Hypervisor From Scratch – Part 1: Basic Concepts & Configure Testing Environment

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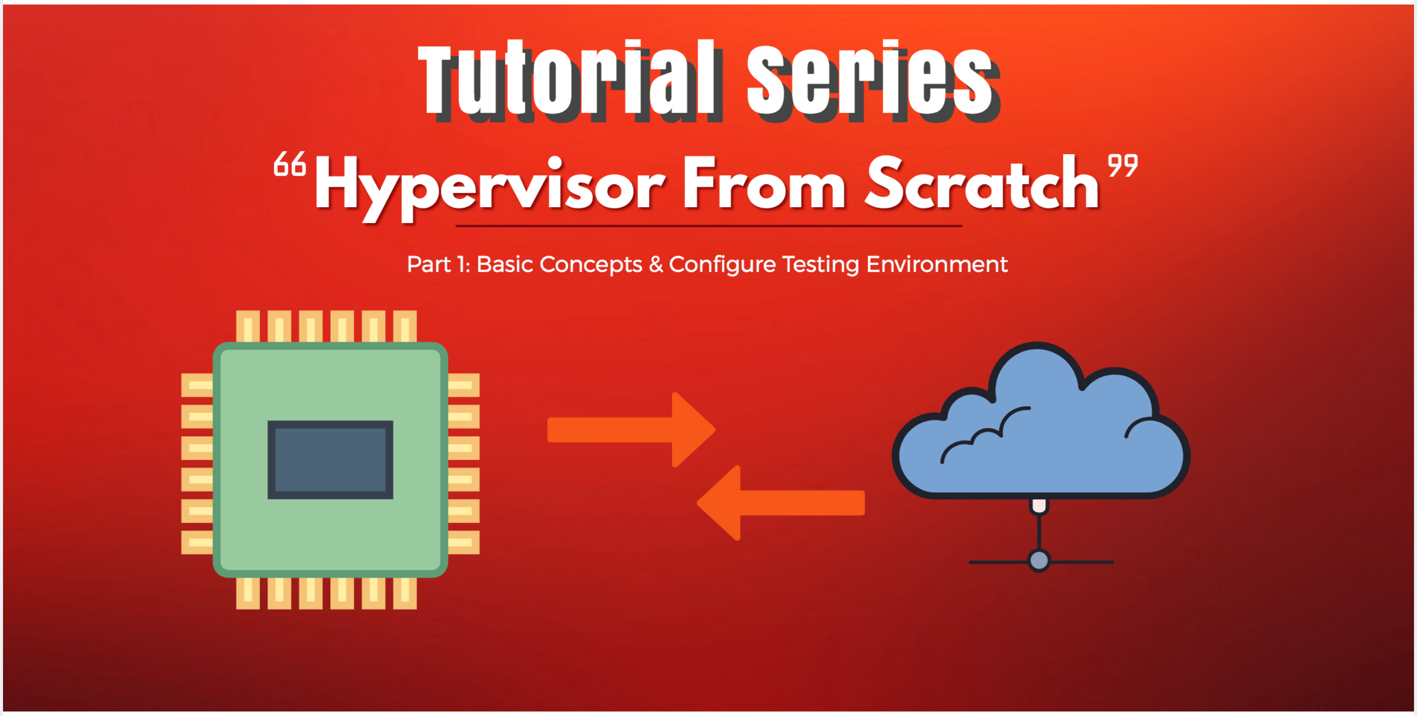


Hello everyone!

Welcome to the first part of a multi-part series of tutorials called “Hypervisor From Scratch”. As the name implies, this course contains technical details to create a basic Virtual Machine based on hardware virtualization. If you follow the course, you’ll be able to create your own virtual environment and you’ll get an understanding of how VMWare, VirtualBox, KVM and other virtualization softwares use processors’ facilities to create a virtual environment.

Introduction

Both Intel and AMD support virtualization in their modern CPUs. Intel introduced **(VT-x technology)** that previously codenamed “**Vanderpool**” on November 13, 2005, in Pentium 4 series. The CPU flag for **VT-x** capability is “**vmx**” which stands for **V**irtual **M**achine e**X**tension.

AMD, on the other hand, developed its first generation of virtualization extensions under the codename “**Pacifica**“, and initially published them as AMD **Secure Virtual Machine (SVM)**, but later marketed them under the trademark *AMD Virtualization*, abbreviated ***AMD-V***.

