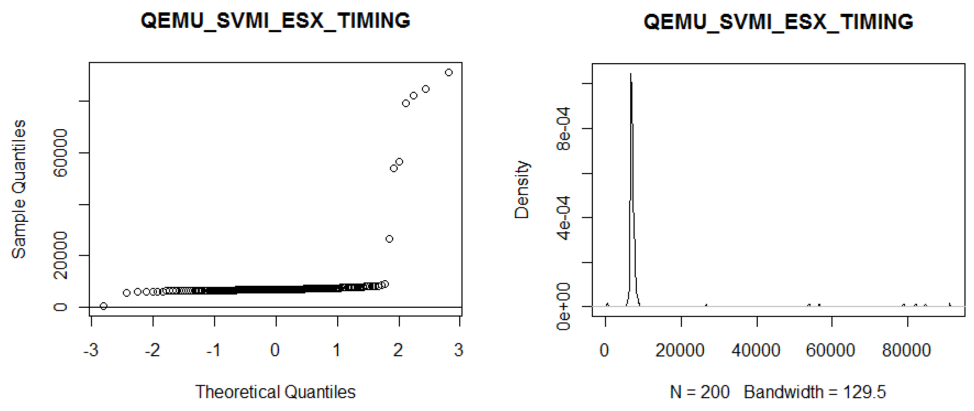


Figure 153. QQ Plot and Density Plot: QEMU_SVMI_ESX_TIMING

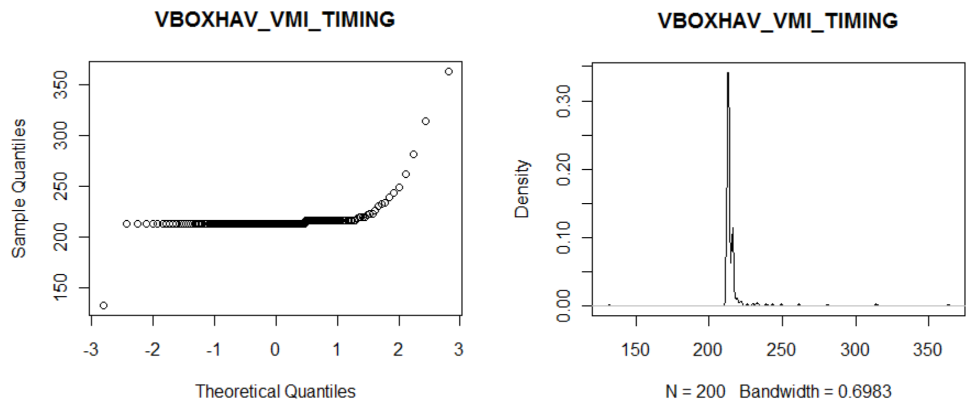


Figure 154. QQ Plot and Density Plot: VBOX_VMI_TIMING

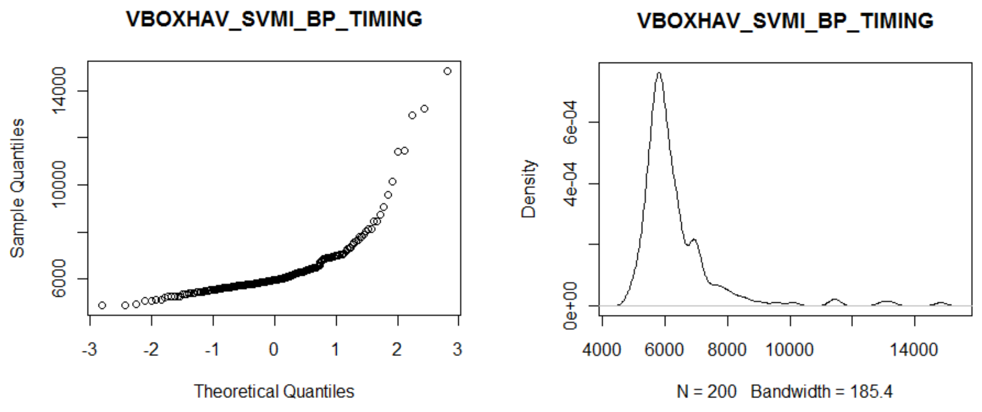


Figure 155. QQ Plot and Density Plot: VBOXHAV_SVMI_BP_TIMING

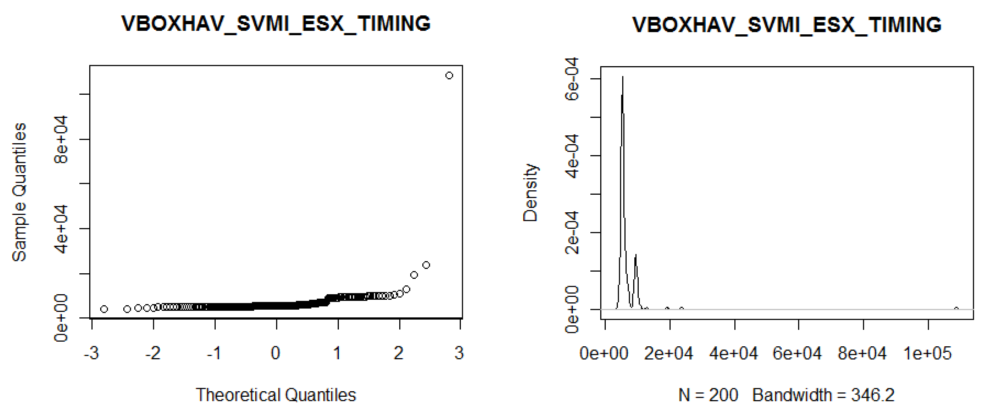
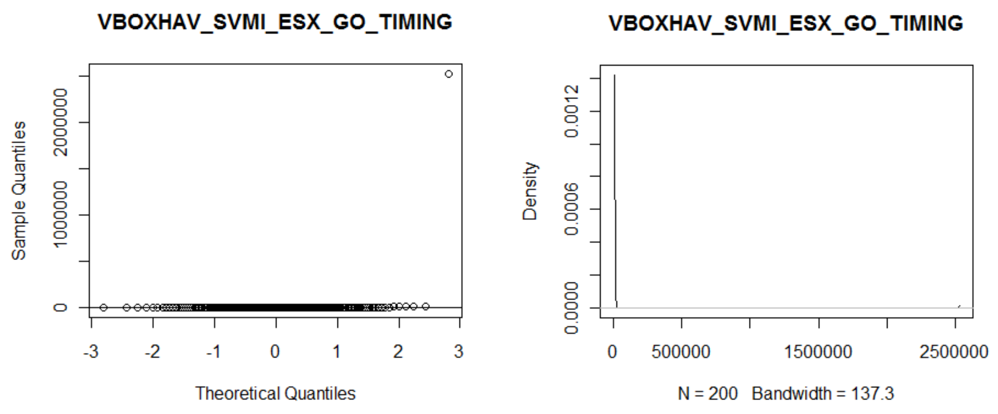


