Techniques for Fuzzing Embedded and Distributed Systems

18 November 2020

Michael D. Brown

Software Assurance Branch Head (interim)

Brian Schultz

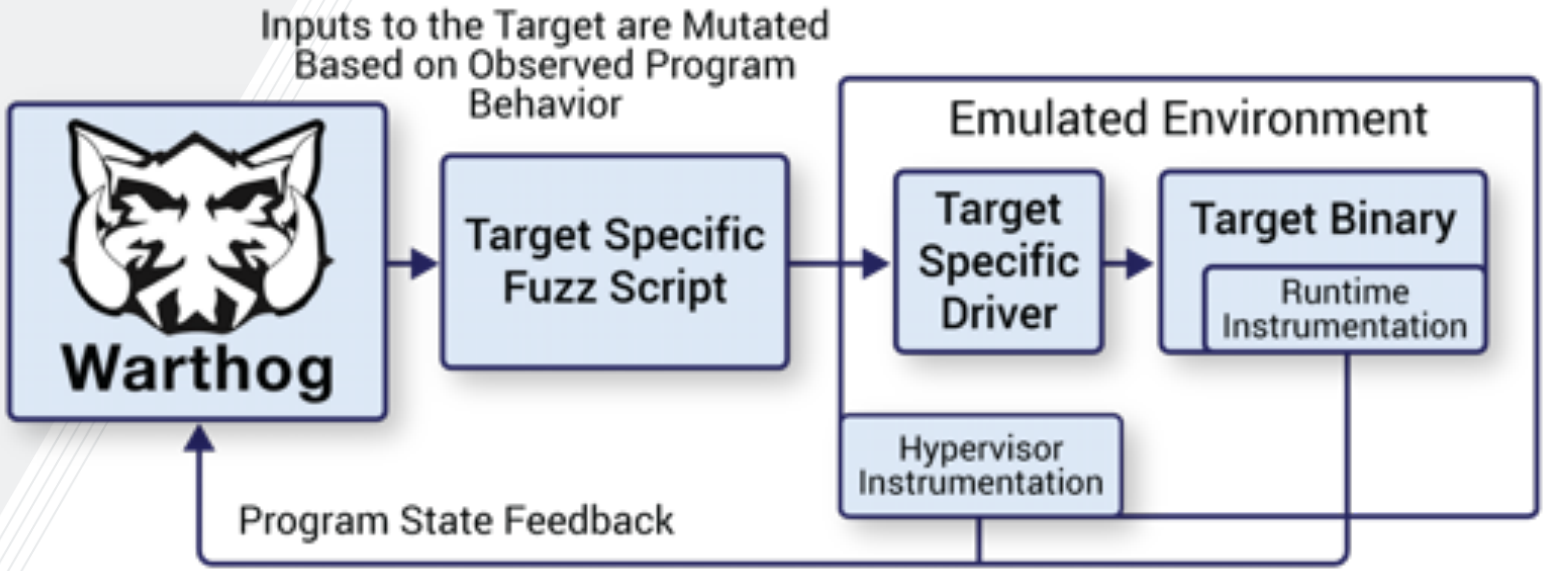
Software Assurance Branch

What is Fuzzing?

- Fuzzing (or Fuzz testing) is an automated technique for vulnerability discovery in programs or systems.
- In its most basic form, fuzzing is a brute force method; repeatedly run a program with randomly generated inputs to see if any of them cause a crash.
- A program crash likely indicates some kind of program bug, which may be exploitable.
- Fuzzing is useful for both DCO (fixing bugs in blue systems) and OCO (finding holes in red systems)
- Basic fuzzing is very inefficient; most of the inputs generated will be invalid and probably won't find interesting bugs.

What is Fuzzing?

- Modern fuzzers incorporate different techniques that increase the likelihood of discovering crashes.
- For example, GTRI's in-house (GOTS) fuzzer, Warthog, uses virtualization to parallelize fuzzing and program feedback to guide the input generator.

