Subverting System Authentication With Context-Aware, Reactive Virtual Machine Introspection

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The University of Texas at Dallas

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Outline

1. Background
2. Detailed Design
3. Implementation
4. Evaluation
5. Related Work
6. Summary

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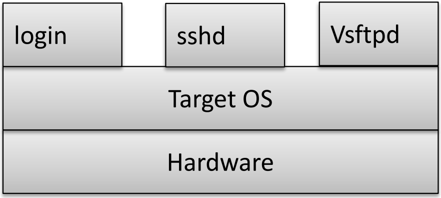
Traditional computer system structure



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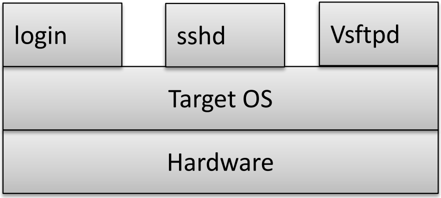

login

sshd

Vsftpd

Target OS

Hardware

Authentication protection Mechanism

- Anti-debugging Logic
- Cryptographic Security
- Code Obfuscation
- Self-Checking

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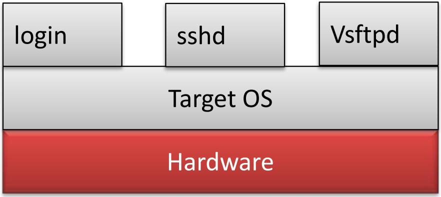
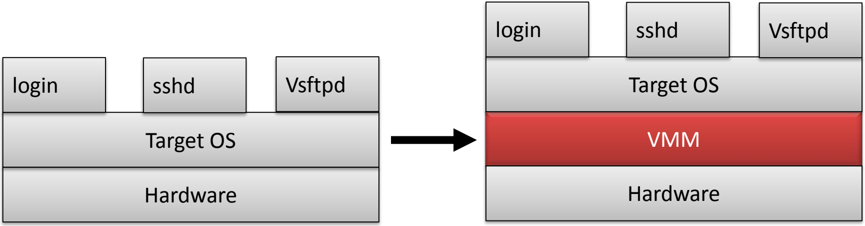


Trust?

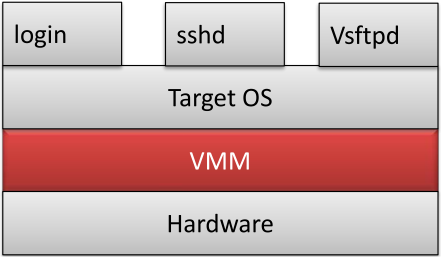
Authentication protection Mechanism

- anti-debugging logic
- cryptographic security
- code obfuscation
- self-checking

Virtualization



Motivations



Adding a virtualization layer

- VMM runs at higher privilege than guest OS
- Great isolation, more stealthy
- A full control of guest OS
- A grand view of the entire state of guest OS.

Malicious VMM

Goal

- Subverting authentication(e.g., `login`) with Context-Aware, Reactive Virtual Machine Introspection(VMI)
- Attackers can gain fun and profit: Accessing sensitive data in a computer (e.g., a laptop, or a VM)

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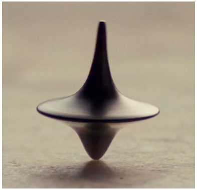
Assumptions

- Assume physical access (lost of laptop, VMs running in a cloud)
- Possible attackers/users
  - Malicious cloud providers (cloud being compromised)
  - Law enforcement (accessing criminal's computer, note that a physical machine can be virtualized)

Running a machine inside a malicious VMM



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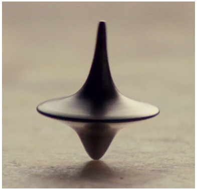
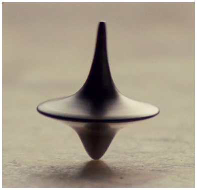


Inception Attack

- Changing your idea using a dream
- Dream can be inside a dream

Running a machine inside a malicious VMM



Inception Attack

- Changing your idea using a dream
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Malicious Virtualization Monitor

- Running a machine inside a **virtual machine**
- We change the guest OS state from the **malicious virtual machine** without the awareness from any insider programs

How it works

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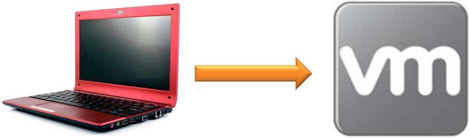

