Follow the WhiteRabbit: Towards Consolidation of On-the-Fly Virtualization and Virtual Machine Introspection

IFIP SEC 2018

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19.09.2018

“Follow the white rabbit.”

— The Matrix

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Introduction & Background

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Modern Operating Systems (OSes) provide a large attack surface

- 334 system calls in Linux kernel v4.18 (excluding compatibility system calls for 32-bit)
- Malware can gain the same privileges as OSes

→ Bypass or disable security mechanisms

Move security applications out of the OS [1]:

- Place security applications into a small environment with higher privileges

→ Employ system virtualization

Some background on system virtualization:

> "x86 virtualization is about basically placing another nearly full kernel, full of new bugs, on top of a nasty x86 architecture which barely has correct page protection. Then running your operating system on the other side of this brand new pile of s****. [...] That's all x86 virtualization is."
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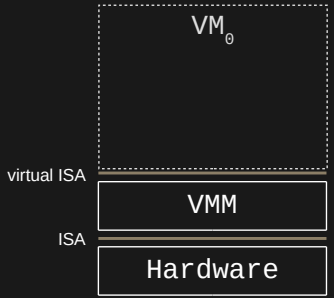

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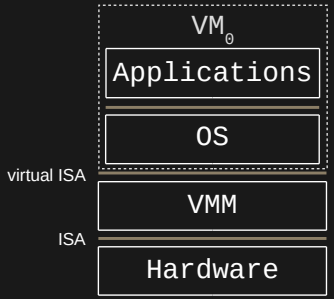

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System virtualization employed for different purposes

- Malware detection [4] and analysis [2, 5]
- System integrity validation [6]

Benefits of system virtualization

- Narrow attack surface
- Strong isolation capabilities
- Complete view over the VM's state

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How can we analyze OS internals from the outside?

Employ Virtual Machine Introspection (VMI) [4] techniques

Virtual Machine Introspection [4]

- Analyze and manipulate the guest OS state from the outside of the VM
- Binary state of guest OSes needs interpretation
  - Map the binary state to OS data structures
  - → Lack of semantic information

Excerpt of the OS binary state

```
1 20 00 00 00 00 00 00 00 FF FF FF FF FF FF 00 00
2 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
3 00 80 54 0C 00 00 FF FF 02 00 00 00 00 01 40 00
4 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
5 01 00 00 00 01 00 00 00 10 00 00 00 00 00 00 00
6 BA EC FE FF 00 00 00 00 80 CF 66 28 00 80 FF FF
7 [...]
```

The Semantic Gap problem [1]

- Use semantic information of the guest OS and virtual hardware to bridge the Semantic Gap [7]

Virtual Machine Introspection [4]

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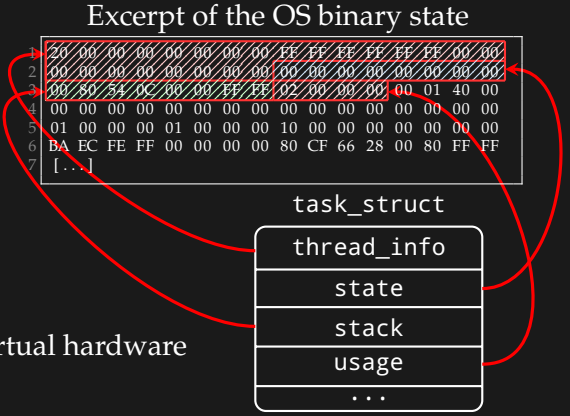

Motivation

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Conventional VMI frameworks

- Employ VMI-aware VMMs (Xen, KVM, etc.)

Issue: Target systems must be explicitely set up for VMI before operation

- Increases the administrative overhead
- Constraints employment of VMI

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Idea: Combine VMI along with on-the-fly virtualization

→ WhiteRabbit VMI framework for forensic analysis

- Based on the idea of the Blue Pill rootkit [9]
- Employs Intel VT-x and ARM virtualization extensions

Goals

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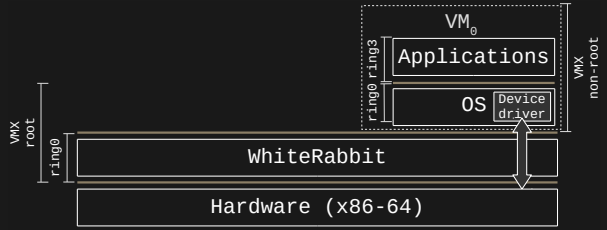
(1) Virtual Machine Monitor
- Take over control of a running Linux (idea not limited to any OS)

(2) Hiding from (split-personality) malware in memory
- Employ Second Stage Address Translation