Figure 156. QQ Plot and Density Plot: VBOX_SVMI_ESX_TIMING



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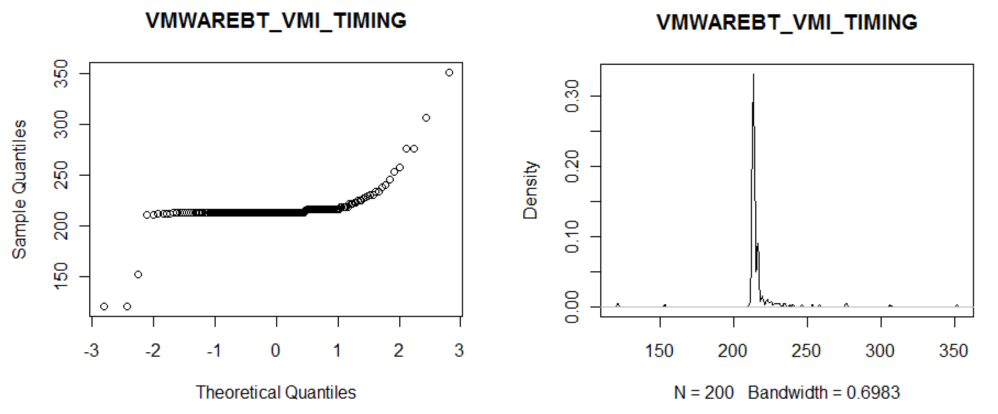
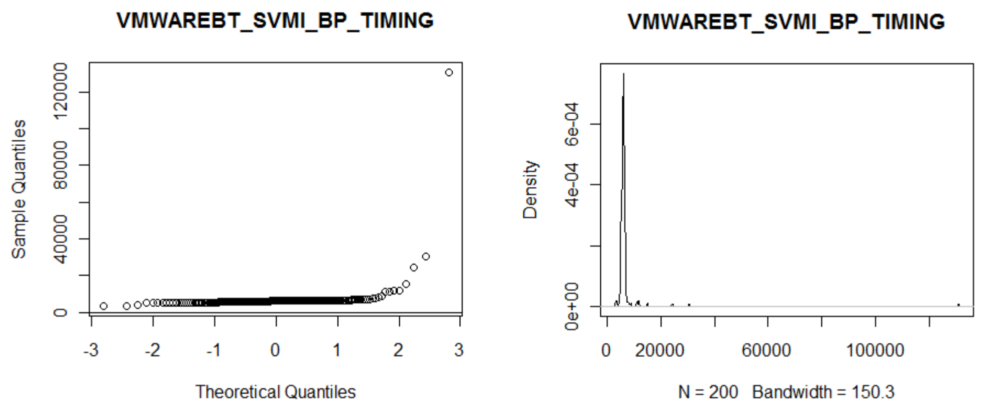


Figure 158. QQ Plot and Density Plot: VMWAREBT_VMI_TIMING



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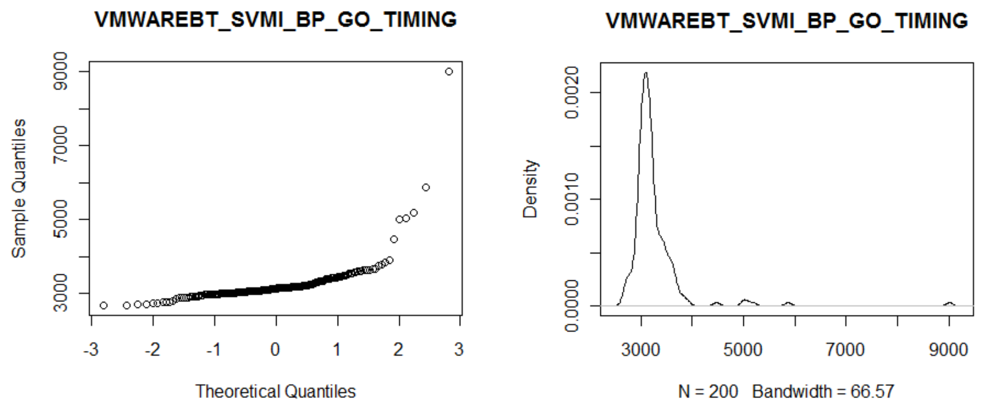

