ReVirt: Enabling Intrusion Analysis through Virtual Machine Logging and Replay

Or

“We Can Remember It for You Wholesale”
(with apologies to Philip K. Dick)

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The Problem

• Security of computer systems today needs to be improved

• Well maintained systems still suffer from break-ins

• CERT has shown a steady increase over the last four years in incidents handled, vulnerabilities reported and advisories posted

• How does one make systems more secure?
  • Prevent vulnerabilities from occurring
  • Analyze attacks after they occur
Preventing Vulnerabilities

• Complexity and rapid rate of change prevent the thorough auditing of code

(Illustration taken from xkcd)

• Infeasible to prevent computer compromises
Post-Attack Analysis

- Help understand an attack and fix the problem

- Audit logs are maintained by the OS, which log all kinds of user activity on the system

- Two failings of current logging system
  - Integrity
  - Completeness
Lack of Integrity

• “Quis custodiet ipsos custodes” (Who will watch the watchman?)

• Assume that the kernel is trustworthy, while the kernel may have been compromised

• Attackers who subvert the kernel can modify and delete log files to hide their presence

• Custom kernel or boot sector can also be inserted
Lack of Completeness

• Do not log sufficient information to recreate the entire attack

• Difficult to determine the cause and extent of the break-in

• Logging of input does not involve non-deterministic effects so difficult to replay conditions like race conditions
Goals of ReVirt

• Encapsulate the target system inside a virtual system

• Logging software is placed beneath this virtual machine

• Completeness of logger is improved by using techniques such as checkpointing, logging and roll-forward recovery

• Replays the complete, instruction by instruction execution of the virtual machine – before, during and after an attack
Virtual Machine Monitors

• Can be run on another operating system (Type II hypervisors) or directly on the bare hardware (Type I hypervisors)

• In the former, the operating system it is run on is called the host OS and the operating system running inside the virtual machine is called the guest operating system

• VMMs make a better trusted computing base because they are smaller and easier to verify than entire operating systems
OS-on-OS vs. Direct-on-Host

- OS-on-OS – Guest OS runs inside a type II hypervisor virtual machine

- Direct-on-Host – Target applications run directly on the operating system

- ReVirt uses an OS-on-OS architecture, with UMLinux being the virtual machine that is hosted on a Linux kernel
Operation of UMLinux

• Virtual machine instructions are executed directly on the host CPU

• Memory access is translated using the host’s MMU

```
0xffffffff
0xc0000000
0xbfffffff
0x70000000
0x6fffffff
0x0

host operating system

guest operating system

guest application
```
Privilege Levels of the Guest OS

• VMM maintains whether the current privilege is set to *kernel* (calls by the guest kernel) or *user* (calls by the guest application)

• VMM checks the privilege level at every system call

• When kernel, then the guest kernel made the call

• Passed through to the host kernel

• When user, then the guest application made a system call

• Redirected to guest kernel using SIGUSR1 signal
Trusted Computing Base

- For ReVirt, it consists of the VMM of UMLinux, and the parts of the host kernel that are directly used by the guest OS.

- Security of OS-on-OS structure is greater than that of direct-on-host structure.

- Smaller attack surface for malicious packets.

- In direct-on-host, a vulnerability can lead to a user having access to the entire host OS, while in OS-on-OS an attack is limited in scope to the guest OS.
Logging in UMLinux

• All non-deterministic events need to be logged

• Time and external input

• Time is the exact place in the instruction stream where the event took place

• External input is the input that accompanies the event – it could be a key press or a network packet
Process of Logging

• Checkpoint of current state is made by cloning the VM

• Log records are added to a circular buffer in kernel memory and written to disk by a user-level daemon

• ReVirt logs the PC and number of branches since last interrupt to allow it to replay correctly

• branch_retired gives the number of branches since last interrupt

• Hardware interrupts, traps and faults are subtracted to get the number of user level branches
Replay

• Two pass method to find the correct instruction at to which to deliver the interrupt

• In the first phase, branch_retired counter generates an interrupt after most branches

• In the second phase, breakpoints are inserted after every branch, where the current number of branches since last interrupt is compared to the required number

• When it matches, the interrupt is delivered
Cooperative Logging

• Logged network messages generate a lot of data

• Messages do not need to be logged on both the sending and the receiving end

• If the sender is being logged, than on replay it will resend the same message

• Receiver does not need to log the received data
Alternative Architectures for Logging

- Direct-on-host structure is another alternative – less secure and more difficult to implement

- Involves logging and replaying multiple processes on the host system

- Larger number of non-deterministic events

- Scheduling order is difficult to replay with interrupts in the kernel

- Solutions such as defining points in the kernel where interrupts are allowed require significant changes to the kernel
Analysis using ReVirt

• Execution sequence can be replayed – partially or completely

• Internal tools can be used to probe the system or change the current files or debug processes

• Tools such as debuggers and analyzers can be run off-line from the host machine

• May detect discrepancies with the view of the system from inside the virtual machine
Performance and Logging Overhead

• Performance of UMLinux is compared to a native Linux (Table 2)

• Overhead ranges from 1% in CPU intensive tasks to around 58% in tasks that issue a large number of guest kernel calls

• Logging adds a further overhead of not more than 8% (Table 3)

• Log data files range from 0.04 GB/day for CPU intensive workloads to approximately 1.4 GB/day for interrupt heavy workloads
Conclusion

• Encapsulates the system inside a virtual machine and logs the entire execution stream

• Replay execution before, during and after the attack

• Analysis of the logs and replay allows administrators to track and fix vulnerabilities

• Non-deterministic events like race conditions can be simulated

• Reasonable space and time overhead is added
Discussion Time

• Security and Privacy

• Performance and Practicality

• Checkpointing

• Automation

• Multicore performance
Security and Privacy

• Why bother to attack the virtual system in UMLinux? Why not just attack the host system?

• If the guest OS is compromised, and it can communicate with the host OS, isn’t the host OS automatically at risk?

• Is OS-on-OS really more secure than the Direct-on-host approach?

• With the system logging all non-deterministic inputs, confidential data and user credentials will also be logged. Isn’t this a privacy issue, especially if ReVirt itself is compromised?
Performance and Practicality

• Isn’t 58% overhead just way too high a price to pay? What would be an acceptable figure?

• Would moving ReVirt to Dom0 of Xen speed it up?

• Is this practical for a home user? What is the ‘normal’ workload tested with?

• Is it possible to make it efficient and useful enough for a home environment, where it alerts the user when an intrusion is detected and transfers the logs off-site?

• Is the logging overhead too much? Is some filtering of things logged necessary?
Checkpointing

• Downtime of a few minutes every few days is unacceptable for highly critical services. Is it practical to checkpoint a running system or would the overhead be too high?

• Is it necessary to checkpoint the entire disk of the system, or could it be done more efficiently by just storing a delta from the last checkpoint?

• Could the checkpoints be used for a snapshot kind of functionality?
Automation and Multi-core Logging

• Is there any automated way to discover that an attack has taken place?

• Can we detect attacks on the fly?

• Sifting through the mounds of collected data is like searching for a needle in the haystack. Can finding the intrusion during replay be automated?

• Can it be used to log and replay over multiple cores?