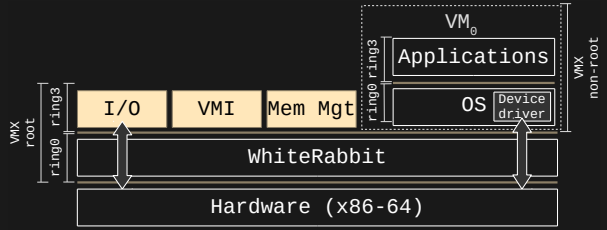
(3) (Remote) Virtual Machine Introspection
- Expose LibVMI interface to local or remote applications

Goal 1: WhiteRabbit VMM



Microkernel architecture designed for on-the-fly virtualization

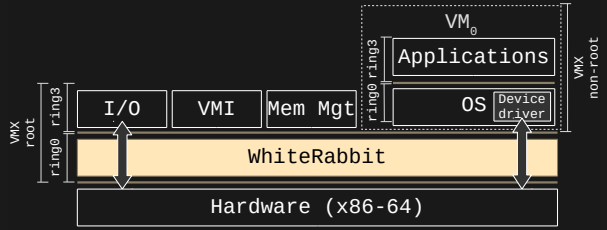
Goal 1: WhiteRabbit VMM



Microkernel architecture designed for on-the-fly virtualization

- Subsystems placed in user space (ring 3 on Intel; EL0 on ARM)
- I/O drivers isolated from the guest
  - Establish a secure communication channel
  - Leverage unused I/O devices or hardware multiplexing (e.g., Intel VT-d, ARM SMMU)

Goal 1: WhiteRabbit VMM



Microkernel architecture designed for on-the-fly virtualization

- Only essential functionality in ring 0 on Intel (VMX root) and EL2 on ARM
  - Reduced size and complexity of the VMM
- Can be deployed in an OS-dependent or OS-independent way

Goal 1: On-the-Fly Virtualization

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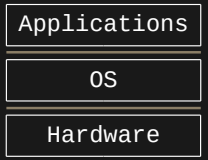
A VMM distributes its tasks across [8] :

- Allocator
- Dispatcher
- Interpreter

Goal 1: On-the-Fly Virtualization

The Allocator



The allocator moves a running OS into a virtual environment

Goal 1: On-the-Fly Virtualization

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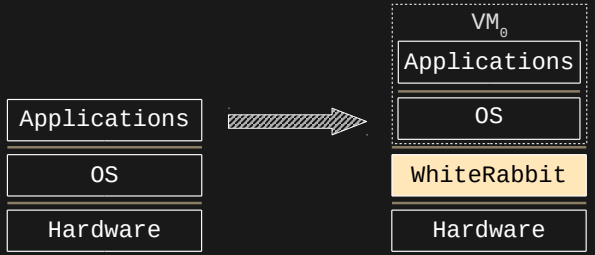

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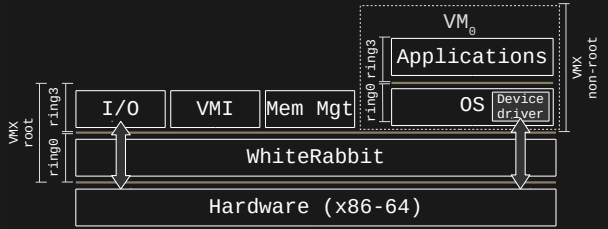
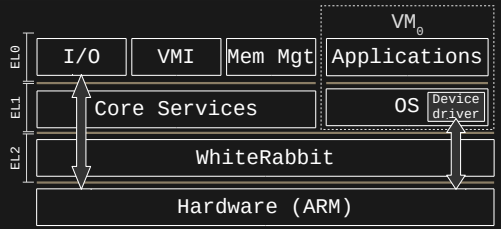


The allocator moves a running OS into a virtual environment

- Intel: Initializes the Intel VT-x defined VMCS data structure
  - Guest state initialized with the current system state
  - Set up host state representing the VMM
  - Initiates virtualization

Goal 1: On-the-Fly Virtualization

The Allocator



The allocator moves a running OS into a virtual environment

- ARM: Uses the hypervisor stub to take control of the exception levels in EL2
  - Boot loader launches OS kernel in EL2 before entering EL1
  - OS installs a general purpose hypervisor stub in EL2
  - Use the hypervisor stub to place running OS into a VM

Goal 1: WhiteRabbit VMM

The Dispatcher & The Interpreter

The dispatcher determines which task to perform next

- Can be regarded as a task scheduler
- Dispatcher triggered on every VM exit
- Relays tasks to subsystems or the interpreter

The interpreter simulates behavior of guest events

- Emulation routines for trapped instructions and events
- Is leveraged for VMI purposes

Goal 2: Hiding Techniques

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Split-personality malware

- Employ anti-virtualization to reveal a VMM (red pills)

Perfect VM transparency is unfeasible [3]

- Insufficient to reveal virtual environments alone!