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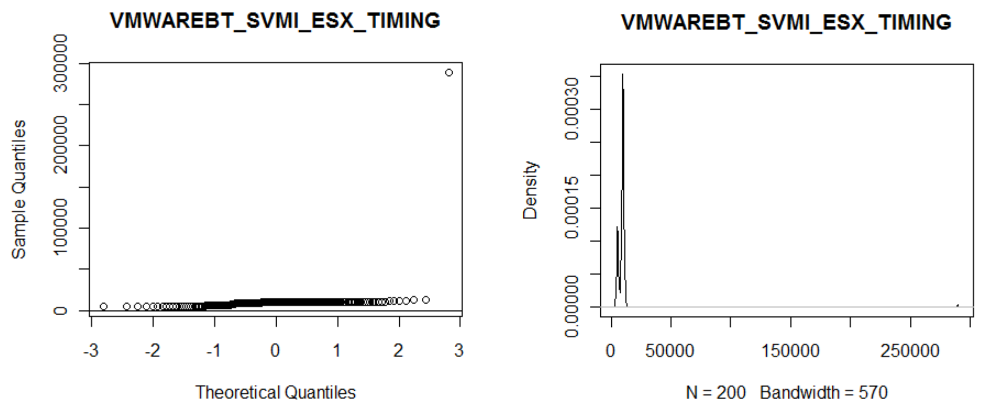

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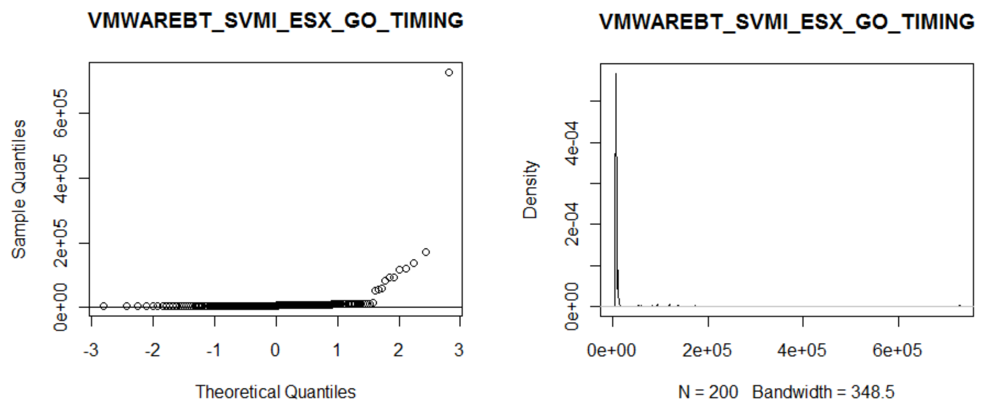

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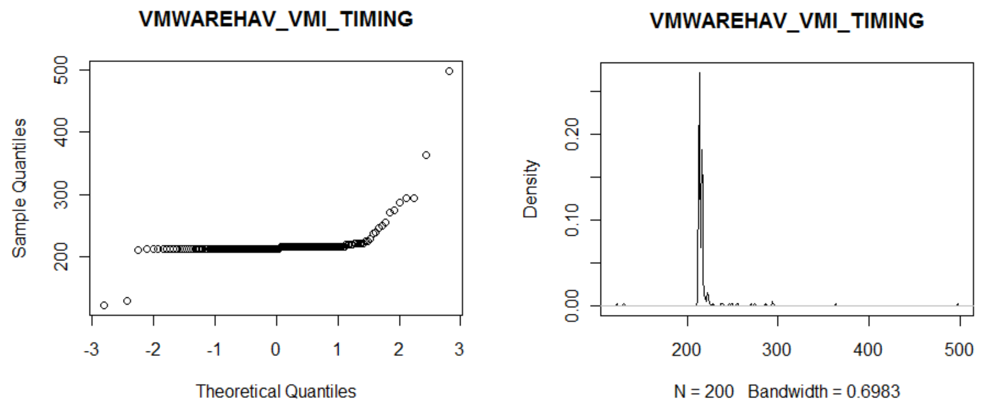

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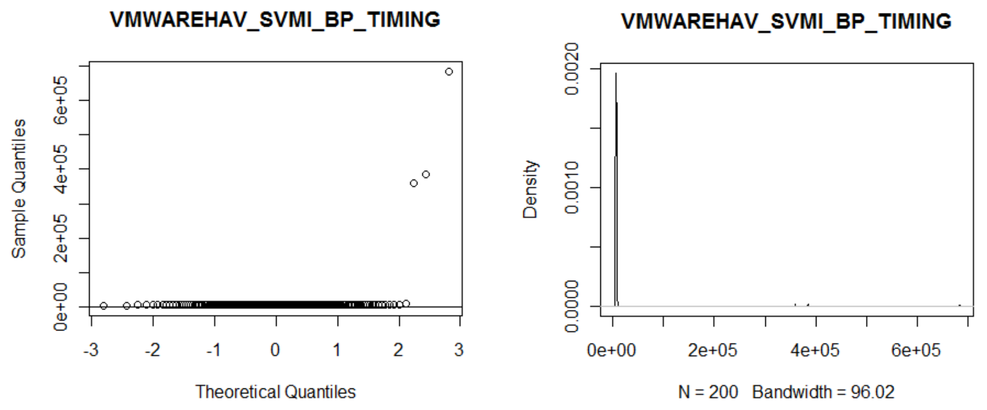