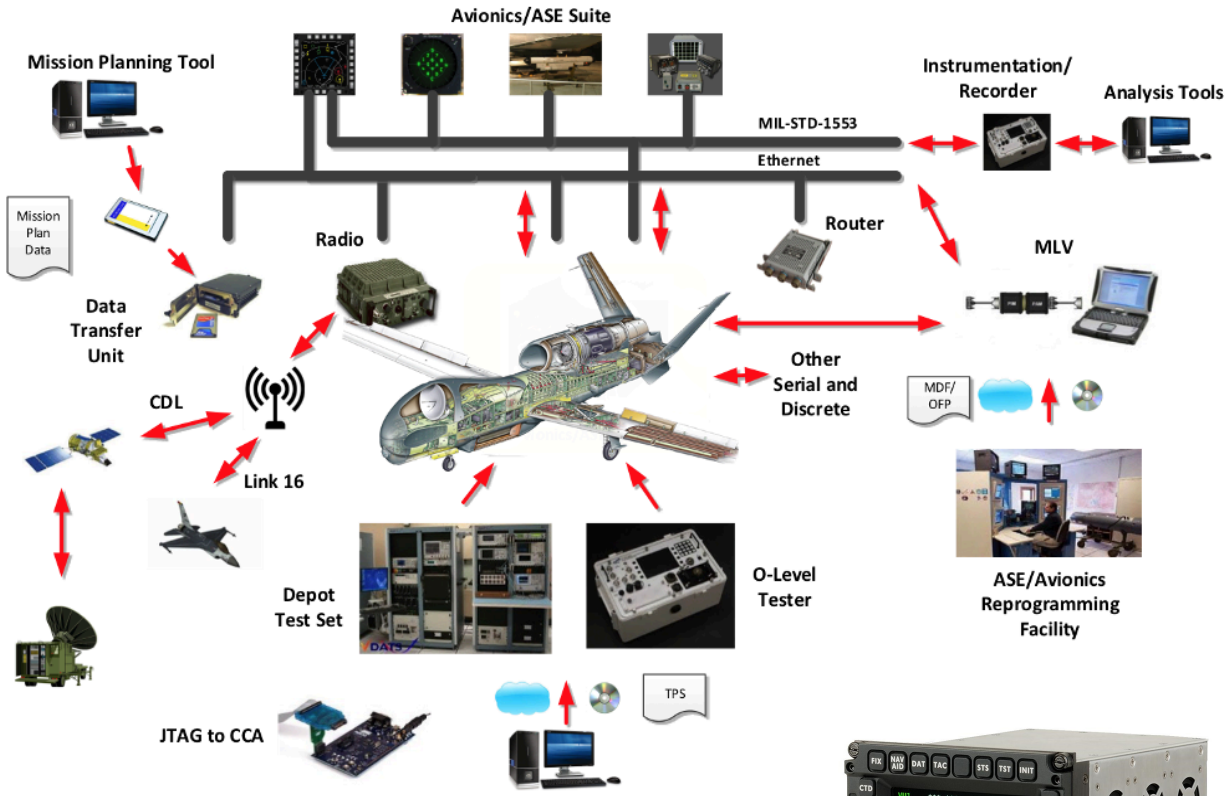


Fuzzing Tools and Their Limitations

- Modern fuzzers that employ these advanced techniques have been shown to be very effective at discovering exploitable bugs.
- However, these tools are still far from universal; they largely target enterprise software running on general purpose computing systems.
- This is very different from embedded systems which exhibit tight coupling between software, the OS, and the hardware (which is often non-standard).
- Modern fuzzers are also difficult to use on distributed systems due to their reliance on a 1:1 fuzzing paradigm. This model is a poor fit for distributed systems that are made up of several interconnected components working in concert.

Fuzzing Weapons System Software

- Most DoD weapons systems we have analyzed are implemented as either embedded systems, distributed systems, or both (cyber-physical systems)
- This means modern fuzzing tools cannot be brought to bear on these systems without significant effort.
- Unfortunately, this affects both small scale systems like aircraft avionics and large scale platforms like helicopters and ships.



Techniques for Fuzzing Weapons System Software

- To overcome these limitations, GTRI has researched and developed several candidate techniques for applying modern fuzzing capabilities to DoD weapons systems.
- In the first part of this presentation, we discuss prototype extensions to Warthog that allow us to virtualize embedded systems and fuzz them.
- In the second part of this presentation, we discuss a prototype fuzzing tool we have developed called NetFuzz. NetFuzz is purpose built for fuzzing distributed systems and can also identify non-crashing bugs such as resource exhaustion vulnerabilities.

Embedded Systems

Warthog Embedded Systems Extensions

Fuzzing Embedded Software

Problem:

- Fuzzing embedded systems software running on real-time operating systems (RTOS) is not possible with existing fuzzers.
- Embedded systems software is tightly coupled to RTOS and hardware, both of which are abstracted in general purpose computing systems.

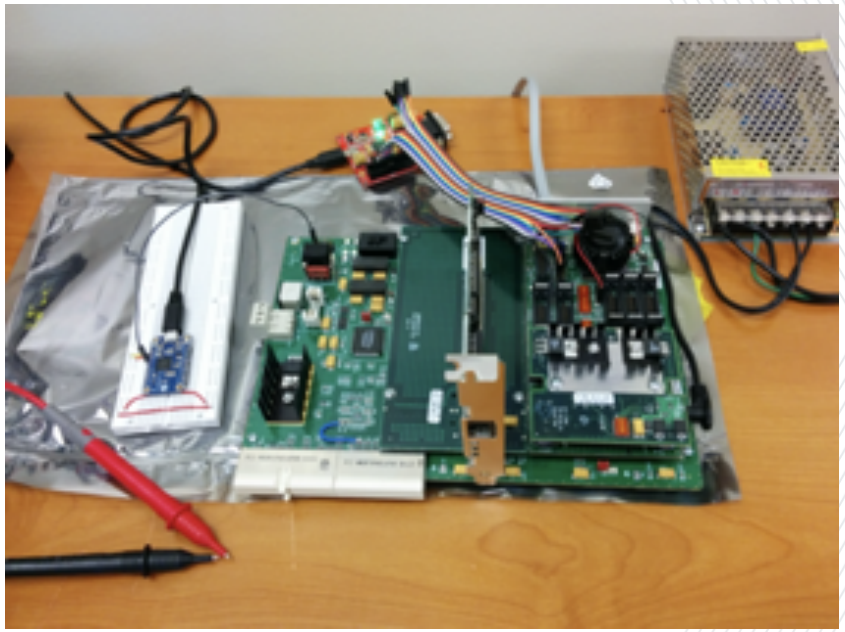
Approach:

- Emulate an embedded system's hardware
- Create a virtual environment that can run instrumented embedded software on emulated hardware
- Fuzz this environment with Warthog to discover vulnerabilities
- Verify these vulnerabilities actually exist on physical hardware

Fuzzing Embedded Software

Implementation:

- Built support for PPMC7400 test bed device in to QEMU.
- Required building custom emulation support for the board's memory controller and network hardware.