More interesting to know whether the system is being analyzed

→ Hide analysis artifacts from the guest

Goal 2: Hiding Techniques

Second Level Address Translation

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Harden disclosure of the analysis framework in memory

- Leverage Second Level Address Translation
- Intercept and redirect access to memory used by WhiteRabbit

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Issue: If WhiteRabbit deployed as a kernel module

- First instruction of the VM is one of the last instructions of module initialization
- The `struct task_struct` filled with remaining information after module loading

→ Both regions are masked within Second Level Address Translation (SLAT) tables

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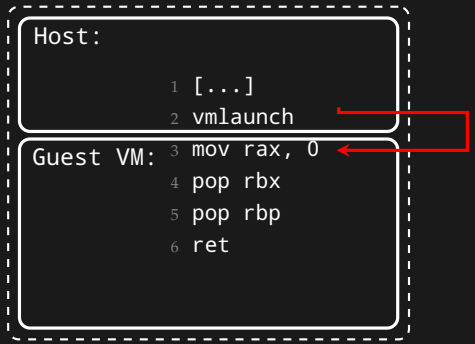

Module Initialization Routine

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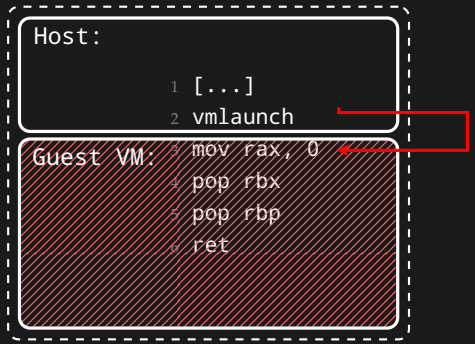

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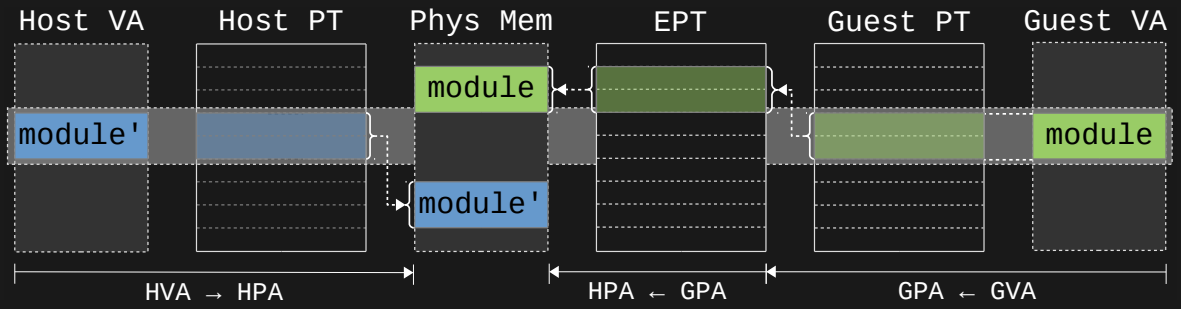
SLAT & Module Relocation



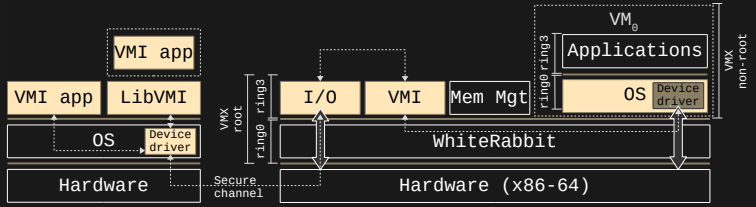
Relocate code and data segments of WhiteRabbit

- `module'` and `module` mapped to the same virtual address space (guest and host)

Remove the kernel module inside of the guest OS

- `module` returns a negative value (visible via `dmesg`)
- Better: Use a work-queue to initiate a clean module destruction

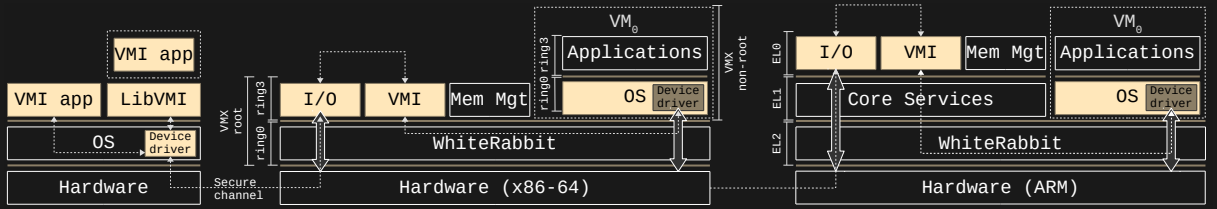
Goal 3: Virtual Machine Introspection



WhiteRabbit offers a LibVMI-compatible interface towards remote clients

- WhiteRabbit acts as a vehicle for generic VMI tools
- Remote VMI tools perform arbitrary VMI on the virtualized OS
  - Need for a secure communication channel