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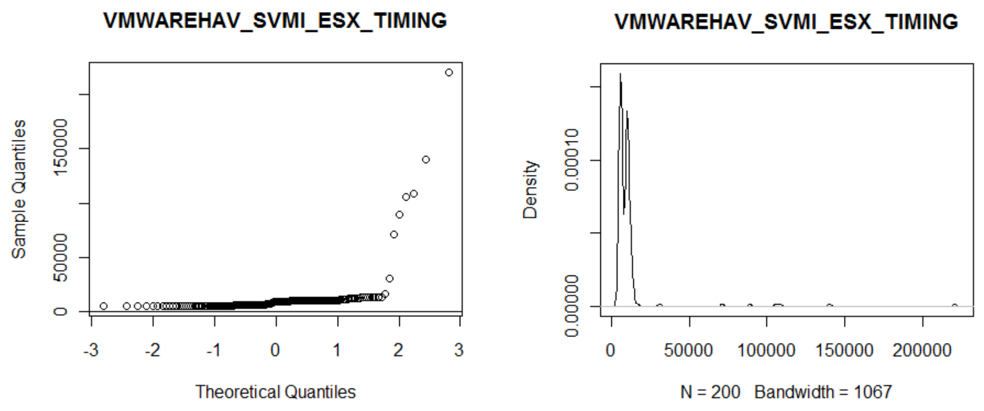

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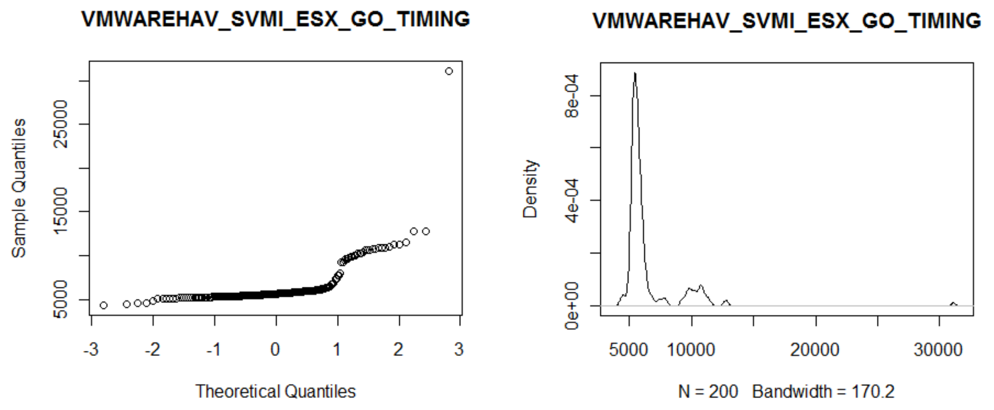


Figure 166. QQ Plot and Density Plot: VMWAREHAV_SVMI_ESX_TIMING

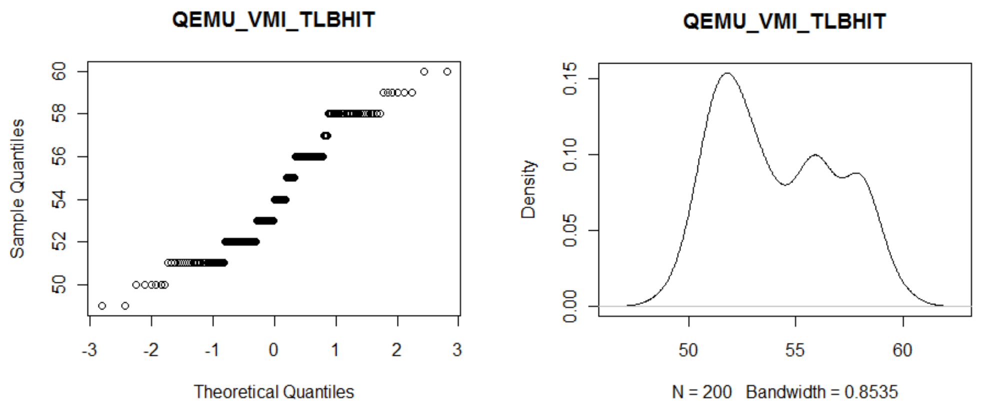
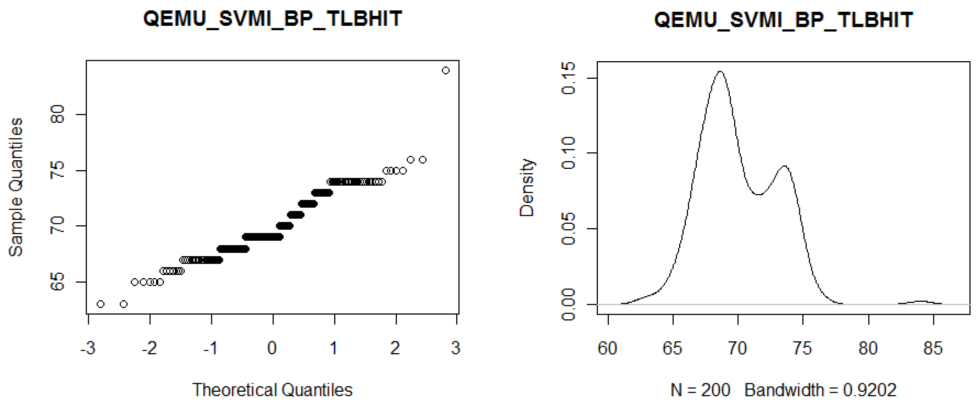


