Fuzzing Firmware Running on Intel® Simics® Virtual Platforms

Jakob Engblom, Intel, Sweden
Robert Guenzel, Intel, Germany
Virtual Platforms? Why and What?

- **Technology**
  - Software model of hardware
  - Run **the same software** as the hardware
  - In our case, fast transaction-based models (TLM)

- **Use case examples**
  - Explore system architecture
  - Develop software early
  - Continuous integration of software and hardware
  - Debug and test software

**Virtual platform framework**

- **User-level application code**
- **Operating system**
  - Core
  - Core
  - Core
  - USB
  - PCIe
  - Net
  - Serial
- **Boot loader**
  - Firmware
  - Core
  - Core
  - Subsystem

**Target virtual platform (simulated)**

- Host operating system
- Host hardware

Fuzzing is a test technology
Fuzzing? Why and What?

• Send “random” inputs to software
  • Tests are typically small unit tests
  • Observe software behavior – usually test failures or crashes
  • “Random”: A set (corpus) of inputs is mutated according to various rules

• Coverage-guided fuzzing
  • Improve fuzzing effectiveness
  • Discern tested code
  • Guide mutation rules towards exploring new code/paths
  • Can be done without source code!

• Find more errors than manually written fixed tests
  • Explore corner cases that developers did not think about

Diagram:
- Fuzzing tool
- Mutator
- Set of inputs
- Software
- Coverage
- Inputs
- Results/failure
- Code coverage (and other feedback)

Typically applied to user-level software
Note: Fuzzing Techniques and Tools

• **Huge and active** research field!
  • Constant flow of new concepts, heuristics, algorithms, ...

• Our goal: **enable standard fuzzer tools** to be used with a virtual platform
  • Reuse the fuzzer logic as-is
  • Provide the execution platform
  • In practice, done per-fuzzer

• **Levels of insight into target**
  • Black-box
    • Opaque target
  • Grey-box
    • Some feedback data
    • No source code
  • White-box
    • Source code used
Why do Fuzzing on a Virtual Platform?

**Shift-left software quality**
- Fuzzing increases quality
- Software can run on VP in pre-silicon, why wait for hardware?

**Fuzzing system-level code**
- Possible to fuzz code that interacts closely with hardware
- VP can roll back disk and peripheral device state
- Key enabler: determinism, even for multicore targets

**Fuzzing “hidden” code**
- Fuzz code that is hard to interface with on real hardware
- VP provides access to the platform internals

**Richer fuzzing environment**
- VP can observe more types of failures than hardware
- VPs can inject hardware stimuli

**The VP exists anyway**
- Additional value from existing investment in model
- Avoid constructing complicated setups based on a standard VMs
Typical Fuzzing Setups

- **Black-box fuzzing at target system boundary**
  - VP use: replace hardware unit with virtual hardware
  - Same input/output, standard real-world connections suffice

- **Fuzzing individual applications running inside a standard software stack**
  - Easy to do with standard tools
  - VP use: when user-level software uses new hardware (instruction sets etc.) – run on VP

- **Fuzzing low-level code, firmware, drivers, that run directly on the hardware**
  - Not doable with standard tools
  - Requires support in the VP to interface the fuzzer and the software
  - Focus of this presentation
Types of Software under Consideration

Target virtual platform (simulated)

User-level application code

Operating system
- Feature support
- Device driver

Boot loader
- Module (UEFI)

Firmware
- Core
- Core

Subsystem

Core  Core  Core  USB
Disk  RAM  PCIe  Net  Serial
Standard User-Level Guided Fuzzing

- Fuzzer and fuzzing target run side-by-side on the host
  - Fuzzer uses host operating-system mechanisms to control and track the target
  - Application compiled with instrumentation, coverage, and sanitizers to provide feedback
  - On Linux, use “fork” to quickly rewind fuzz target state
Virtual-Platform-Based Guided Fuzzing

• Concept: Make the virtual platform look like a user-level program
  • Reuse existing fuzzers and their fuzzing logic as-is...
  • ... while facilitating access to the firmware using virtual-platform techniques
Virtual-Platform-Based Guided Fuzzing: Details

- Test driver
- Fuzz target
- Fuzzed module/component
- Firmware
- Target virtual platform (simulated)
- Input driver
- State manager
- System monitor
- Coverage collector
- Coverage (etc)
- Control
- Results
- Inputs
- Fuzzing tool

