What You Corrupt Is Not What You Crash: Challenges in Fuzzing Embedded Devices

Marius Muench[1] Jan Stijohann[2,3]
Frank Kargl[3] Aurélien Francillon[1] Davide Balzarotti[1]

[1]EURECOM
[2]Siemens AG
[3]Ulm University

EURECOM
Sophia Antipolis

SIEMENS

universität ulm

Introduction

- Embedded devices are becoming increasingly more important
- Vulnerabilities go beyond misconfigurations, weak authentication, hard-coded keys, etc.
- Fuzz testing is a popular and effective method for uncovering *programming errors*
    - A variety of work improves input generation and fault detection for fuzzing

Problem Statement

How efficient are we at fuzzing embedded devices?

Can we do it better?

Fuzzing, Corruptions & Crashes

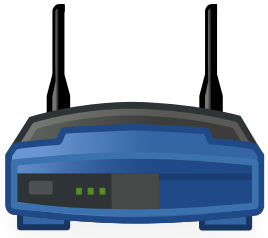
Starting Point

Corruption $\neq$ Crash

Embedded Devices: A minimalistic classification

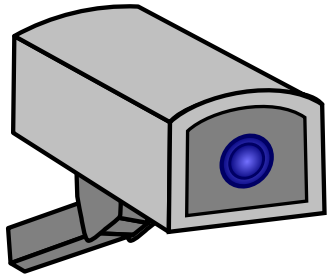
Type-I:

General purpose OS-based



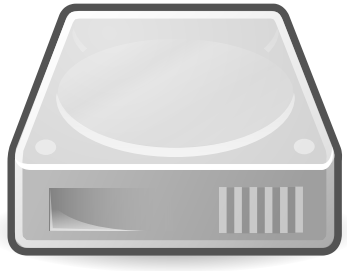
Type-II:

Embedded OS-based



Type-III:

No OS-Abstraction



Challenge #1: Fault Detection

- Lack of basic features, such as:
  - Memory Management Unit (MMU)
  - Heap consistency checks
  - Canaries
- Often only solution: Basic liveness checks

Challenge #2: Performance & Scalability

- Fuzzing greatly benefits from parallelization
  - This would mean 1 device per instance
- Frequent restarts are required
  - Fast for software, slow for full systems

Challenge #3: Instrumentation

- Hard to retrieve coverage information
- Tools for turning *silent* corruptions into observable ones rarely available
  - Unsupported instruction set architecturess
  - Operation tied to OS-specific features

Measuring the effect of memory corruptions

- Five common types of memory corruptions
- Insertion of artificial bugs in two popular open source programs
  - Expat
  - mbedTLS
- Trigger condition inspired by LAVA [1]
- Vulnerable programs are compiled for four different devices

---

[1] Dolan-Gavitt, Brendan, et al. "Lava: Large-scale automated vulnerability addition." IEEE Symposium on Security and Privacy (SP), 2016.

Effects of Corruptions accross different systems

	Platform			
	Desktop	**Type-I**	**Type-II**	**Type-III**
Format String	✓	✓	✗	✗
Stack-based buffer overflow	✓	✓	✓ (opaque)	! (hang)
Heap-based buffer overflow	✓	! (late crash)	✗	✗
Double Free	✓	✓	✗	✗ (malfunc.)
Null Pointer Dereference	✓	✓	✓ (reboot)	✗ (malfunc.)