There two types of the hypervisor. The hypervisor type 1 called “bare metal hypervisor” or “native” because it runs directly on a bare metal physical server, a type 1 hypervisor has direct access to the hardware. With a type 1 hypervisor, there is no operating system to load as the hypervisor.

Contrary to a type 1 hypervisor, a type 2 hypervisor loads inside an operating system, just like any other application. Because the type 2 hypervisor has to go through the operating system and is managed by the OS, the type 2 hypervisor (and its virtual machines) will run less efficiently (slower) than a type 1 hypervisor.

Even more of the concepts about Virtualization is the same, but you need different considerations in **VT-x** and **AMD-V**. The rest of these tutorials mainly focus on **VT-x** because Intel CPUs are more popular and more widely used. In my opinion, AMD describes virtualization more clearly in its manuals but Intel somehow makes the readers confused especially in Virtualization documentation.

Hypervisor and Platform

These concepts are platform independent, I mean you can easily run the same code routine in both Linux or Windows and expect the same behavior from CPU but I prefer to use Windows as its more easily debuggable (at least for me.) but I try to give some examples for Linux systems whenever needed. Personally, as Linux kernel manages faults like #GP and other exceptions and tries to avoid kernel panic and keep the system up so it's better for testing something like hypervisor or any CPU-related affair. On the other hand, Windows never tries to manage any unexpected exception and it leads to a blue screen of death whenever you didn't manage your exceptions, thus you might get lots of BSODs.By the way, you'd better test it on both platforms (and other platforms too.).

At last, I might (and definitely) make mistakes like wrong implementation or misinformation or forget about mentioning some important description so I should say sorry in advance if I make any faults and I'll be glad for every comment that tells me my mistakes in the technical information or misinformation.

That's enough, Let's get started!

The Tools you'll need

You should have a Visual Studio with WDK installed. you can get Windows Driver Kit (WDK) here.

The best way to debug Windows and any kernel mode affair is using **Windbg** which is available in Windows SDK here. (If you installed WDK with default installing options then you probably install WDK and SDK together so you can skip this step.)

You should be able to debug your OS (in this case Windows) using Windbg, more information here.

Hex-rays IDA Pro is an important part of this tutorial.

OSR Driver Loader which can be downloaded here, we use this tools in order to load our drivers into the Windows machine.

SysInternals DebugView for printing the **DbgPrint()** results.

Creating a Test Environment

Almost all of the codes in this tutorial have to run in kernel level and you must set up either a Linux Kernel Module or Windows Driver Kit (WDK) module. As configuring VMM involves lots of assembly code, you should know how to run inline assembly within you kernel project. In Linux, you shouldn't do anything special but in the case of Windows, WDK no longer supports inline assembly in an x64 environment so if you didn't work on this problem previously then you might have struggle creating a simple x64 inline project but don't worry in one of my post I explained it step by step so I highly recommend seeing this topic to solve the problem before continuing the rest of this part.

Now its time to create a driver!

There is a good article here if you want to start with Windows Driver Kit (WDK).

The whole driver is this :

```
#include <ntddk.h>
#include <wdf.h>
#include <wdm.h>

extern void inline AssemblyFunc1(void);
extern void inline AssemblyFunc2(void);

VOID DrvUnload(PDRIVER_OBJECT  DriverObject);
NTSTATUS DriverEntry(PDRIVER_OBJECT  pDriverObject, PUNICODE_STRING  pRegistryPath);

#pragma alloc_text(INIT, DriverEntry)
#pragma alloc_text(PAGE, Example_Unload)

NTSTATUS DriverEntry(PDRIVER_OBJECT  pDriverObject, PUNICODE_STRING  pRegistryPath)
{
 NTSTATUS NtStatus = STATUS_SUCCESS;
 UINT64 uiIndex = 0;
 PDEVICE_OBJECT pDeviceObject = NULL;
 UNICODE_STRING usDriverName, usDosDeviceName;

 DbgPrint("DriverEntry Called.");

 RtlInitUnicodeString(&usDriverName, L"\Device\MyHypervisor");
 RtlInitUnicodeString(&usDosDeviceName, L"\DosDevices\MyHypervisor");

 NtStatus = IoCreateDevice(pDriverObject, 0, &usDriverName, FILE_DEVICE_UNKNOWN, FILE_DEVICE_SECURE_OPE

 if (NtStatus == STATUS_SUCCESS)
 {
 pDriverObject->DriverUnload = DrvUnload;
 pDeviceObject->Flags |= IO_TYPE_DEVICE;
 pDeviceObject->Flags &= (~DO_DEVICE_INITIALIZING);
 IoCreateSymbolicLink(&usDosDeviceName, &usDriverName);
 }
 return NtStatus;
}

VOID DrvUnload(PDRIVER_OBJECT  DriverObject)
{
 UNICODE_STRING usDosDeviceName;
 DbgPrint("DrvUnload Called rn");
 RtlInitUnicodeString(&usDosDeviceName, L"\DosDevices\MyHypervisor");
 IoDeleteSymbolicLink(&usDosDeviceName);
 IoDeleteDevice(DriverObject->DeviceObject);
}
```