Fuzzing Embedded Software

Implementation:

- For our proof of concept, we targeted the Unix pipe library in VxWorks 5.4.
- We created a simple wrapper program for the OS library and placed it (along with the VxWorks 5.4 RTOS) on this virtual hardware.
- Provide seed inputs and necessary scripting to enable warthog to fuzz this environment.
  - Fuzz script (pictured right) is written in Python and is less than 100 lines of code.

```python
class TestMonitor(vxworks.Monitor):
    def fuzz(self, input_):
        input1 = input_[0:(len(input_)) // 2] + b'\x00'
        input2 = input_[(len(input_) // 2):] + b'\x00'
        spec = {
            'params': {
                '1': [0x01, 0x64, 0x02, 0x0],
                '2': [],
                '4': [len(input2) - 1 if len(input2) > 0 else 1],
                'ptr': [input1, input2, b"x" * (len(input_))],
            },
            'funcs': [
                {
                    'name': 'pipeDrv',
                    'ret_index': 100,
                    'args': [],
                },
                {
                    'name': 'pipeDevCreate',
                    'ret_index': 101,
                    'args': [
                        (vxworks.ARG_PTR, 0),
                        (vxworks.ARG_1_BYTE, 0),
                        (vxworks.ARG_1_BYTE, 1),
                    ],
                },
                {
                    'name': 'open',
                    'ret_index': 0,
                    'args': [
                        (vxworks.ARG_PTR, 0),
                        (vxworks.ARG_1_BYTE, 2),
                    ],
                },
```

Fuzzing Embedded Software

Results:

- Warthog discovered a vulnerability in the `ioFullFileNameGet` library function, which we verified on the actual hardware.
- Using the information collected by the fuzzer, we were able to craft an exploit that compromises a file open operation on the embedded system.
- When delivered via the board's network interface, the attacker can open a system shell on the device with full system privileges (a complete compromise).

Fuzzing Embedded Software

Takeaways:

- It is possible to fuzz embedded systems with modern tools, but it requires significant effort to put devices and RTOS under emulation.
- Biggest payoffs from employing this technique will be on systems / software packages that are common to multiple platforms.

Future Efforts:

- Add support for different types of hardware and RTOS.
- GTRI is currently exploring advanced software analysis and transformation techniques to fuzz embedded software without requiring emulation.

Distributed Systems

NetFuzz Distributed Systems Fuzzer

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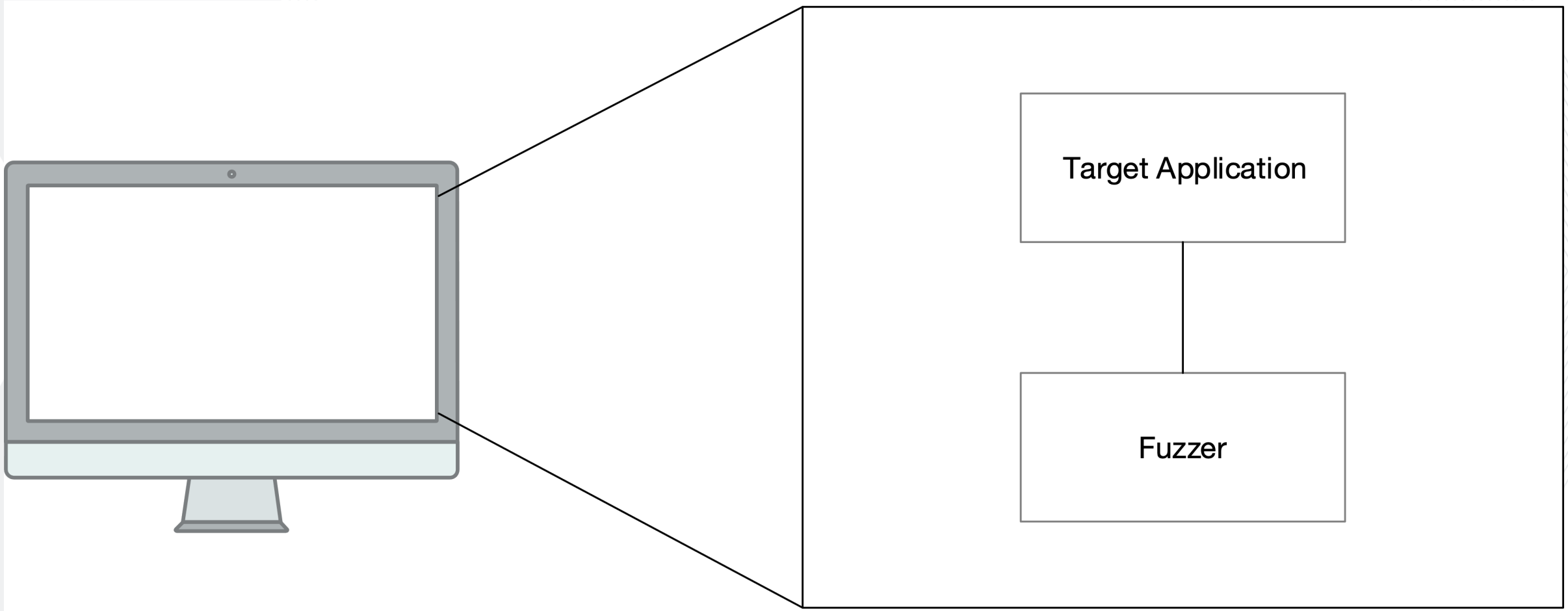
Traditional vs Distributed System Fuzzing