Possible Directions for Improvement

- Static Instrumentation
- Binary Rewriting
- Pysical Re-Hosting
- Full Emulation
- Partial Emulation
- Hardware-Supported Instrumentation

Possible Directions for Improvement

- Static Instrumentation
- Binary Rewriting
- Pysical Re-Hosting
- Full Emulation
- Partial Emulation
- Hardware-Supported Instrumentation

Leveraging (partial) emulation to improve fuzz testing

Set-up: Overview

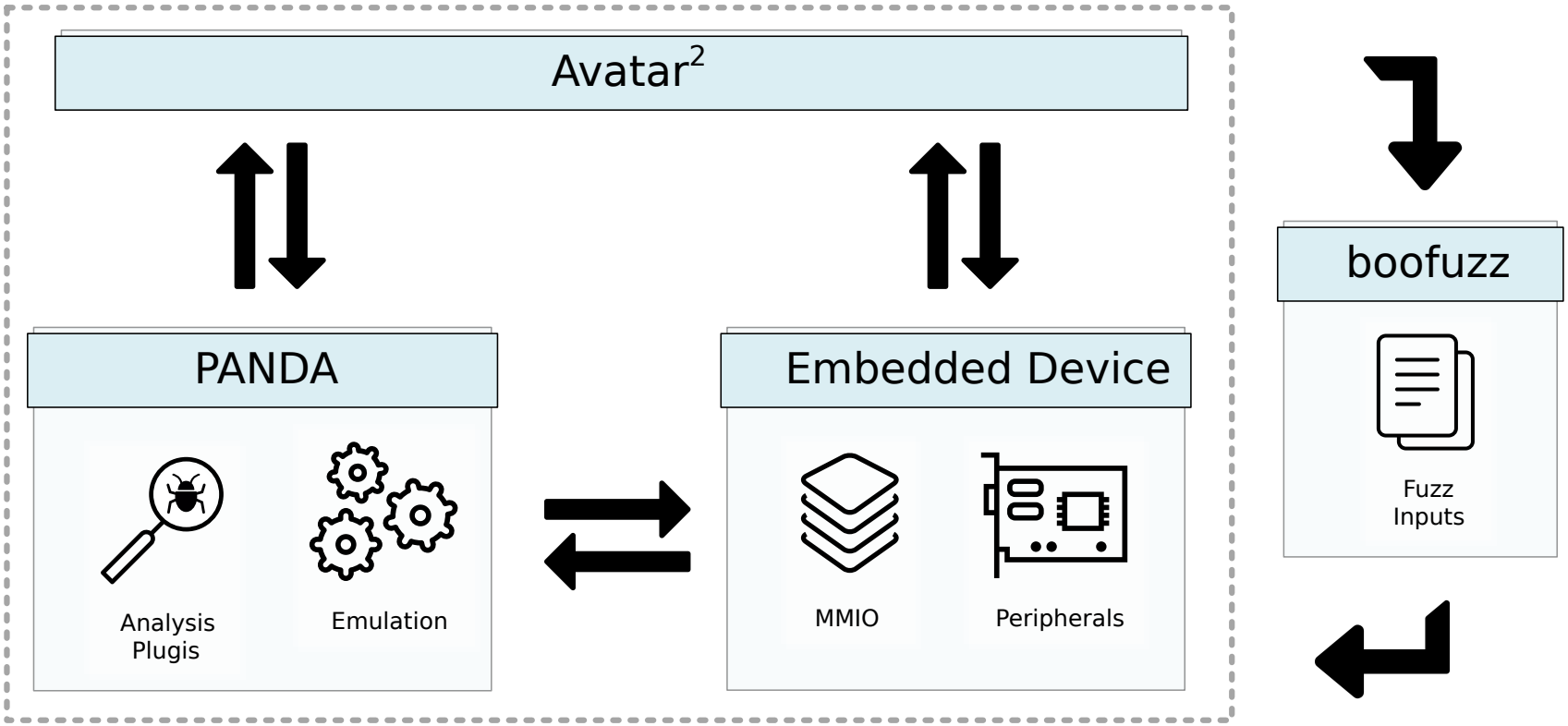


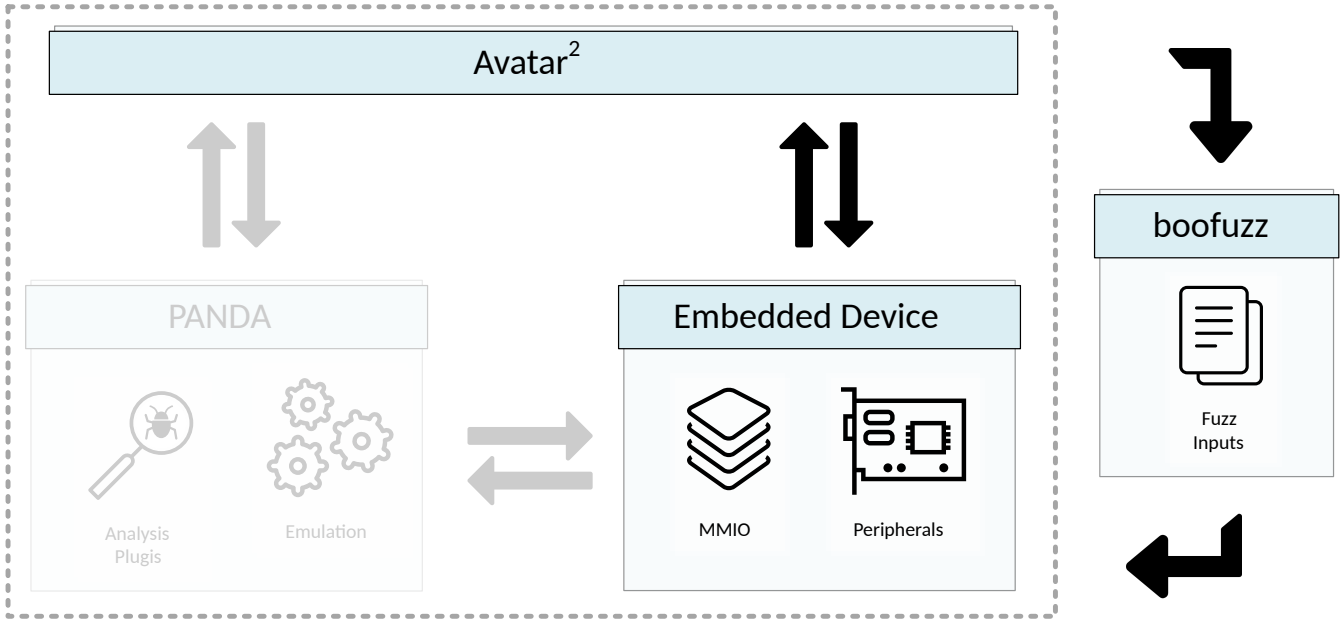
Figure 1: Setup for fuzzing utilizing partial emulation