AssemblyFunc1 and **AssemblyFunc2** are two external functions that defined as inline x64 assembly code.

Our driver needs to register a device so that we can communicate with our virtual environment from User-Mode code, on the hand, I defined **DrvUnload** which use PnP Windows driver feature and you can easily unload your driver and remove device then reload and create a new device.

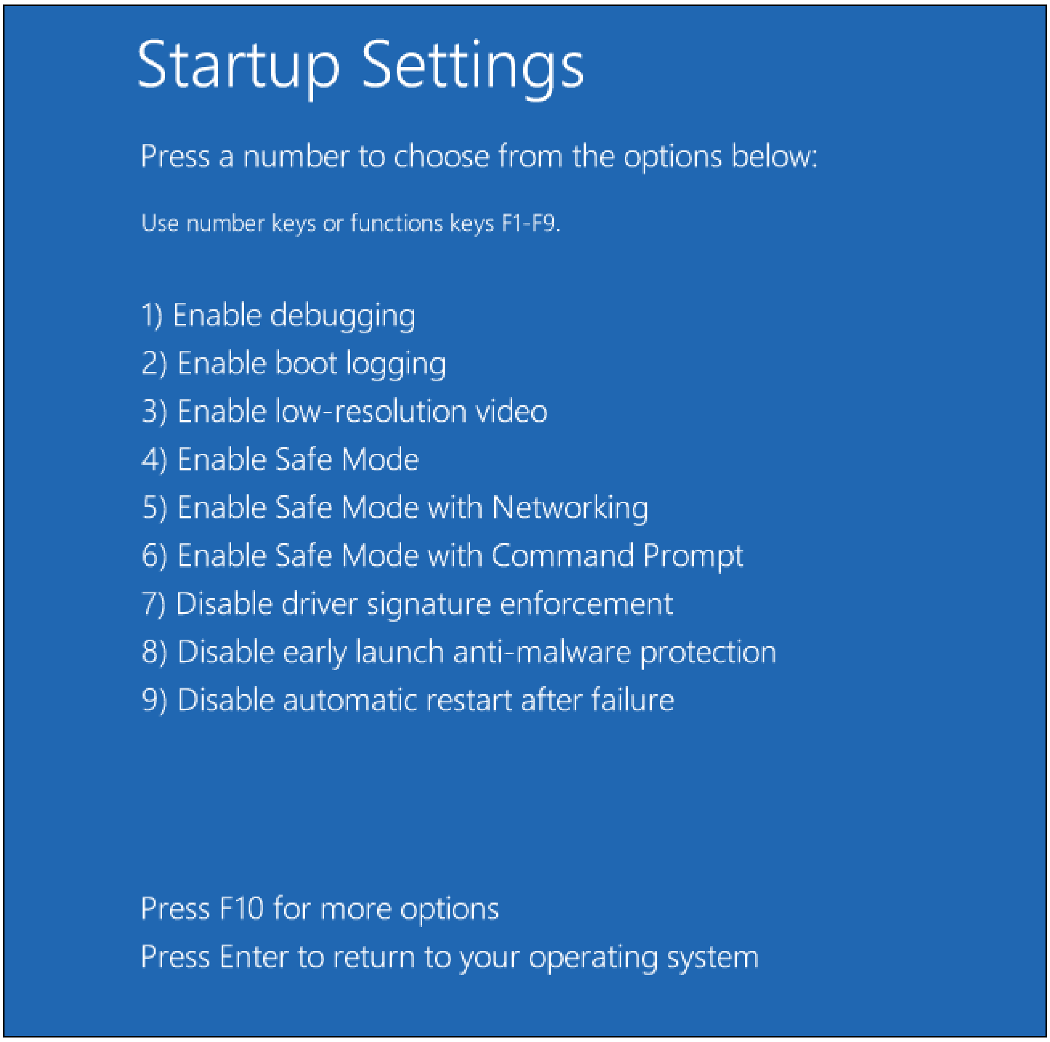
The following code is responsible for creating a new device :

```
 RtlInitUnicodeString(&usDriverName, L"\Device\MyHypervisor");
 RtlInitUnicodeString(&usDosDeviceName, L"\DosDevices\MyHypervisor");

 NtStatus = IoCreateDevice(pDriverObject, 0, &usDriverName, FILE_DEVICE_UNKNOWN, FILE_DEVICE_SECURE_OPE

 if (NtStatus == STATUS_SUCCESS)
 {
 pDriverObject->DriverUnload = DrvUnload;
 pDeviceObject->Flags |= IO_TYPE_DEVICE;
 pDeviceObject->Flags &= (~DO_DEVICE_INITIALIZING);
 IoCreateSymbolicLink(&usDosDeviceName, &usDriverName);
 }
```