Traditional Fuzzing Setup



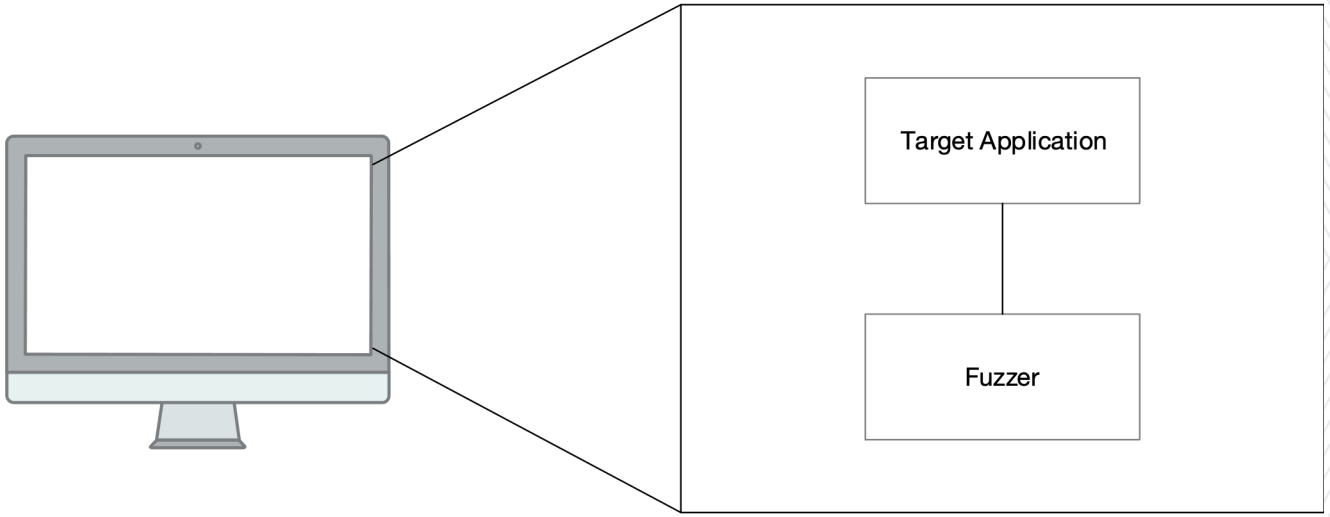
Traditional Fuzzing

Benefits

- Usually deterministic output
- Many variants and programs
- Well studied
- “Small” Input Space

Limitations

- Simple Applications