Code will be available at: `https://github.com/avatartwo/ndss18_wycinwyc`

Set-up: Target

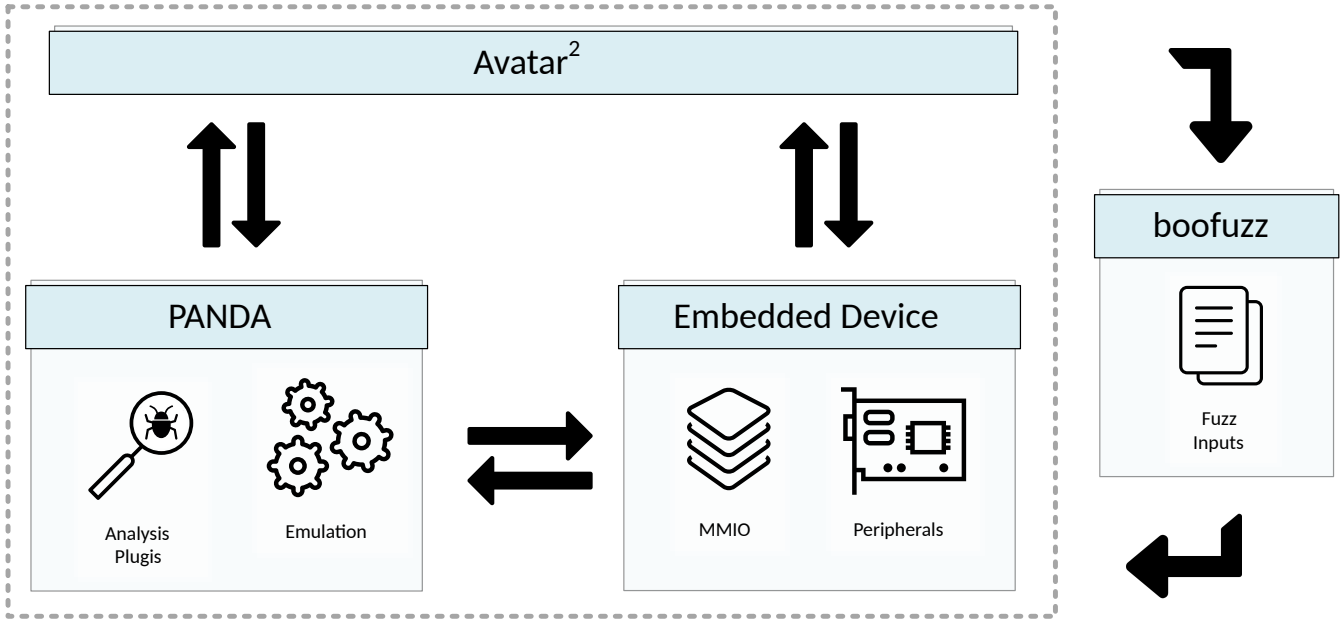
- The vulnerable `expat` program, as seen in the last part
- Focus on a Type-III device
- Fuzzed in four different configurations

Set-up: Native



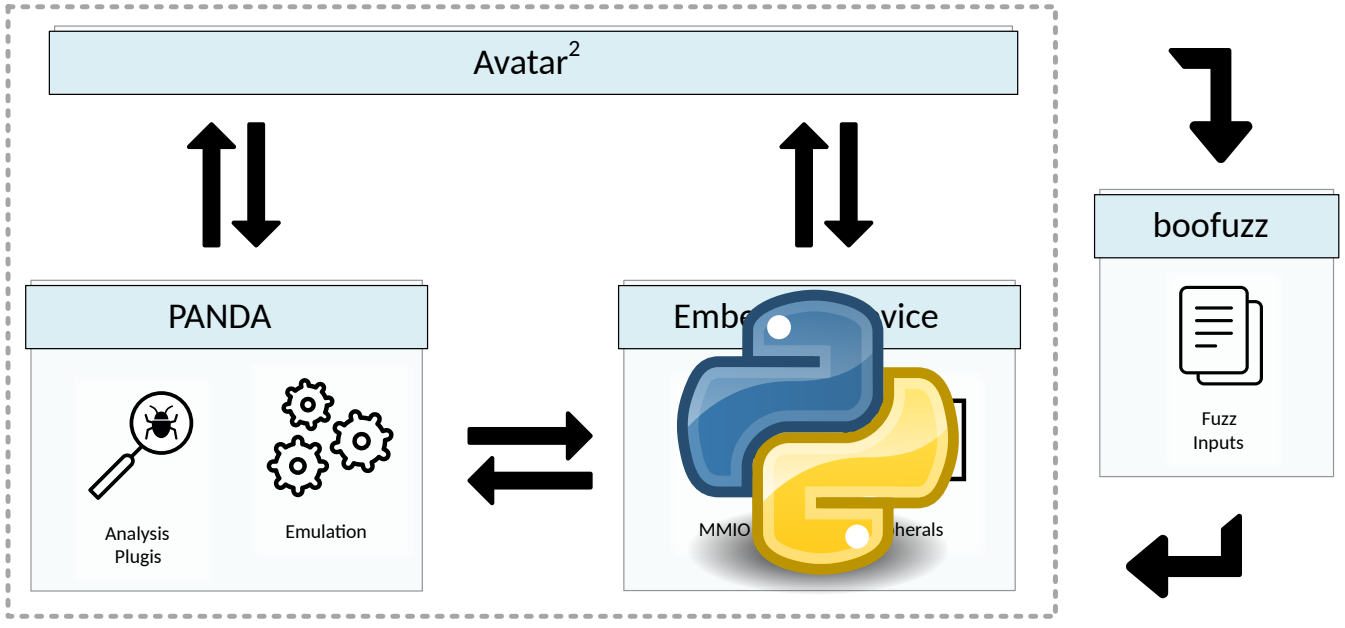
1. Native (NAT)
2. Partial Emulation with Memory Forwarding (PE/MF)
3. Partial Emulation with Peripheral Modeling (PE/PM)
4. Full Emulation (FE)