Figure 167. QQ Plot and Density Plot: QEMU_VMI_TLBHIT



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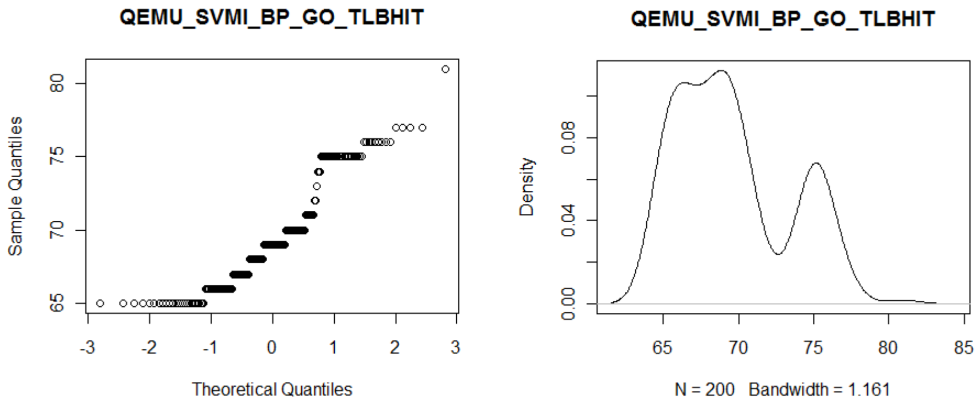

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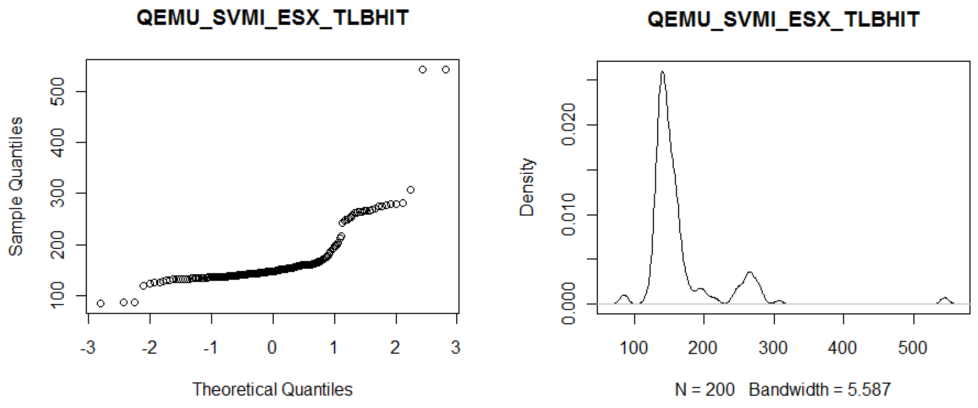

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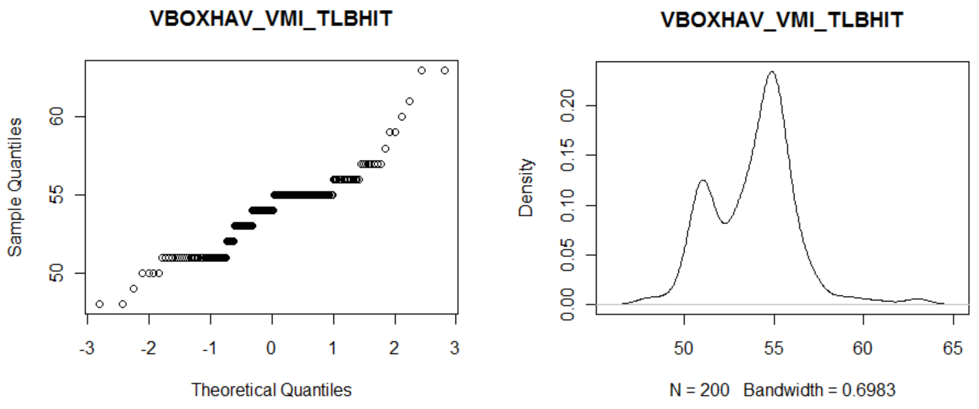
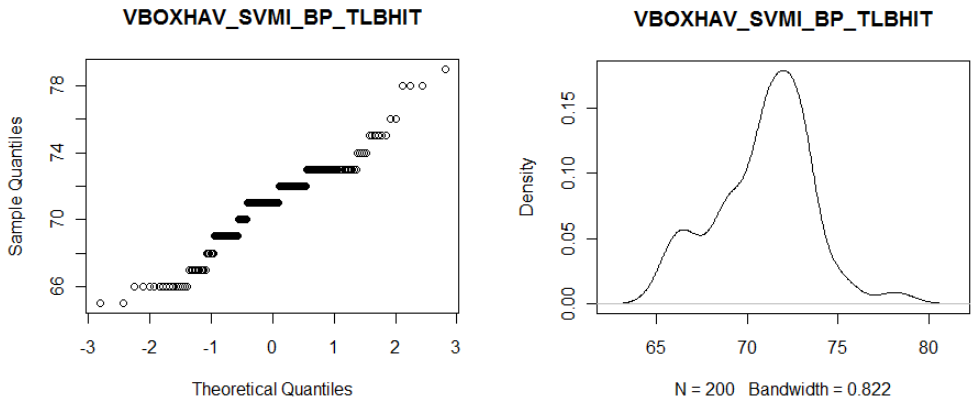