If you use Windows, then you should disable Driver Signature Enforcement to load your driver, that's because Microsoft prevents any not verified code to run in Windows Kernel (Ring 0).

To do this, press and hold the shift key and restart your computer. You should see a new Window, then

1. Click **Advanced options**.
2. On the new Window Click **Startup Settings**.
3. Click on **Restart**.
4. On the Startup Settings screen press 7 or F7 to disable driver signature enforcement.



The latest thing I remember is enabling Windows Debugging messages through registry, in this way you can get **DbgPrint()** results through **SysInternals DebugView**.

Just perform the following steps:

In regedit, add a key:

HKEY_LOCAL_MACHINE\SYSTEM\CurrentControlSet\Control\Session Manager\Debug Print Filter

Under that , add a DWORD value named IHVDRIVER with a value of 0xFFFF

Reboot the machine and you'll good to go.

Some thoughts before the start

There are some keywords that will be frequently used in the rest of these series and you should know about them (Most of the definitions derived from **Intel software developer's manual, volume 3C**).

Virtual Machine Monitor (VMM): VMM acts as a host and has full control of the processor(s) and other platform hardware. A VMM is able to retain selective control of processor resources, physical memory, interrupt management, and I/O.

Guest Software: Each virtual machine (VM) is a guest software environment.

VMX Root Operation and VMX Non-root Operation: A VMM will run in VMX root operation and guest software will run in VMX non-root operation.

VMX transitions: Transitions between VMX root operation and VMX non-root operation.

VM entries: Transitions into VMX non-root operation.

Extended Page Table (EPT): A modern mechanism which uses a second layer for converting the guest physical address to host physical address.

VM exits: Transitions from VMX non-root operation to VMX root operation.

Virtual machine control structure (VMCS): is a data structure in memory that exists exactly once per VM, while it is managed by the VMM. With every change of the execution context between different VMs, the VMCS is restored for the current VM, defining the state of the VM's virtual processor and VMM control Guest software using VMCS.

The VMCS consists of six logical groups:

- Guest-state area: Processor state saved into the guest state area on VM exits and loaded on VM entries.
- Host-state area: Processor state loaded from the host state area on VM exits.
- VM-execution control fields: Fields controlling processor operation in VMX non-root operation.
- VM-exit control fields: Fields that control VM exits.
- VM-entry control fields: Fields that control VM entries.
- VM-exit information fields: Read-only fields to receive information on VM exits describing the cause and the nature of the VM exit.