Intel® Simics® Simulator

 simulator mechanisms
 in-software mechanisms
Fuzzing Flow using a Virtual Platform

**Fuzzer**

- Orders a reset to start the next iteration
- Provides the input for the next test

**Simulator startup**
- Simulator startup

**Software boot and setup**
- Software boot and setup

**Create VP**
- Load software
- Set up monitor breakpoints
- Software setup scripting

**Initial state for fuzzing**

**Load input**

**Run test case**

**Reset**

**Detect stop condition**
- Success
- Failure
- Coverage etc.

**Save state**

**Saved (initial) state**

**Restore state**

**(Runs VP)**

- Fuzzer provides the input for the next test
- Fuzzer orders a reset to start the next iteration

**Main fuzzing loop**
Test Driver and Input Driver

- Test driver (target software)
  - *(Calling into software from VP directly is difficult and brittle)*
  - Depends on target and fuzzing setup
    - Knows how to apply inputs from fuzzer
    - Knows how to call into/activate the target
  - Polling loop, using **magic instructions** to talk to the **input driver**

- Input driver (simulator module)
  - Implements the interface towards the fuzzing tool – depends on how the simulator and fuzzer communicate
  - Passes data from the fuzzer to the test driver software – dumb pipe
State Manager

• State manager functions:
  • Reset the state of the fuzzing target
  • Start the simulation

• Simulation state is restored using in-memory snapshots
  • Device state
  • Memory and disk contents
  • Excepting tools and simulator core
  • (Standard Intel® Simics® Simulator feature)
  • Critical for performance
    • Minimize the virtual platform size
    • Optimize the framework (WIP)
  • Why not use forking?
    • Linux fork does not work well with a threaded simulator
System Monitor

• Wait for conditions that designate errors in the system under fuzz
  • Use VP mechanisms to watch the execution – typically breakpoints
  • Not visible to the software

• Specific conditions are set up by the setup script
  • List of conditions + messages
  • Passed to the system monitor

• If a condition is hit:
  • Stop the current run
  • Return to fuzzer, with message

• Example conditions:
  • Running outside of allowed memory
  • Accesses outside of allowed memory
  • Undefined instructions
  • Processor resets and triple faults
  • ... whatever makes sense ...

[Diagram: System Monitor flowchart]
Coverage Collector

• Coverage is key to guided fuzzing
  • Reflect how well the test cases explore the behavior of the code

• Current solution: Branch (edge) coverage
  • Coverage data looks like it came from code instrumentation compiled into user code
  • Cover all executed code
    • Hashing approach = unlimited reach
    • Test driver code is small and does not hurt
  • Using the standard Intel® Simics® Simulator instrumentation API to get reports about all branches

• “Grey-box” fuzzing
  • No source code needed
  • No compiled-in instrumentation
  • … but still looking at the code flow

• Branch coverage details
  • Get the address branched to
  • Combine with the previous destination (i.e., current basic block)
  • Hash the result and increment counter

• Reusable and generic as long as the data produced makes sense to the fuzzer
## Portability, Summary

<table>
<thead>
<tr>
<th>Component</th>
<th>Firmware dependent?</th>
<th>Target dependent?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test driver (target software)</td>
<td>Yes</td>
<td>Yes (registers, magic, …)</td>
</tr>
<tr>
<td>Input driver (simulator module)</td>
<td>No (test driver has to adapt)</td>
<td>No</td>
</tr>
<tr>
<td>State manager (simulator module)</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>System monitor (simulator module)</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>System monitor configuration (script)</td>
<td>Yes (reflect error conditions)</td>
<td>Yes</td>
</tr>
<tr>
<td>Coverage collector (simulator module)</td>
<td>No</td>
<td>Yes (ID branch instructions)</td>
</tr>
</tbody>
</table>

Note that porting to a new fuzzer tool will likely require updates to all the modules.
Possible Future Extensions

• Fuzzing with hardware inputs
  • Current effort mostly using libAFL
    = built for software fuzzing
  • VP-side this is not very hard

• Adding sanitizers into firmware
  • Compilers generally support it
  • Requires a custom output library
    (have seen that done)
Questions?

Get the Intel® Simics® Simulator
https://developer.intel.com/simics-simulator

Try the TSFFS fuzzing setup (close to what was presented here)
https://github.com/intel/tsffs/
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