Figure 171. QQ Plot and Density Plot: VBOXHAV_VMI_TLBHIT



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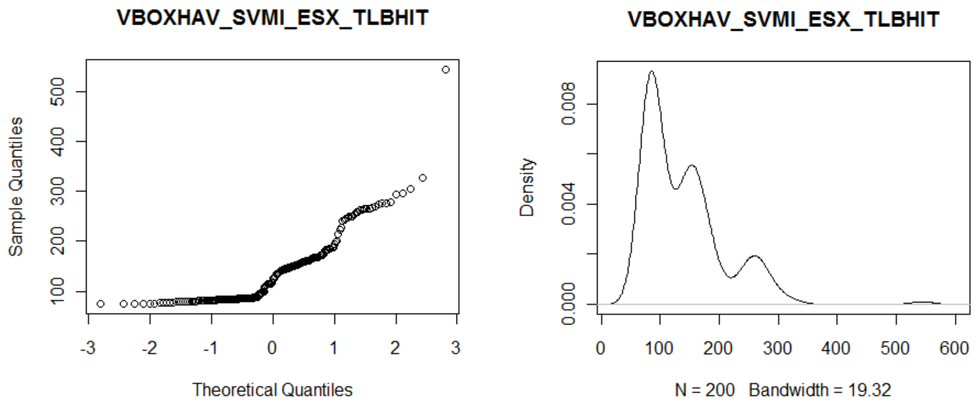

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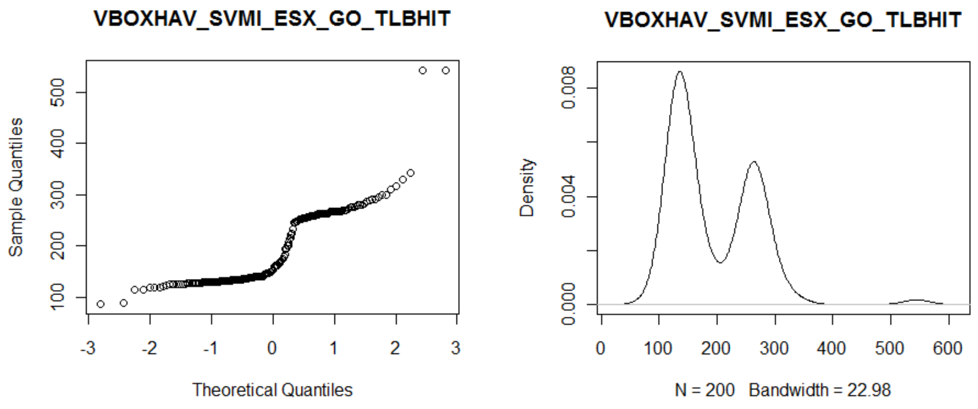

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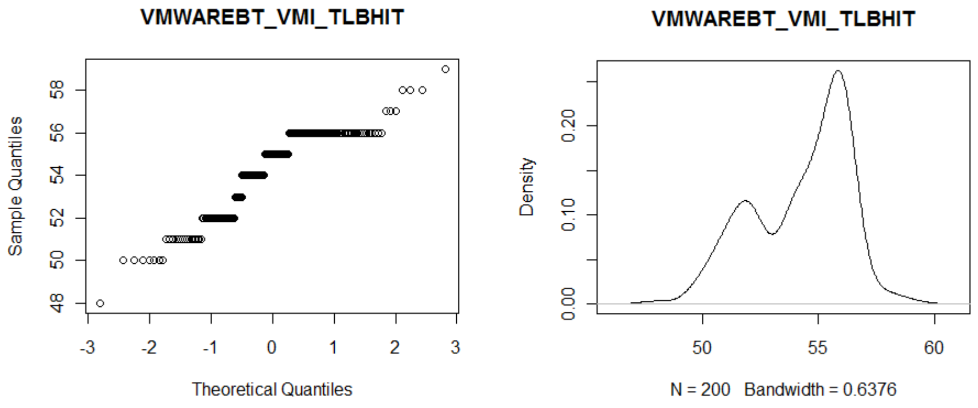
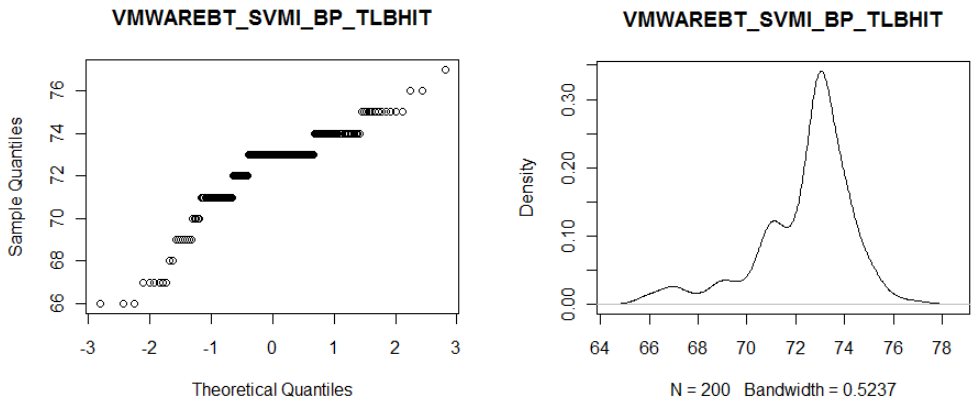