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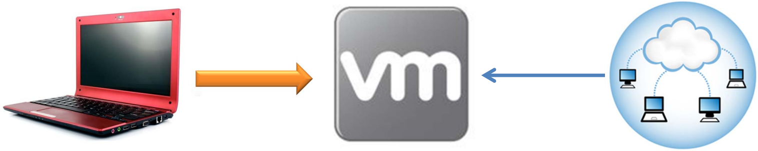

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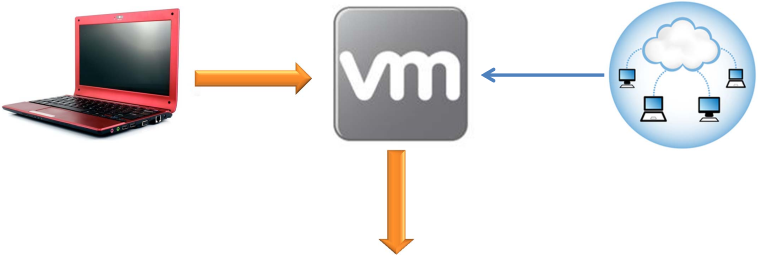

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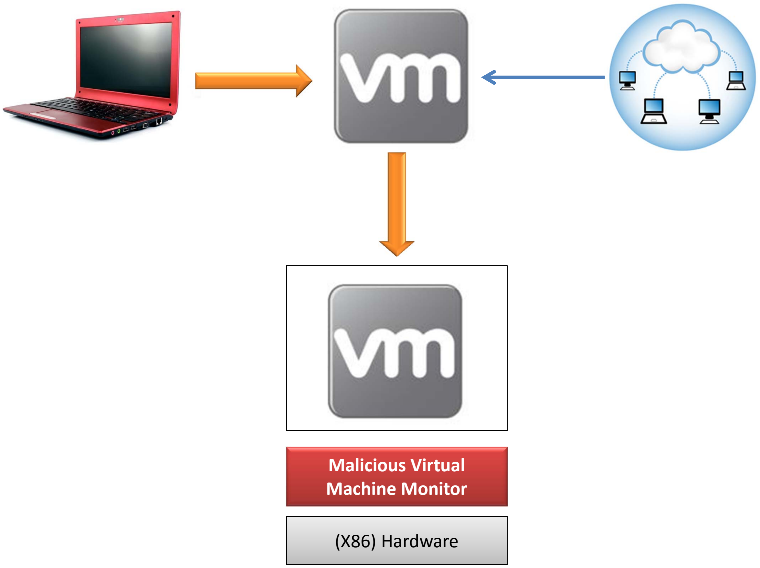

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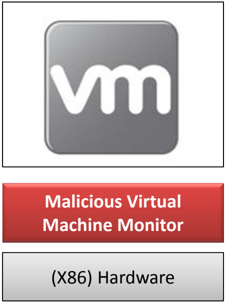

Malicious Virtual Machine Monitor

(X86) Hardware

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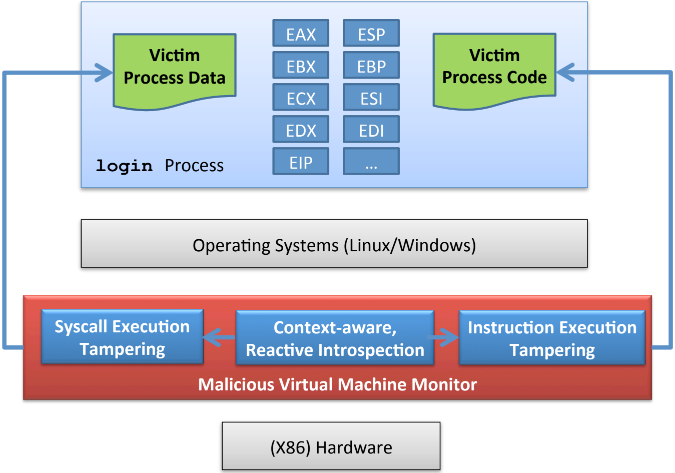
Overview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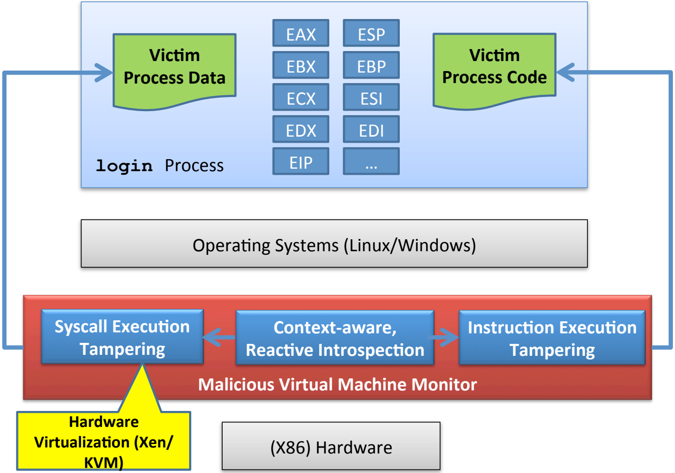
Using Hardware Virtualization