- Limited Interactions
- Instrumentation and stub services
- Misses soft errors



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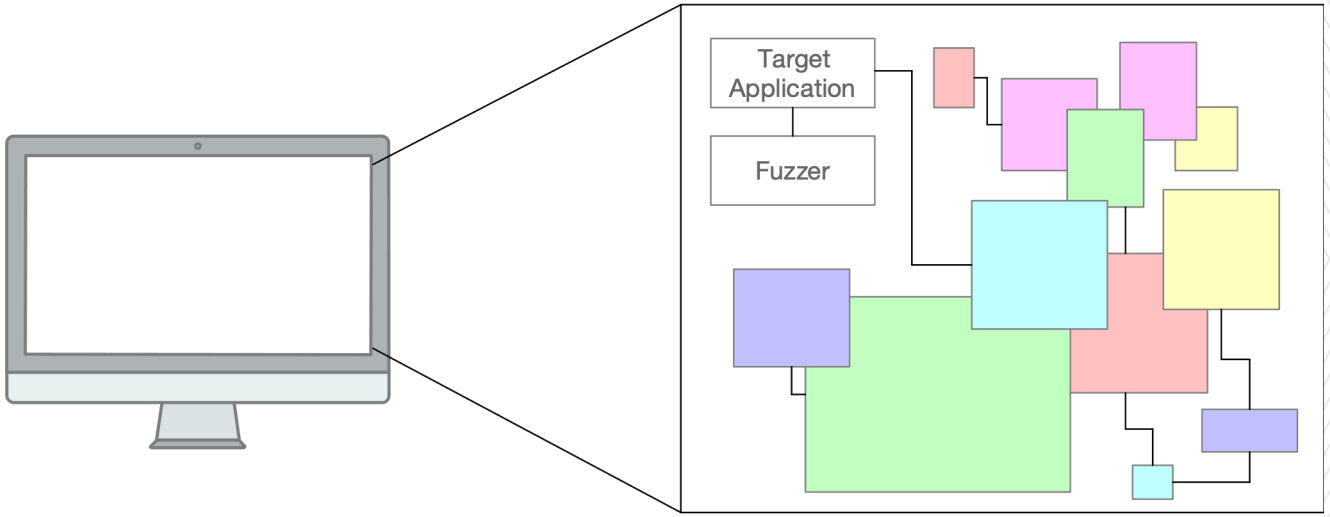
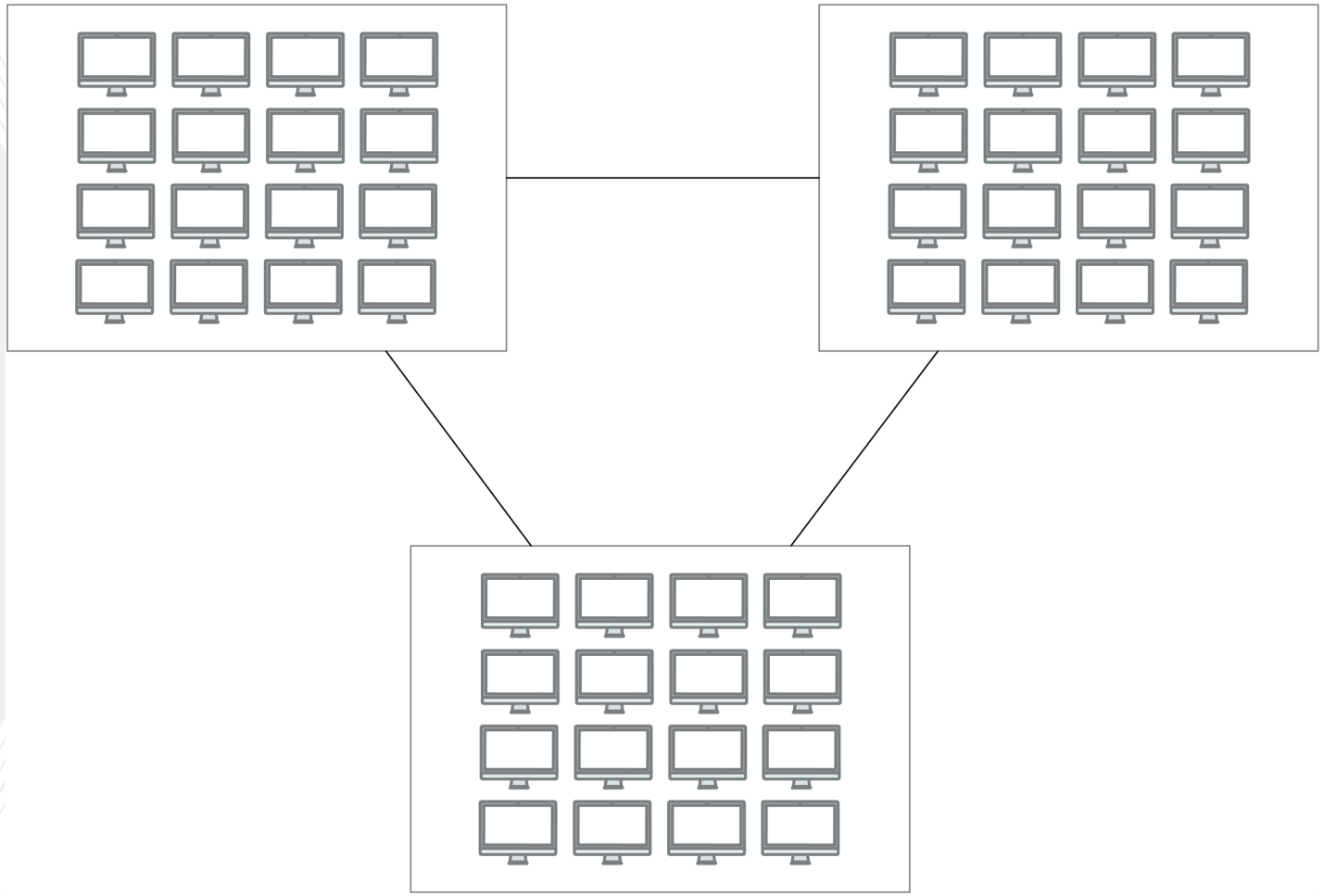