Set-up: PE/MF



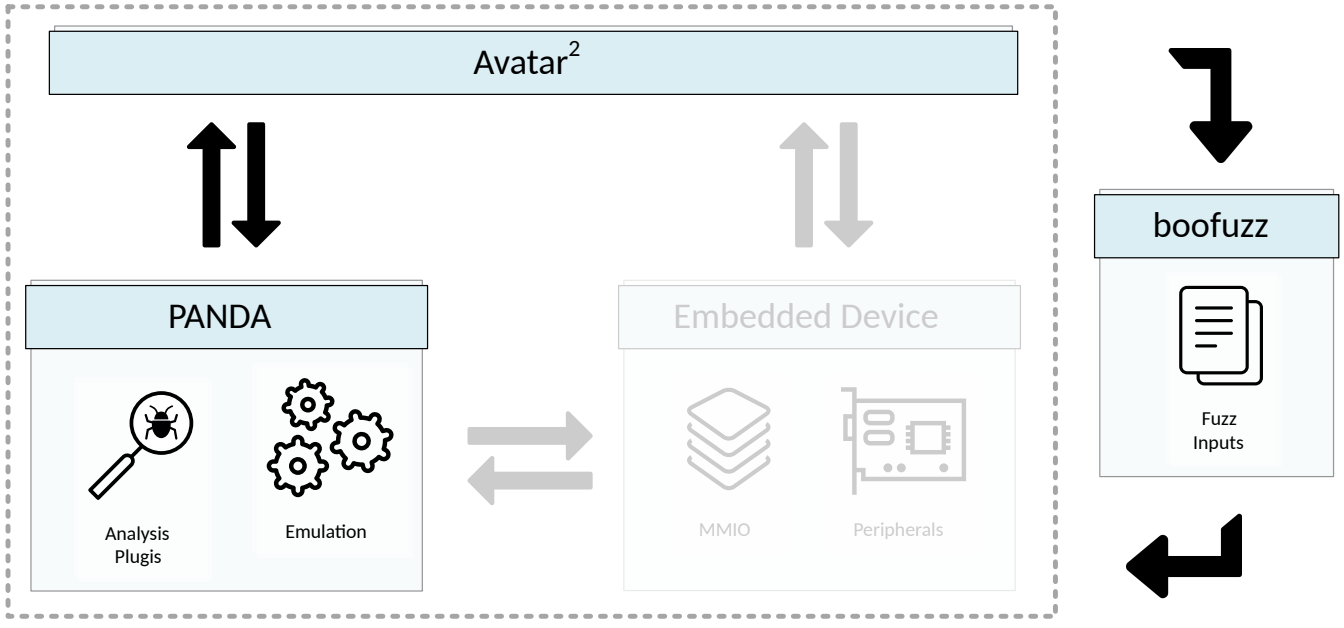
1. Native (NAT)
2. Partial Emulation with Memory Forwarding (PE/MF)
3. Partial Emulation with Peripheral Modeling (PE/PM)
4. Full Emulation (FE)