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`login` Process

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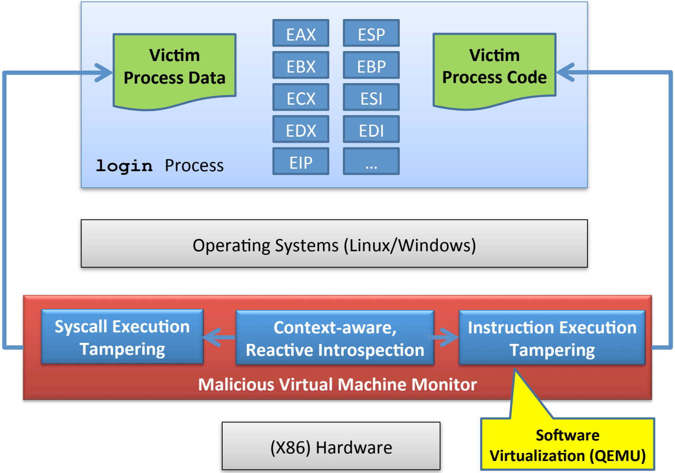
Malicious Virtual Machine Monitor

Hardware Virtualization (Xen/KVM)

(X86) Hardware

Using Software Virtualization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Software Virtualization (QEMU)

Working Example: from instructions perspective

```
if (pw_auth (user_passwd, username, reason, (char *) 0) == 0) {
 804a868:    a1 0c 62 05 08              mov    0x805620c,%eax
 804a86d:    c7 44 24 0c 00 00 00        movl   $0x0,0xc(%esp)
 804a874:    00
 804a875:    89 3c 24                    mov    %edi,(%esp)
 804a878:    89 44 24 08                 mov    %eax,0x8(%esp)
 804a87c:    a1 48 65 05 08              mov    0x8056548,%eax
 804a881:    89 44 24 04                 mov    %eax,0x4(%esp)
 804a885:    e8 86 87 00 00              call   8053010<pw_auth>
 804a88a:    85 c0                       test   %eax,%eax
 804a88c:    0f 84 6d fd ff ff           je     804a5ff<main+0x64f>
            goto auth_ok;
}
```

Figure : Binary Code Snippet of the `login` Program.

Insight-I

Instruction Execution Tampering

- Tampering with Instruction Opcode
  - `804a88c:0f 84 (je)` → `0f 85 (jne)`
- Tampering with Instruction Operand
  - `804a88a:test %eax,%eax` → Tampering w/ `eax`/`EFLAGS`
- Tampering with both Opcode and Operand
  - `804a885:call 8053010` → `mov $0,%eax`

Working Example: from system call perspective

```
  1 execve("/bin/login", ["login"], [/* 16 vars */]) = 0
  2 uname({sys="Linux", node="ubuntu", ...}) = 0
...
409 open("/etc/passwd", O_RDONLY)                 = 4
410 fcntl64(4, F_GETFD)                           = 0
411 fcntl64(4, F_SETFD, FD_CLOEXEC)               = 0
412 _llseek(4, 0, [0], SEEK_CUR)                  = 0
413 fstat64(4, {st_mode=S_IFREG|0644, st_size=952, ...}) = 0
414 mmap2(NULL, 952, PROT_READ, MAP_SHARED, 4, 0) = 0x4021a000
415 _llseek(4, 952, [952], SEEK_SET)              = 0
416 munmap(0x4021a000, 952)                       = 0
417 close(4)                                      = 0
418 open("/etc/shadow", O_RDONLY)                 = 4
419 fcntl64(4, F_GETFD)                           = 0
420 fcntl64(4, F_SETFD, FD_CLOEXEC)               = 0
421 _llseek(4, 0, [0], SEEK_CUR)                  = 0
422 fstat64(4, {st_mode=S_IFREG|0640, st_size=657, ...}) = 0
423 mmap2(NULL, 657, PROT_READ, MAP_SHARED, 4, 0) = 0x4021a000
424 _llseek(4, 657, [657], SEEK_SET)              = 0
425 munmap(0x4021a000, 657)                       = 0
426 close(4)                                      = 0
...
```