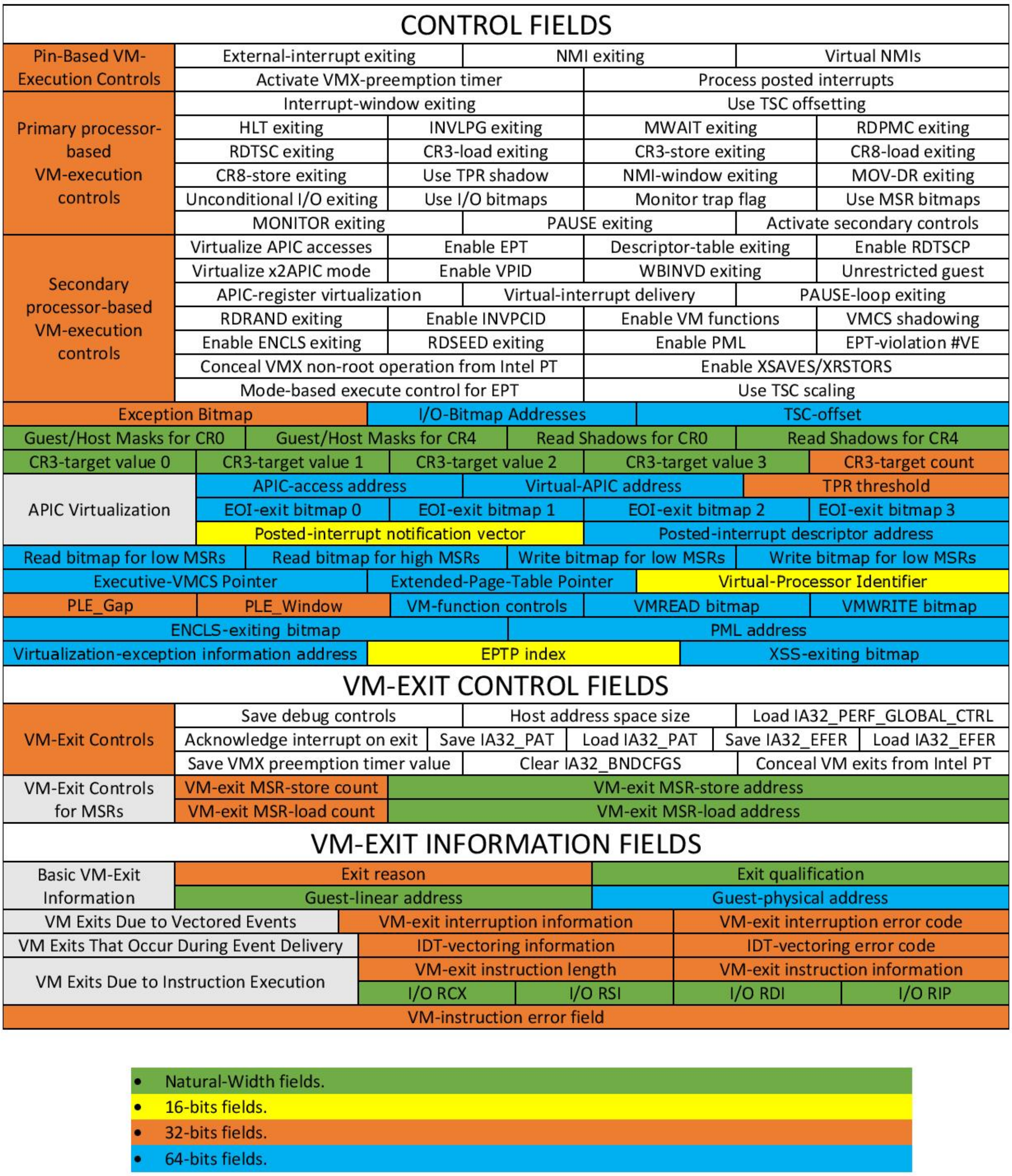
I found a great work which illustrates the VMCS, The PDF version is also available here.

GUEST STATE AREA

CR0	CR3		CR4	
DR7				
RSP	RIP		RFLAGS	
CS	Selector	Base Address	Segment Limit	Access Right
SS	Selector	Base Address	Segment Limit	Access Right
DS	Selector	Base Address	Segment Limit	Access Right
ES	Selector	Base Address	Segment Limit	Access Right
FS	Selector	Base Address	Segment Limit	Access Right
GS	Selector	Base Address	Segment Limit	Access Right
LDTR	Selector	Base Address	Segment Limit	Access Right
TR	Selector	Base Address	Segment Limit	Access Right
GDTR	Selector	Base Address	Segment Limit	Access Right
IDTR	Selector	Base Address	Segment Limit	Access Right
IA32_DEBUGCTL	IA32_SYSENTER_CS	IA32_SYSENTER_ESP	IA32_SYSENTER_EIP	
IA32_PERF_GLOBAL_CTRL	IA32_PAT	IA32_EFER	IA32_BNDCFGS	
SMBASE				
Activity state	Interruptibility state			
Pending debug exceptions				
VMCS link pointer				
VMX-preemption timer value				
Page-directory-pointer-table entries	PDPTE0	PDPTE1	PDPTE2	PDPTE3
Guest interrupt status				
PML index				

HOST STATE AREA

CR0	CR3	CR4
RSP	RIP	
CS	Selector	
SS	Selector	
DS	Selector	
ES	Selector	
FS	Selector	Base Address
GS	Selector	Base Address
TR	Selector	Base Address
GDTR	Base Address	
IDTR	Base Address	
IA32_SYSENTER_CS	IA32_SYSENTER_ESP	IA32_SYSENTER_EIP
IA32_PERF_GLOBAL_CTRL	IA32_PAT	IA32_EFER



CopyLeft 2017, @Noteworthy (Intel Manuel of July 2017)

Don't worry about the fields, I'll explain most of them clearly in the later parts, just remember VMCS Structure varies between different version of a processor.