Distributed System Fuzzing



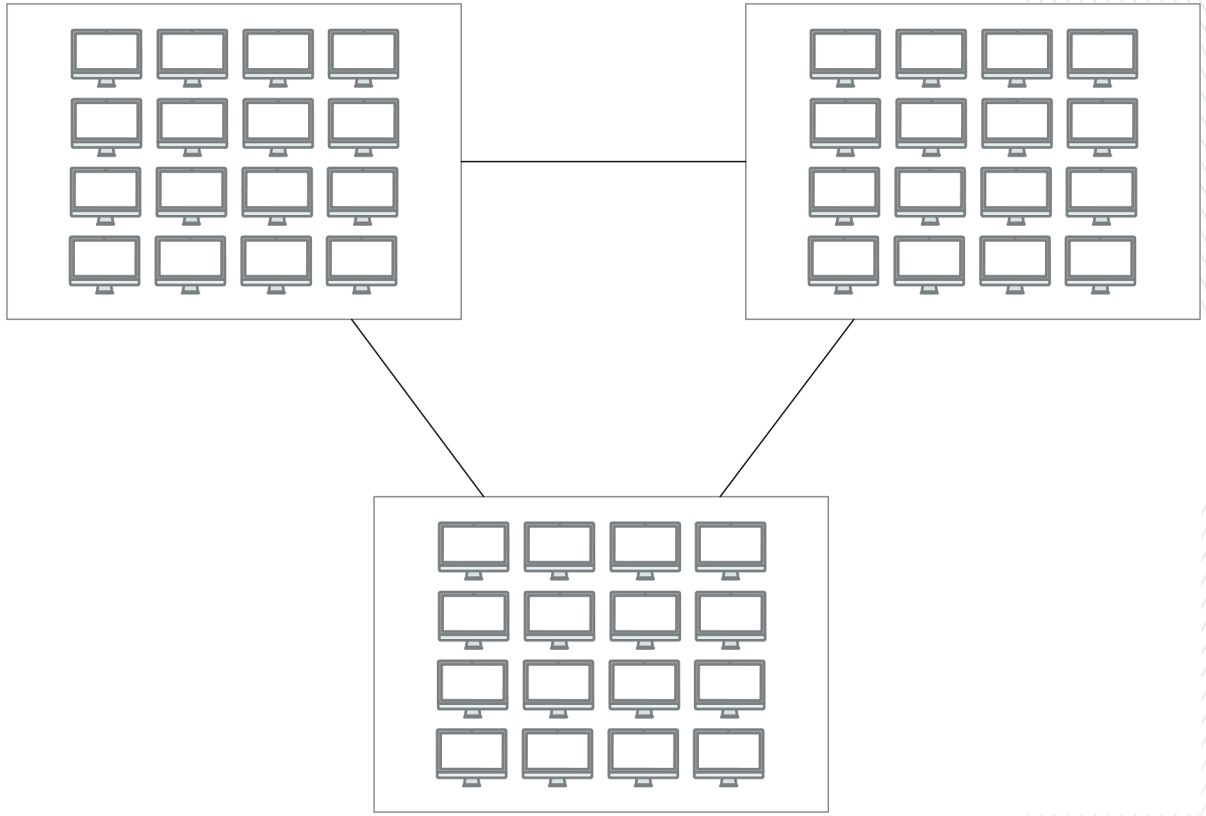
Distributed System Fuzzing

Benefits

- Side Effects
- Aggregate Effects
- Resource Exhaustion
- Correlational Inputs

Difficulties

- Large Input Space
- State Management
- Initialization
- Input Tracing



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NetFuzz

NetFuzz

What it does

- Fuzzes one or more processes in a distributed system
- Monitors one or more processes for crashes
- Ends fuzzing when a crash is detected
- Saves window of inputs leading up to crash

Design

- Distributed system for fuzzing distributed systems
- Python 3.7+
- Async support via *asyncio*
- Inter-process communication via *zmq*

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NetFuzz Components

Fuzz Controller

- Single central unit
- Status messages
- Start/stop fuzzing

Fuzz Node

- One or more
- Performs fuzzing
- Captures sequence of fuzzing inputs
- Fuzzing replay