Figure : System Call Trace Snippet of the `login` Program.

Insight-II

System Call Execution Tampering

- Tampering with Disk-IO Syscall
  - Replacing `/etc/shadow` file when it loads to the memory. Essentially a man-in-the-middle Attack. We can hijack the file `open` syscall and provide an attacker controlled password file
- Tampering with Memory-Map Syscall
  - Tampering with `mmap2` syscall by replacing the memory contents mapped by this syscall (immediately after it finishes) with the password hash values we control.

Insight-II

System Call Execution Tampering

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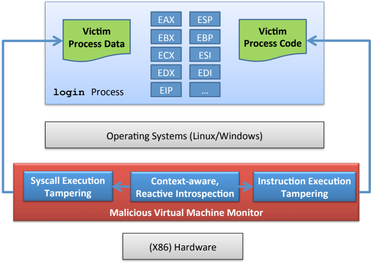
  - Replacing `/etc/shadow` file when it loads to the memory. Essentially a man-in-the-middle Attack. We can hijack the file `open` syscall and provide an attacker controlled password file
- Tampering with Memory-Map Syscall
  - Tampering with `mmap2` syscall by replacing the memory contents mapped by this syscall (immediately after it finishes) with the password hash values we control.

Advantages

- Transparent, can work for many other `login` types of programs
- No binary code reverse engineering

Challenges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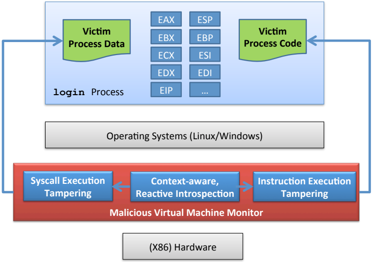
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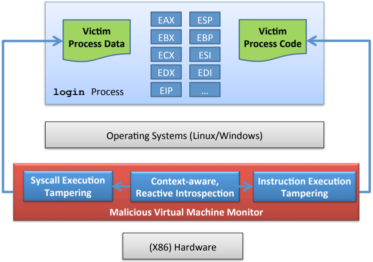
Identifying the "dreaming" context at the VMM layer

- (**C1**) a particular process execution;
- (**C2**) a particular syscall in **C1**;
- (**C3**) a particular instruction in **C1**;
- (**C4**) a particular instruction in **C1** under a particular call stack.

Solutions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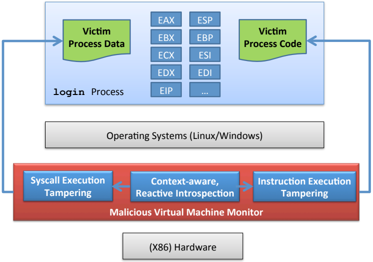
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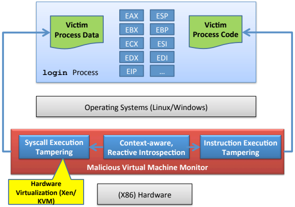
Context-Aware, reactive introspection

- **Introspection**: a variant of Virtual Machine Introspection [Garfinkel et al, NDSS'03]
- **Reactive**: not a passive, read-only introspection, it is reactive
- **Context-Aware**: context ranges from **C1** to **C4**

Solutions: Designing with Xen/KVM (SYSVMI)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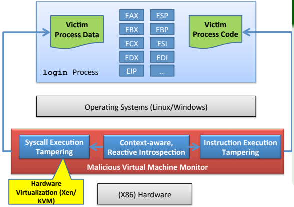
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Execution Context Identification

- (**C1**) – process context: CR3 and code hash of `login`
- (**C2**) – syscall in **C1**: `sysenter/sysret,int 0x80/iret`