Figure 175. QQ Plot and Density Plot: VMWAREBT_VMI_TLBHIT



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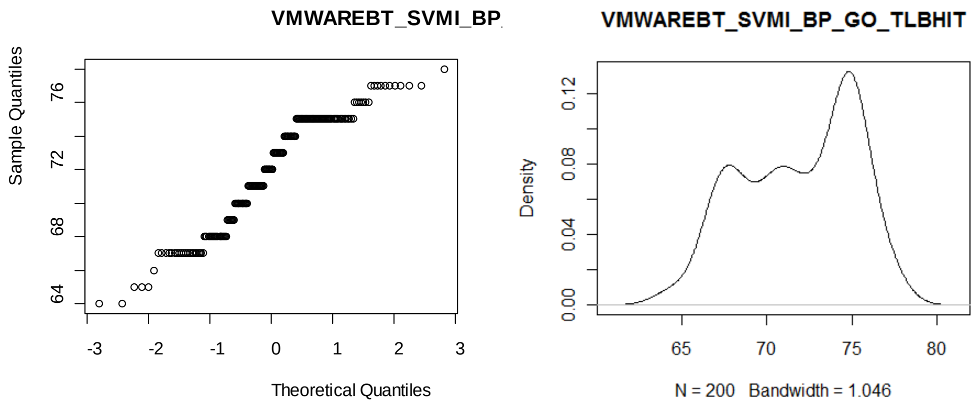

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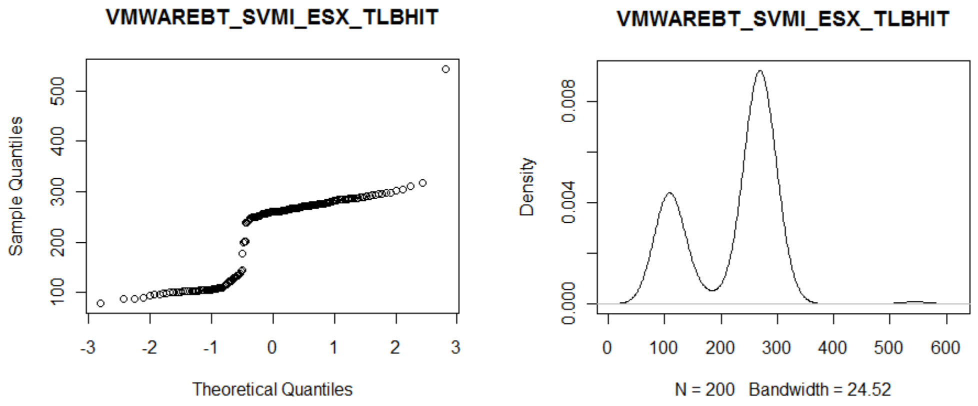

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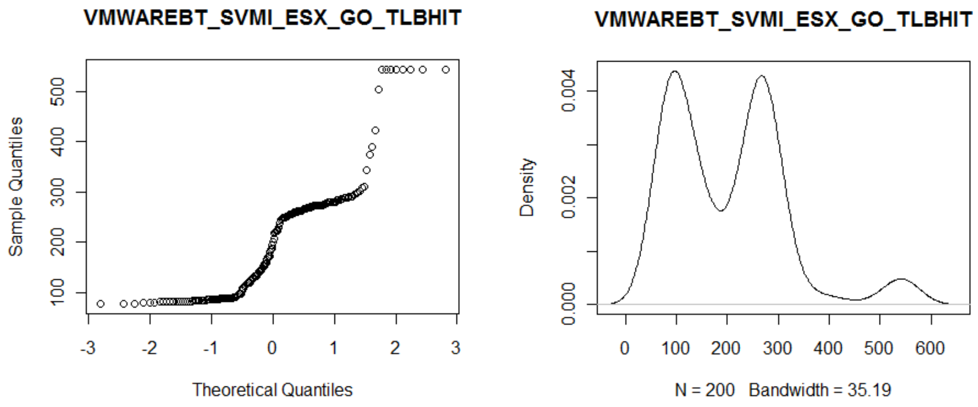

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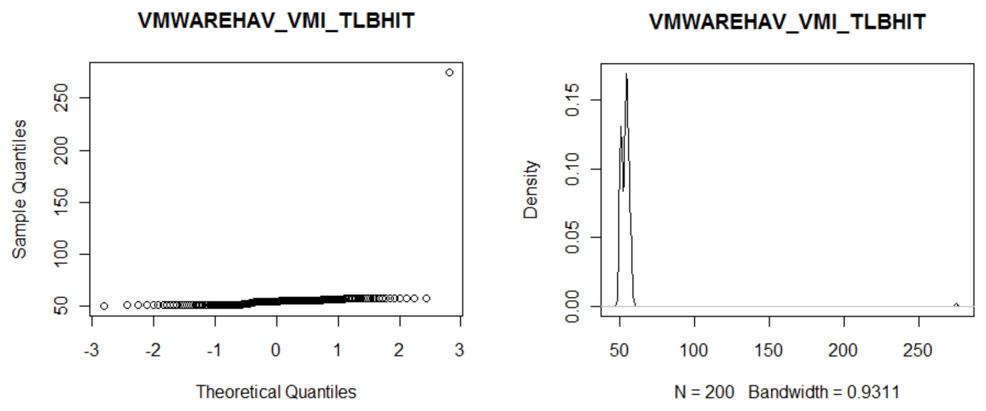