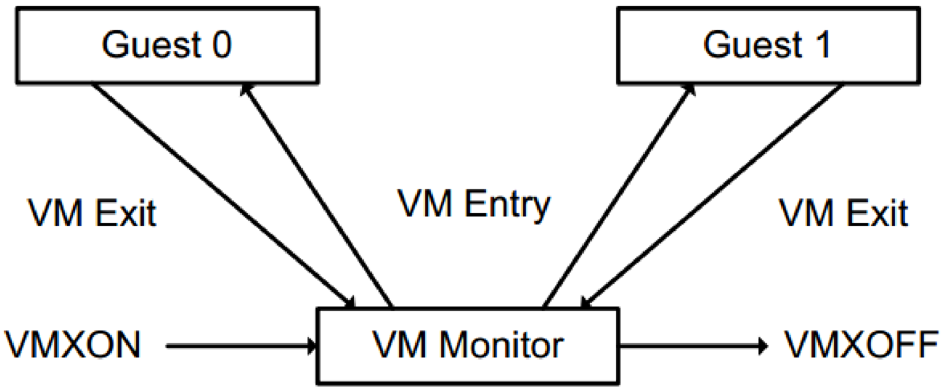
VMX Instructions

VMX introduces the following new instructions.

Intel/AMD Mnemonic	Description
`INVEPT`	Invalidate Translations Derived from EPT
`INVVPID`	Invalidate Translations Based on VPID
`VMCALL`	Call to VM Monitor

VMCLEAR	Clear Virtual-Machine Control Structure
VMFUNC	Invoke VM function
VMLAUNCH	Launch Virtual Machine
VMRESUME	Resume Virtual Machine
VMPTRLD	Load Pointer to Virtual-Machine Control Structure
VMPTRST	Store Pointer to Virtual-Machine Control Structure
VMREAD	Read Field from Virtual-Machine Control Structure
VMWRITE	Write Field to Virtual-Machine Control Structure
VMXOFF	Leave VMX Operation
VMXON	Enter VMX Operation

Life Cycle of VMM Software



- The following items summarize the life cycle of a VMM and its guest software as well as the interactions between them:
  - Software enters VMX operation by executing a VMXON instruction.
  - Using VM entries, a VMM can then turn guests into VMs (one at a time). The VMM effects a VM entry using instructions VMLAUNCH and VMRESUME; it regains control using VM exits.
  - VM exits transfer control to an entry point specified by the VMM. The VMM can take action appropriate to the cause of the VM exit and can then return to the VM using a VM entry.
  - Eventually, the VMM may decide to shut itself down and leave VMX operation. It does so by executing the VMXOFF instruction.

That's enough for now!

In this part, I explained about general keywords that you should be aware and we create a simple lab for our future tests. In the next part, I will explain how to enable VMX on your machine using the facilities we create above, then we survey among the rest of the virtualization so make sure to check the blog for the next part.

References

[1] Intel® 64 and IA-32 architectures software developer's manual combined volumes 3 (https://software.intel.com/en-us/articles/intel-sdm)

[2] Hardware-assisted Virtualization (http://www.cs.cmu.edu/~412/lectures/L04_VTx.pdf)

[3] Writing Windows Kernel Driver (https://resources.infosecinstitute.com/writing-a-windows-kernel-driver/)

[4] What Is a Type 1 Hypervisor? (http://www.virtualizationsoftware.com/type-1-hypervisors/)

[5] Intel / AMD CPU Internals (https://github.com/LordNoteworthy/cpu-internals)

[6] Windows 10: Disable Signed Driver Enforcement (https://ph.answers.acer.com/app/answers/detail/a_id/38288/~/windows-10%3A-disable-signed-driver-enforcement)

[7] Instruction Set Mapping » VMX Instructions (https://docs.oracle.com/cd/E36784_01/html/E36859/gntbx.html)

Sinaei

Judas tree , What kind of mystery is this, that every spring, Comes with our hearts' mourning, Judas tree, You be elate, You sing my unsang song...

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