Set-up: PE/PM



1. Native (NAT)
2. Partial Emulation with Memory Forwarding (PE/MF)
3. Partial Emulation with Peripheral Modeling (PE/PM)
4. Full Emulation (FE)

Set-up: FE



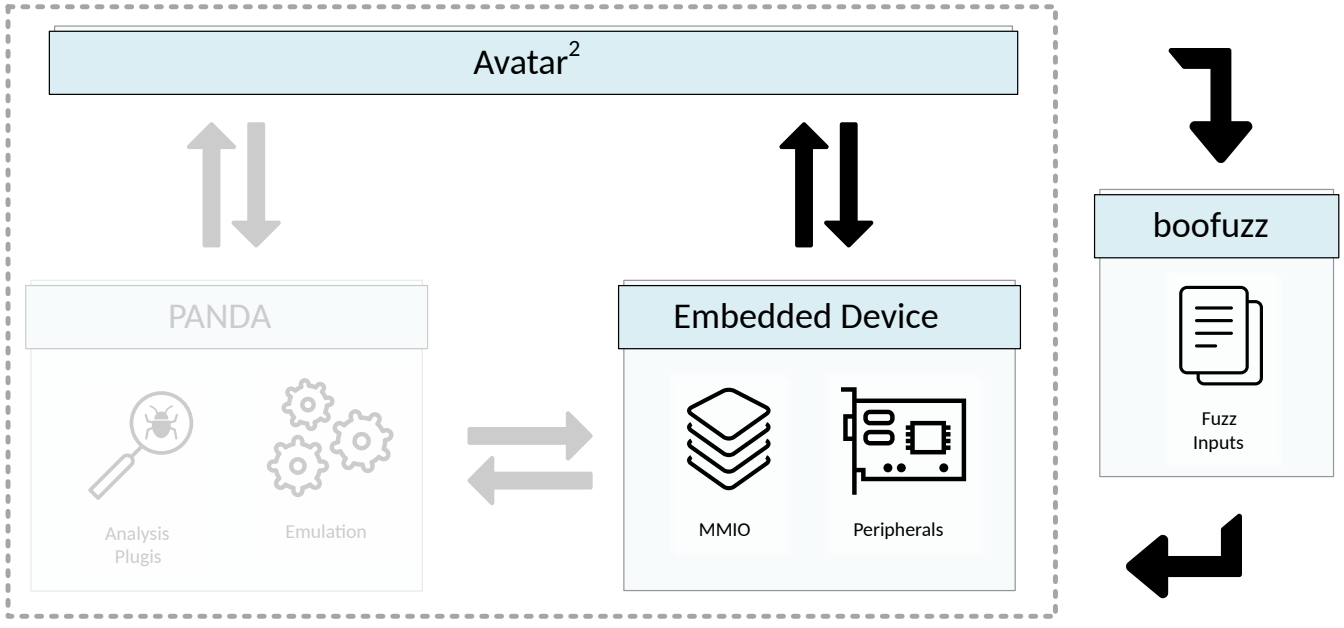
1. Native (NAT)
2. Partial Emulation with Memory Forwarding (PE/MF)
3. Partial Emulation with Peripheral Modeling (PE/PM)
4. Full Emulation (FE)

Set-up: Fuzzer

- `boofuzz` [2], a python-based fuzzer based on `Sulley`
- Configured to trigger the corruptions with different ratios
- Used for 100 fuzzing sessions over one hour each