Goal 3: Virtual Machine Introspection



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Evaluation

Performance: Virtualization Overhead

VMM	CPU	Memory
WhiteRabbit	0.74%	3.48%
Xen	2.66%	3.48%
Linux KVM	4.02%	4.92%

Table: Averaged results of CPU- and memory-intensive macro-benchmarks

System setup

- Linux kernel v4.13
- Skylake μarchitecture with Intel Core i7-6700
- CPU- and memory-intensive macro-benchmarks of the Phoronix Test Suite v7.6.0

Evaluation

Effectiveness: Anti-Virtualization Techniques

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- Virtualization artifacts:
  - → No system configuration changes and no guest-visible artifacts
- Hardware artifacts:
  - Guest can directly access the hardware without emulation
  - Timing can reveal the VMM
    - → Today, it is insufficient to reveal the virtual environment alone
- User behavior artifacts:
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- User behavior artifacts:
  - → Virtualize production systems with realistic wear-and-tear relics
- Hardware deficiencies:
  - Foreshadow [10]!

Conclusion & Future Work

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- Design of WhiteRabbit VMI framework
  - Virtualizes Linux OSes upon Intel and ARM architectures
- Hardened WhiteRabbit exposure
  - Employs SLAT tables to delude memory carving
- Virtual Machine Introspection
  - Exposes a LibVMI-compatible interface to local (and remote) parties
- Future Work:
  - Explore the need for nested on-the-fly virtualization
  - Open source WhiteRabbit!

Evaluation cont.

Performance: Makro-benchmarks

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Table: Virtualization overhead (OHD) of WhiteRabbit, Xen, and KVM measured by the Phoronix Test Suite v7.6.0 on x86-64.

Benchmark (*unit*)	**w/o**	**KVM**	**(OHD)**	**Xen**	**(OHD)**	**WhiteRabbit**	**(OHD)**
Blake2 (*Cycles/Byte*)	5.94	5.94	(0.00%)	5.94	(0.00%)	5.94	(0.00%)
C-Ray (*s*)	107.08	108.56	(1.38%)	107.67	(0.55%)	107.09	(0.00%)
Gzip Compression (*s*)	11.50	12.06	(4.86%)	11.98	(4.17%)	11.74	(2.08%)
John-the-Ripper DES (*Real C/s*)	5,419,000	5,340,000	(1.45%)	5,394,000	(0.46%)	5,417,667	(0.02%)
John-the-Ripper MD5 (*Real C/s*)	16,844	16,583	(1.54%)	16,748	(0.56%)	16,822	(0.13%)
N-queens (*s*)	216.70	220.94	(1.95%)	217.77	(0.49%)	216.80	(0.04%)
OpenSSL (*Signs/s*)	145	141.83	(2.18%)	142.53	(1.70%)	144.70	(0.20%)
7-Zip Compression (*MIPS*)	4,603	3,736	(18.83%)	3,988	(13.36%)	4,443	(3.47%)
RAMspeed Integer (*MB/s*)	17,370.73	16,630.25	(4.26%)	16,942.71	(2.46%)	17,016.09	(2.04%)
RAMspeed Floating Point (*MB/s*)	17,734.84	16,744.56	(5.58%)	16,875.53	(4.84%)	16,861.26	(4.92%)

Evaluation cont.

Performance: Makro- and Micro-benchmarks

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Table: SPEC CPU2017, in sec.

Benchmark	w/a	WhiteRabbit	OHD
600.perlbench_s	282	286	(1.41%)
602.gcc_s	409	419	(2.44%)
605.mcf_s	624	641	(2.72%)
620.omnetpp_s	382	406	(6.28%)
623.xalancbmk_s	283	294	(3.88%)
625.x264_s	378	378	(0.00%)
631.deepsjeng_s	357	363	(1.68%)
641.leela_s	460	460	(0.00%)
648.exchange2_s	264	265	(0.37%)
657.xz_s	2220	2379	(7.16%)

Table: Lmbench 3.0, in μsec

Benchmark	w/a	WhiteRabbit	OHD
fork+execve	50.04	58.23	(16.36%)
fork+/bin/sh	254.36	289.84	(13.94%)
pipe	1.51	1.65	(9.27%)
protection fault	0.30	0.31	(3.33%)
read	0.09	0.09	(0.00%)
select 500 fd	2.46	2.52	(2.38%)
select 500 TCP fd	8.16	8.35	(2.32%)
signal handle	0.66	0.65	(1.51%)
sock	1.99	2.07	(4.02%)
write	0.05	0.06	(19.99%)

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