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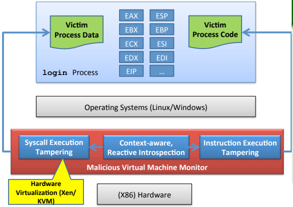
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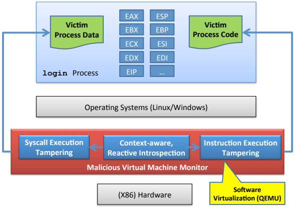
Attack Strategies

- **A1**: Tampering with Instruction Code.
- **A2**: Tampering with Syscall Arguments and Return Values
- **A3**: Tampering with Syscall Produced Data
- **A4**: Using IO Virtualization

Solutions: Designing with QEMU (INSTVMI)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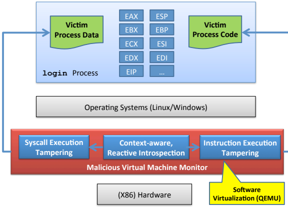
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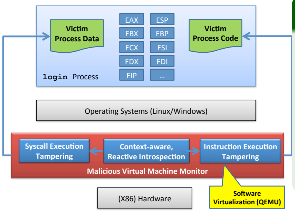
Execution Context Identification

- (**C3**) – instruction execution: Program Counter (PC)
- (**C4**) – call stack: instrumenting `call/ret`

Solutions: Designing with QEMU (INSTVMI)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Execution Context Identification

- (**C3**) – instruction execution: Program Counter (PC)
- (**C4**) – call stack: instrumenting `call/ret`

Attack Strategies

- **A5**: Tampering with Instruction Code at PC Level
- **A6**: Tampering with Instruction Operand
- **A7**: Tampering with Function Call Arguments and Return Values

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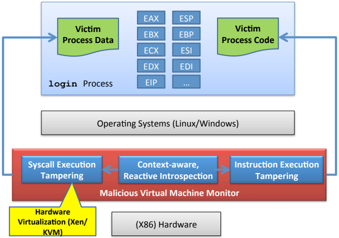
Implementation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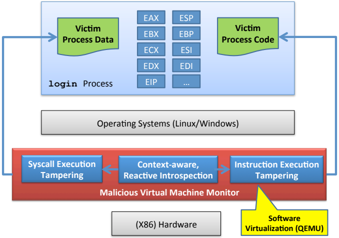
SYSVMI: Using Xen-4.12

Malicious-VMM w/ Xen-4.12	C1∼C2	A1	A2	A3	A4	Total
	1,748	17	10	75	45	1,895

- Implementing **A1** to **A4** with only 1,895 LOC in total (a very low cost for attacker).

Implementation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INSTVMI: Using QEMU-1.01

Malicious-VMM w/	C1 $\sim$ C4	A5	A6	A7	Total
QEMU-1.01	3,513	35	34	25	3,607

- INSTVMI$_a$ ported the SYSVMI implementation (**C1** and **C2**, and **A1** – **A4**) to a most recent QEMU-1.01
- INSTVMI$_b$ implemented the new attacks unique to the software virtualization (**A5** – **A7**) with fine-grained execution context identification (**C3** and **C4**)

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Overall Result

Target	SYSVMI			INSTVMI$_a$			INSTVMI$_b$		
	A1	A2,A3	A4	A1	A2,A3	A4	A5	A6	A7
`login`	✓	✓	✓	✓	✓	✓	✓	✓	✓
`sshd`	✓	✓	✓	✓	✓	✓	✓	✓	✓
`vsftpd`	✓	✓	✓	✓	✓	✓	✓	✓	✓
`telnetd`	✓	✓	✓	✓	✓	✓	✓	✓	✓

Table : Effectiveness of our virtual machine inception attack against the authentication program. Each ✓symbols denotes a successful way of incepting the victim software.