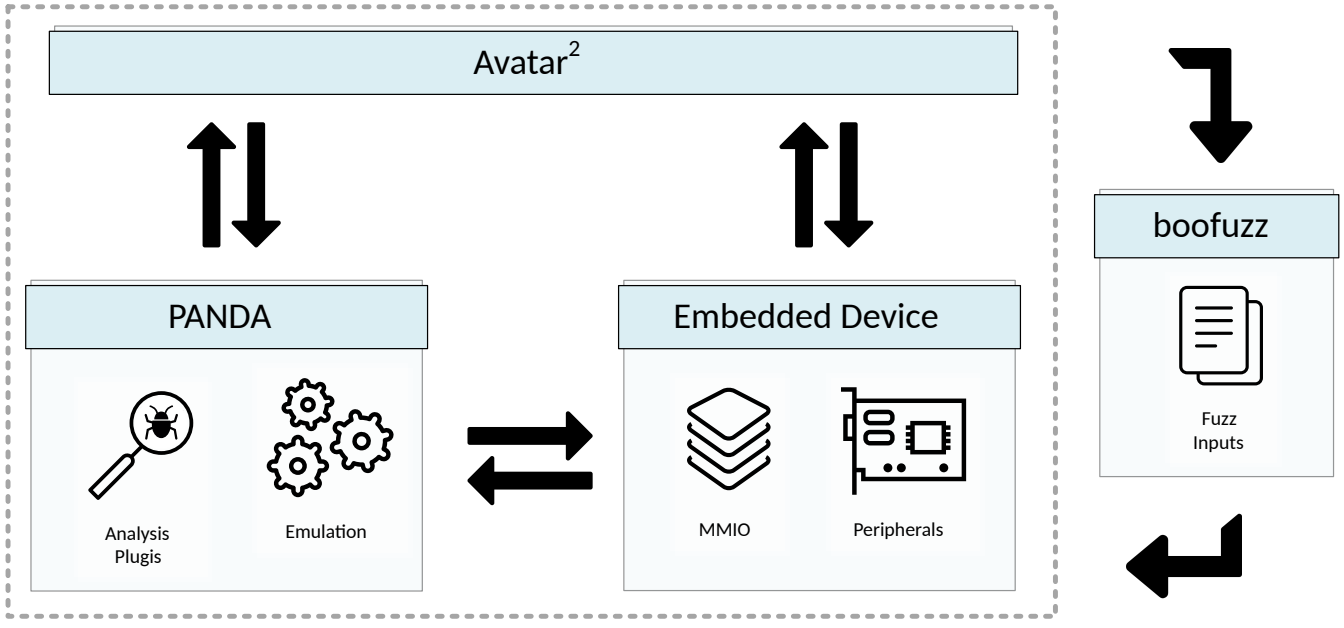
[2] `https://github.com/jtpereyda/boofuzz`

Set-up: Corruption Detection



1. Native (NAT)
2. Partial Emulation with Memory Forwarding (PE/MF)
3. Partial Emulation with Peripheral Modeling (PE/PM)
4. Full Emulation (FE)