System Monitor

- Zero or more
- Provides feedback

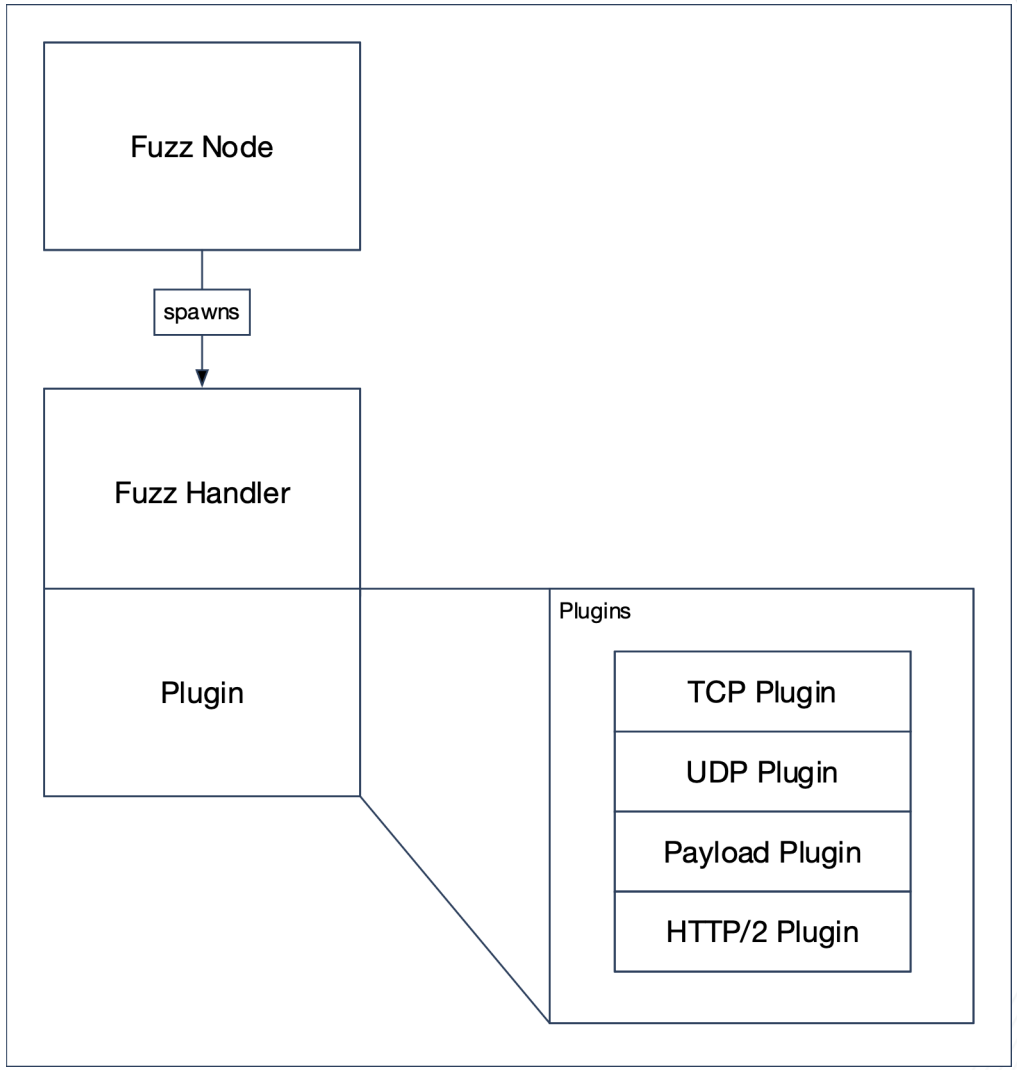
NetFuzz Features

Fuzzing paradigms

- One-to-one
- Many-to-one
- Many one-to-one
- Many-to-many

Plugin Architecture

- Fast protocol integration
- Config file or Python class



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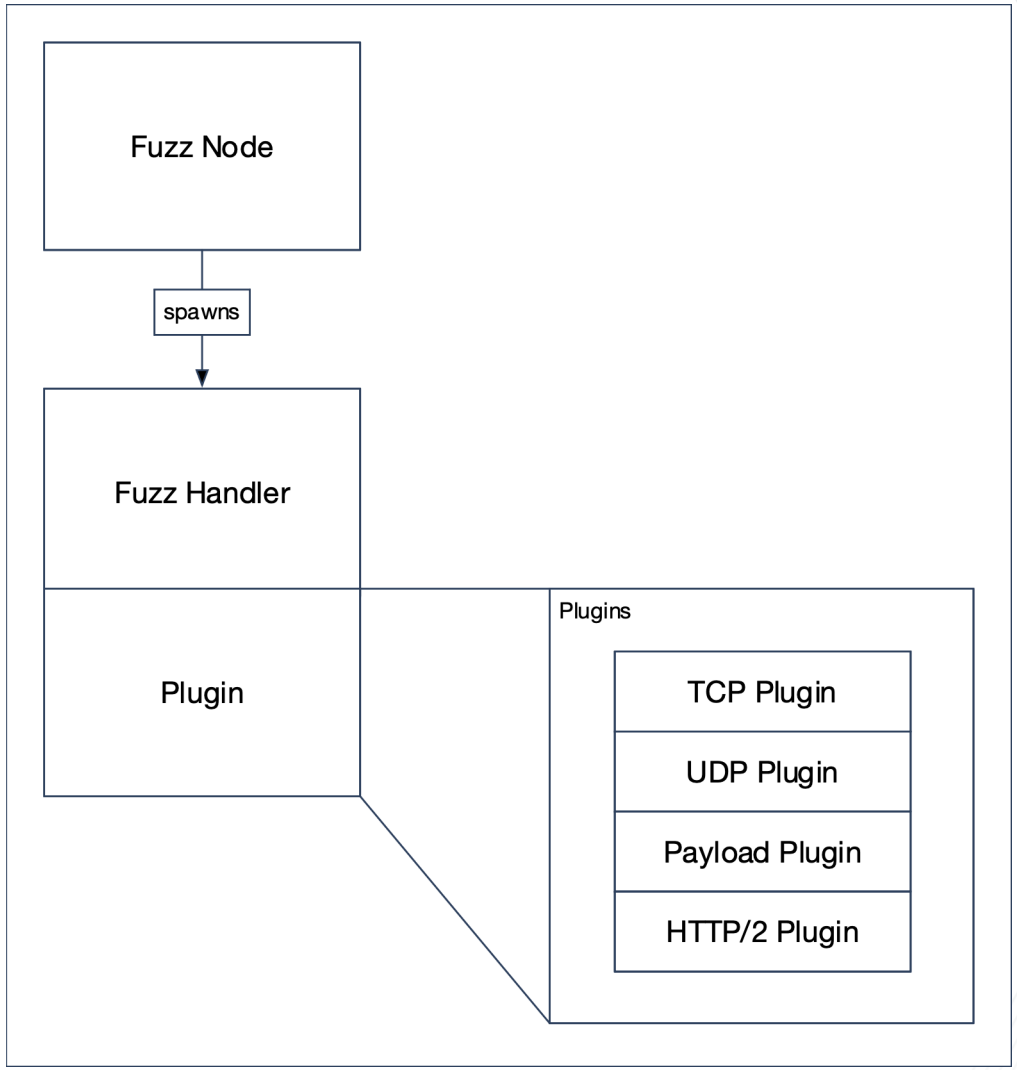