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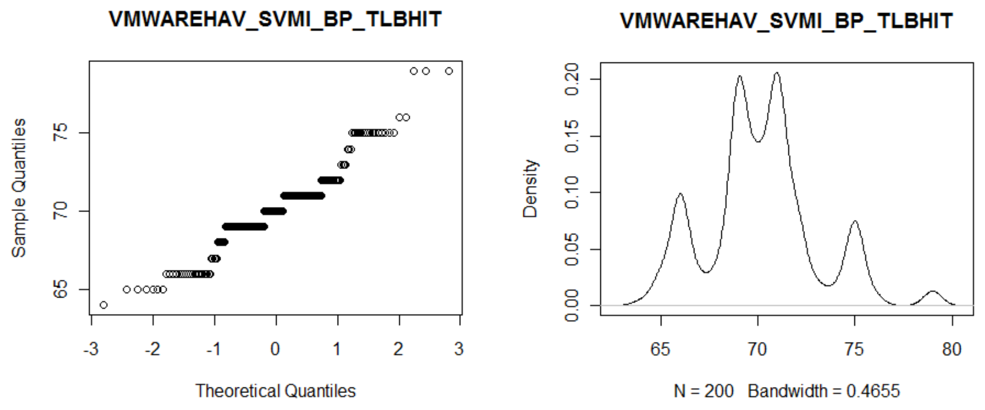

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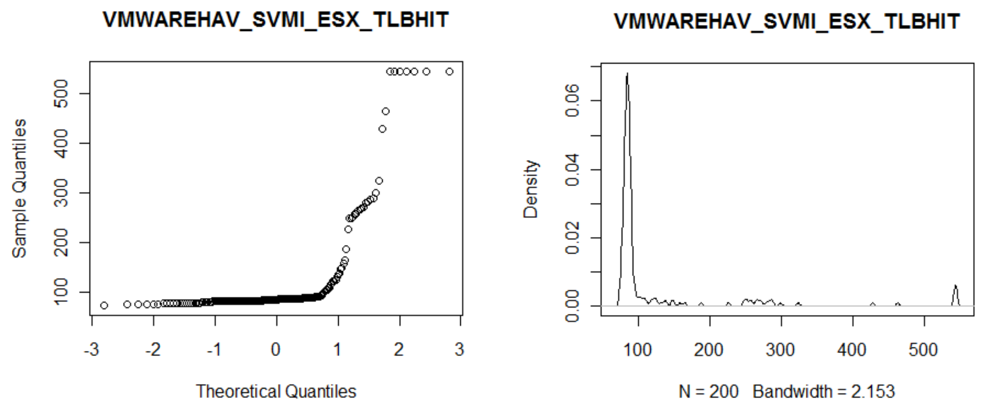

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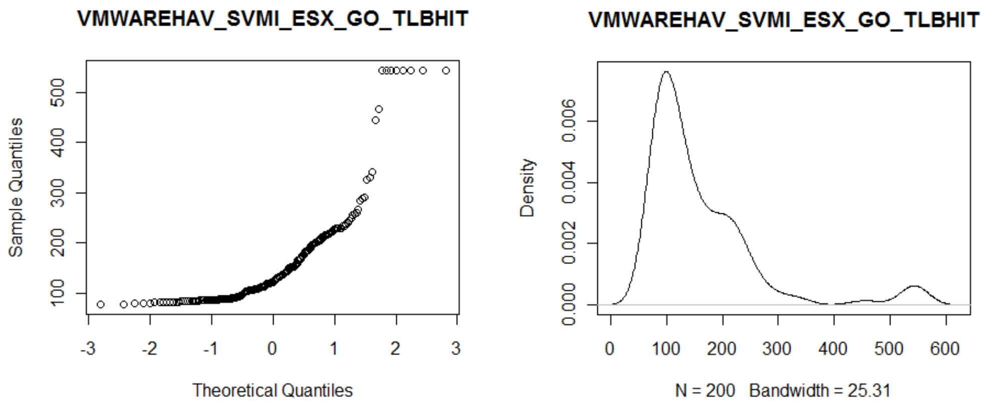

Figure 183. QQ Plot and Density Plot: VMWAREHAV_SVMI_ESX_GO_TLBHIT

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14. ABSTRACT

Virtual machine introspection (VMI) is intended to provide a secure and trusted platform from which forensic information can be gathered about the true behavior of malware within a guest. However, it is possible for malware to escape a guest into the host and for hypervisor rootkits, such as BluePill, to stealthily transition a native OS into a virtualized environment. This research examines the effectiveness of selected detection mechanisms against hardware-assisted virtualization rootkits (HAV-R) within a nested virtualized environment. It presents the design, implementation, analysis, and evaluation of a hypervisor rootkit detection system which exploits both processor and translation lookaside buffer-based mechanisms to detect hypervisor rootkits within a variety of nested virtualized systems. It evaluates the effects of different types of virtualization on hypervisor rootkit detection and explores the effectiveness in-guest HAV-R obfuscation efforts. The results provide convincing evidence that the HAV-Rs are detectable in all SVMI scenarios examined, regardless of HAV-R or virtualization type. Also, that the selected detection techniques are effective at detection of HAV-R within nested virtualized environments, and that the type of virtualization implemented in a VMI system has minimal to no effect on HAV-R detection. Finally, it is determined that in-guest obfuscation does not successfully obfuscate the existence of HAV-R.

15. SUBJECT TERMS

Hypervisor, Rootkit, Nested Virtualization, Detection, Evasion, Subversion, Virtual Machine Introspection, BluePill

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