Set-up: Corruption Detection

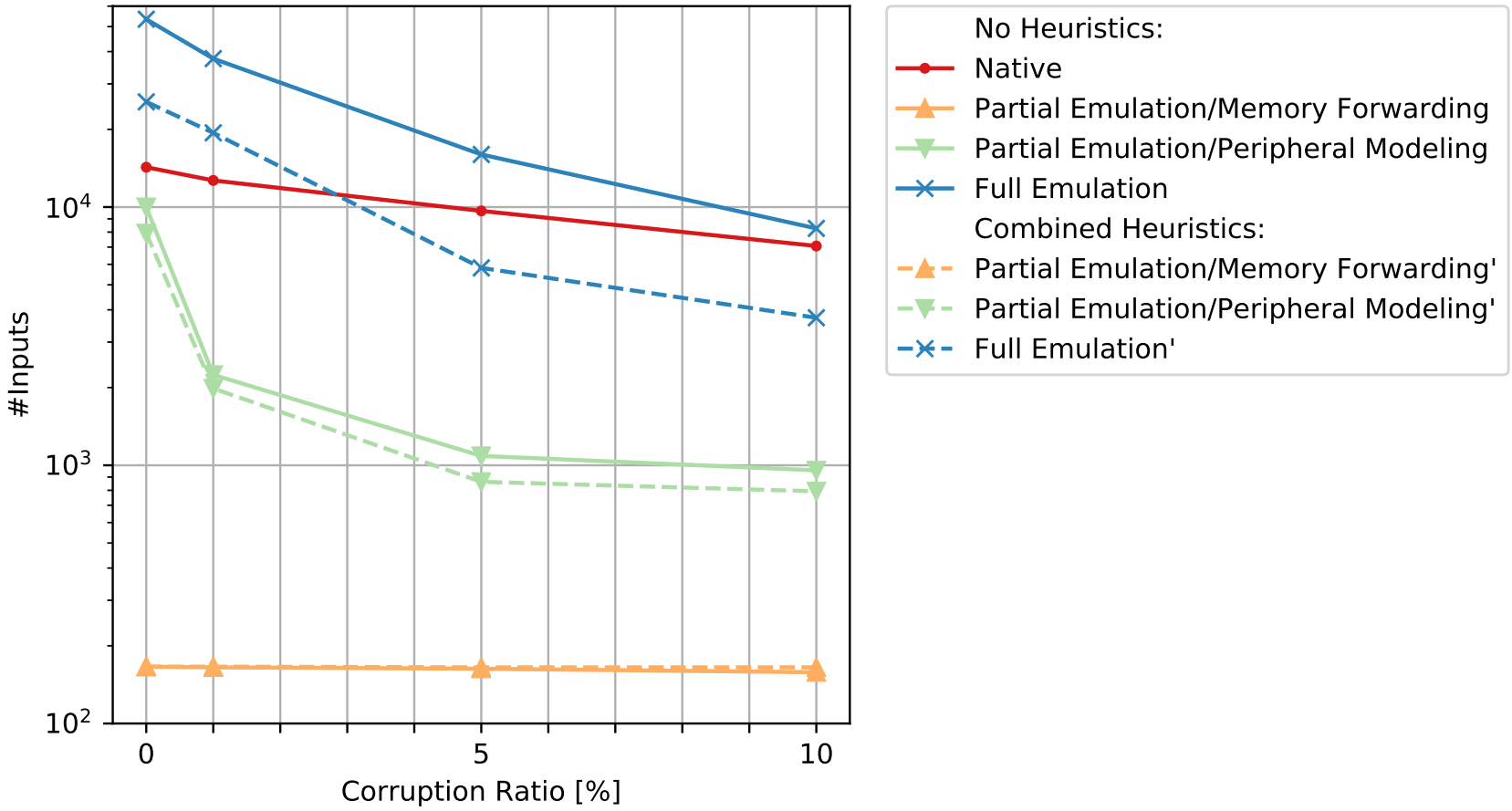


1. Native (NAT)
2. Partial Emulation with Memory Forwarding (PE/MF)
3. Partial Emulation with Peripheral Modeling (PE/PM)
4. Full Emulation (FE)

Set-up: Corruption detection

- 6 simple heuristics, monitoring the execution:
  1. Segment Tracking
  2. Format Specifier Tracking
  3. Heap Object Tracking
  4. Call Stack Tracking
  5. Call Frame Tracking
  6. Stack Object Tracking

Measuring Fuzzing Throughput



Discussion, Future Work & Conclusion

Insights from the experiments

- Liveness checks only is a poor strategy
- Full emulation is good - but rarely possible
- Partial emulation can already help
  - **But** introduces significant performance overhead

Limitations and Future Work

- We focused on improving fault detection
  - Other challenges of fuzzing (e.g., input generation) not addressed in this work
- Our experiments focused on *artificial* vulnerabilities
  - Good for improving our initial understanding
- We investigated solutions based on partial emulation
  - Other approaches still open for research

Conclusion

- Fuzzing embedded devices requires a paradigm shift
- (Partial) emulation can improve fault detection
  - We need good emulators
- Fuzzing of embedded devices needs more investigation