Performance Overhead

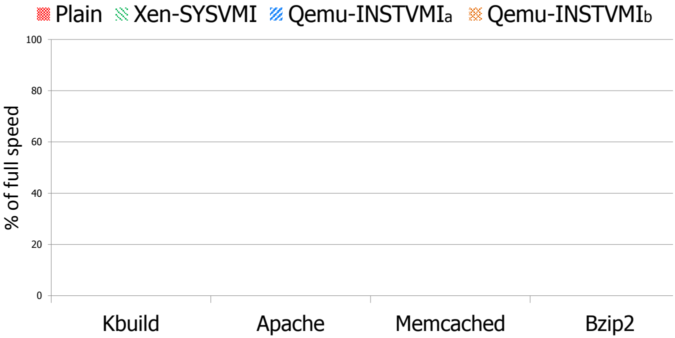

Figure : Macro-benchmark Evaluation of the Performance Overhead of Our VMI

Performance Overhead

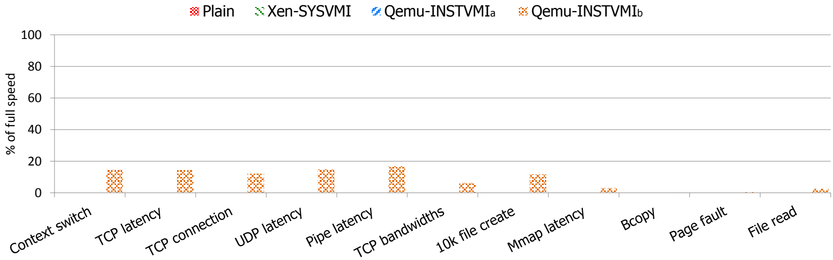

Figure : Micro-benchmark Evaluation of the Performance Overhead of Our VMI

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Hardware Virtualization Rootkits

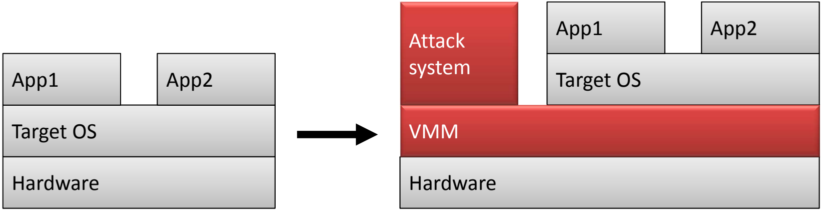
Blue Pill

- The codename for a rootkit based on x86 virtualization. [J. Rutkowska, Blackhat'06]
- Trapping a running instance of the OS by starting a thin hypervisor and virtualizing the rest of the machine under it.
- Vitriol [D. Zov, Blackhat'06] is also a hardware virtualization rootkit

Key Differences

- Thin vs. Thick Hypervisor
- Bluepill aims to compromise other's virtualization
- Our attack owns the virtualization and has rich features

Subvert, SubXen



Before Infection

After Infection

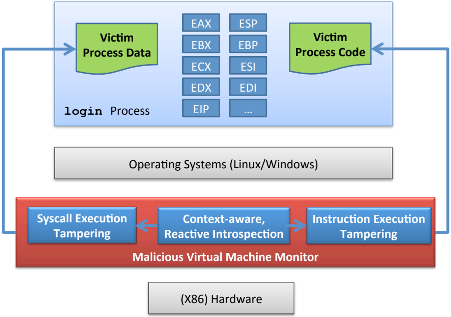
Key Differences

- Subvert [King et al., Oakland'06], a virtualization rootkit
- Thin vs. Thick Hypervisor
- Subvert also aims to infect other's virtualization (to be thin to avoid large footprints)
- Our attack owns the virtualization and has rich features

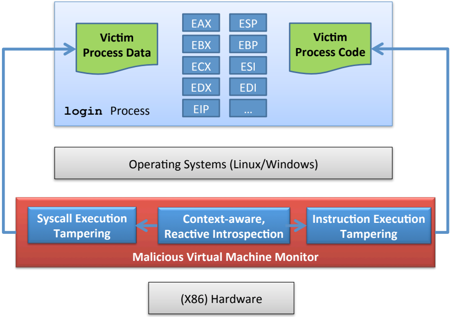
Outline

1. Background
2. Detailed Design
3. Implementation
4. Evaluation
5. Related Work
6. Summary

Summary


Victim Process Data
EAX
EBX
ECX
EDX
EIP
ESP
EBP
ESI
EDI
...
Victim Process Code
login Process
Operating Systems (Linux/Windows)
Syscall Execution Tampering
Context-aware, Reactive Introspection
Instruction Execution Tampering
Malicious Virtual Machine Monitor
(X86) Hardware

Summary



- We design and implement a context-aware, reactive virtual machine to break authentication mechanism.
- Our result indicates that the approach is practical against real-world authentication programs.
- It is useful for both malicious attack and forensics analysis of virtualized systems and software.

Thank you

Questions?

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