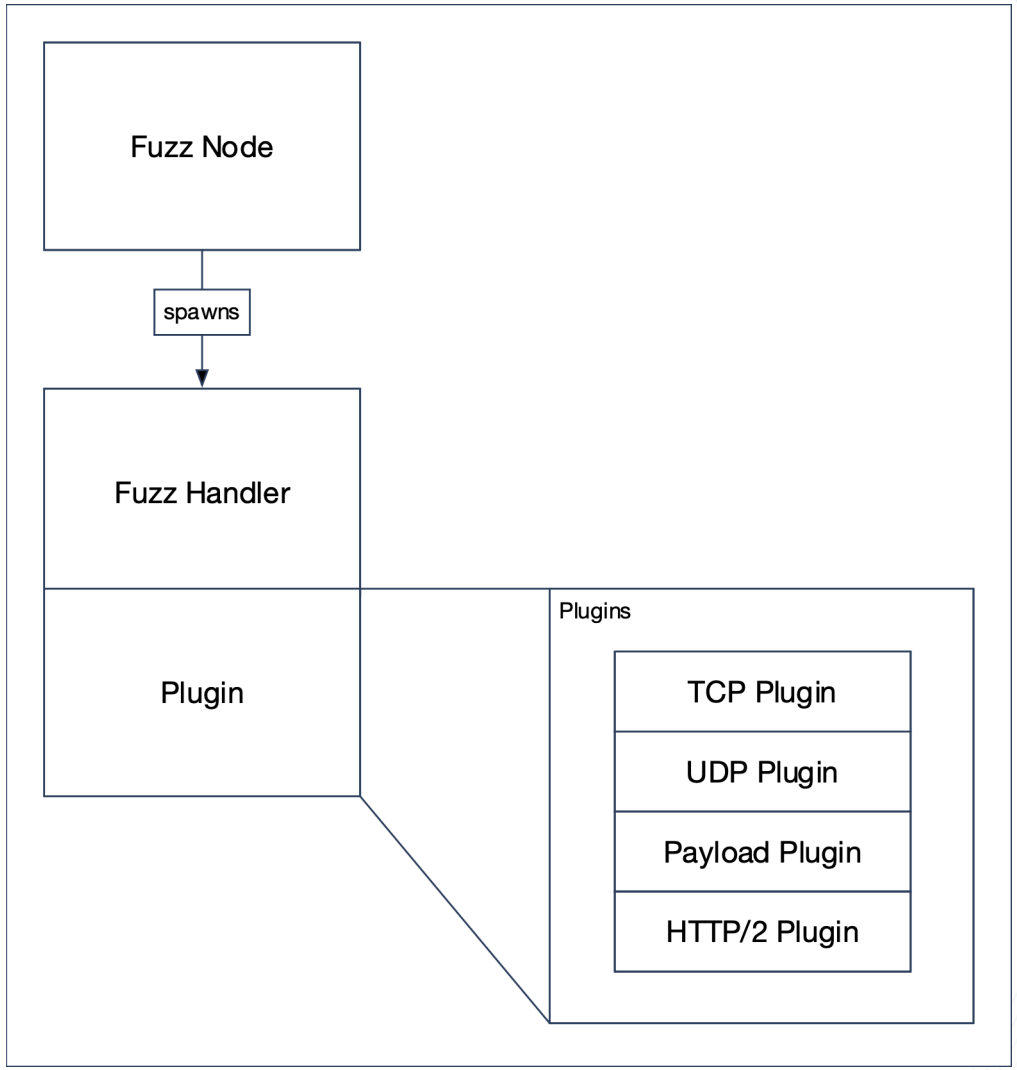
NetFuzz Features

Mutational fuzzing

- Read PCAP files
- Filter and mutate packets

Template fuzzing

- User-defined templates
- Stochastic fields



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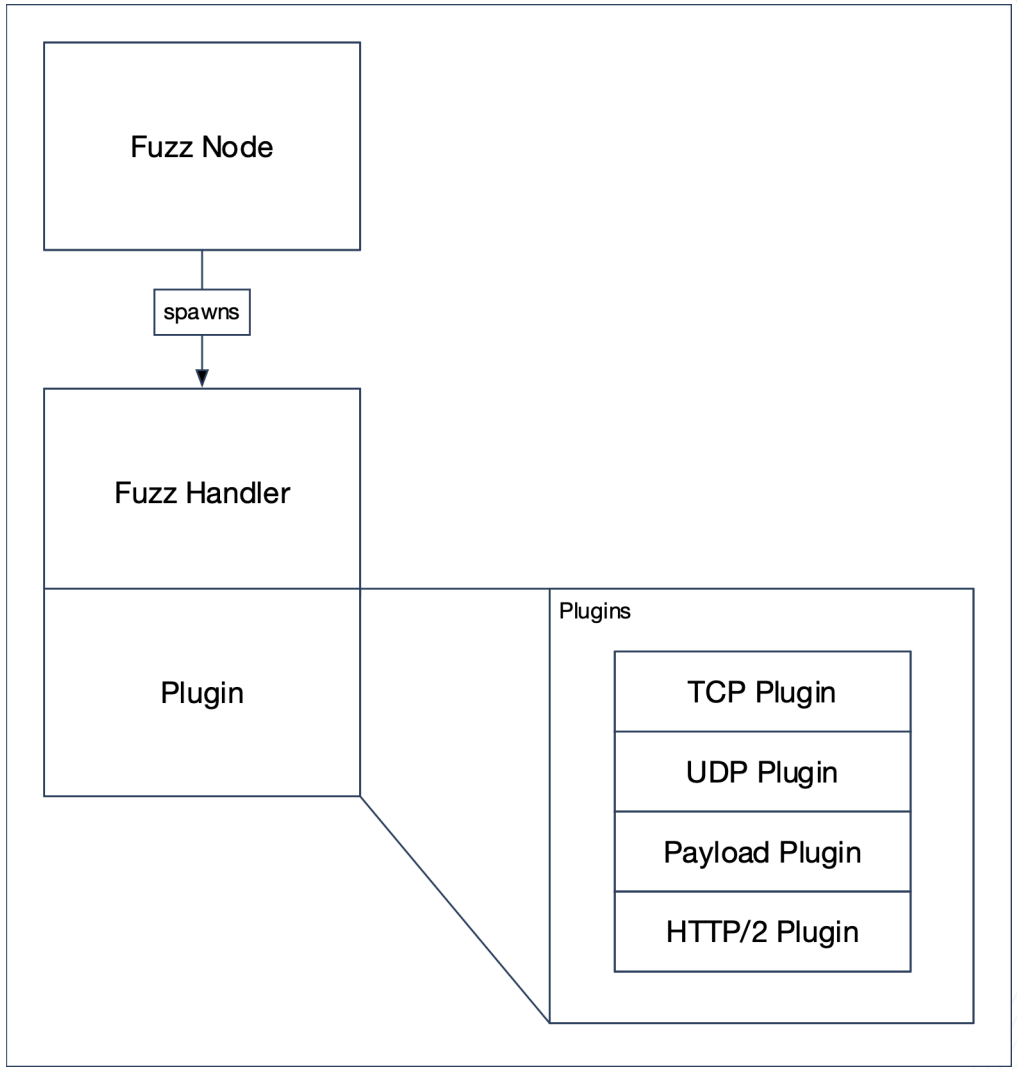

NetFuzz in Action

Vulnerability Assessment of a Large Scale CPS

- Received multiple VMs with customer software
- Installed NetFuzz on additional VM
- Created plugins to target different process

Results

- NetFuzz produced recurring crashes
- System Monitor showed increasing memory consumption
- Identified a resource exhaustion vulnerability caused by specific inputs

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Takeaways and Future Work

Takeaways

- Generalization is difficult
  - Fast protocol iteration
  - Exploration patterns
- Massive input space
  - Fuzzing takes a long time to produce results
  - Human guided inputs help reduce search time

Future Work

- Process state estimation
- Granular feedback mechanism

Questions?

Demonstrations excluded due to virtual workshop format.

michael.brown@gtri.gatech.edu