# *Fault Injection Framework for System Resilience Evaluation*

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# Context

- **Large Scale HPC Systems**
  - **Increased number of components**
  - **Increased complexity (hardware/software)**
- **HPC Applications**
  - **Challenged by scale**
  - **Challenged by failures**

# Motivation

- **Resilience**
  - **Keep HPC applications running in spite of failures**
- **Experimentation**
  - **Investigate methods to support resilience research**
- **Fault Injection**
  - **Provides technique for resilience experimentation**
  - **Repeatable process to study failures**

# Terminology

- **Fault, Errors & Failures (Laprie Taxonomy, DSC'04)**
  - **Fault – a defect in a service, may be "active" or "dormant"**
  - **Error – an "active fault" in a service**
  - **Failure – unsuppressed error, visible outside the service**
- **Fault Injection**
  - **Purposeful introduction of faults (errors) into target/victim**
  - **Hardware or Software**
    - **"SWIFI" – Software Implemented Fault Injection**

# Fault Injection / Testing

- **First purpose: testing our research**
  - **Inject failure at different levels: system, OS, application**
  - **Framework for fault injection**
    - **Controller: Analyzer, Detector & Injector**
    - **Target system & user level targets**
  - **Testing of failure prediction/detection mechanisms**
- **Mimic behavior of other systems**
  - **“Replay” failures sequence on another system**
  - **Based on system logs, we can evaluate the impact of different policies**

# Fault Injection

- **Example faults/errors**
  - **Bit-flips - CPU registers/memory**
  - **Memory errors - mem corruptions/leaks**
  - **Disk faults - read/write errors**
  - **Network faults - packet loss, etc.**
- **Important characteristics**
  - **Representative failures (fidelity)**
  - **Transparency and low overhead**
  - **Detection/Injection are linked**
- **Existing Work**
  - **Techniques:  Hardware vs. Software**
  - **Software FI can leverage perf./debug hardware**
  - **Not many publicly available tools**

# Related Work

- ***Xception*** **– leveraged hardware supported debug/perf monitoring capabilities**
- ***FAUmachine*** **– simulated faults in a user-space process (similar to UML)**
- ***FIG*** **– introduce errors at library level by interposing on calls to shared library (use LD_PRELOAD)**
- ***NFTAPE*** **– component-based fault injection system for distributed environments**
- ***Linux-FI*** **– in kernel fault injector with current support for areas of the memory and IO subsystems**

# Existing System Level Fault Injection

- **“Existing” source that is free & publicly available**
- **Virtual Machines**
  - **FAUmachine**
    - **Pro: focused on FI & experiments, code available**
    - **Con: older project, lots of dependencies, slow**
  - **FI-QEMU (patch)**
    - **Pro: works with ‘qemu’ emulator, code available**
    - **Con: patch for ARM arch, limited capabilities**
- **Operating System**
  - **Linux (>= 2.6.20)**
    - **Pro: extensible, kernel & user level targets, maintained by Linux community**
    - **Con: immature, focused on testing Linux**

# Linux Fault Injection (Linux-FI)

- **Kernel supported fault injection**
  - **Linux >= 2.6.20**
  - **Send faults to user-space (PID) and system-level (module/addr)**
  - **Supports faults in several key kernel subsystems**
- **Supports injecting (*as of v2.6.25.7*)**
  - **Slab errors**
  - **Page allocation errors**
  - **Disk IO errors**
- **Interface via *debugfs***
  - **Enable Linux FI via entries in `/debug` file-system**
  - **Set probability for given fault**
    - **Example: 0 (never) …to… 100 (always)**

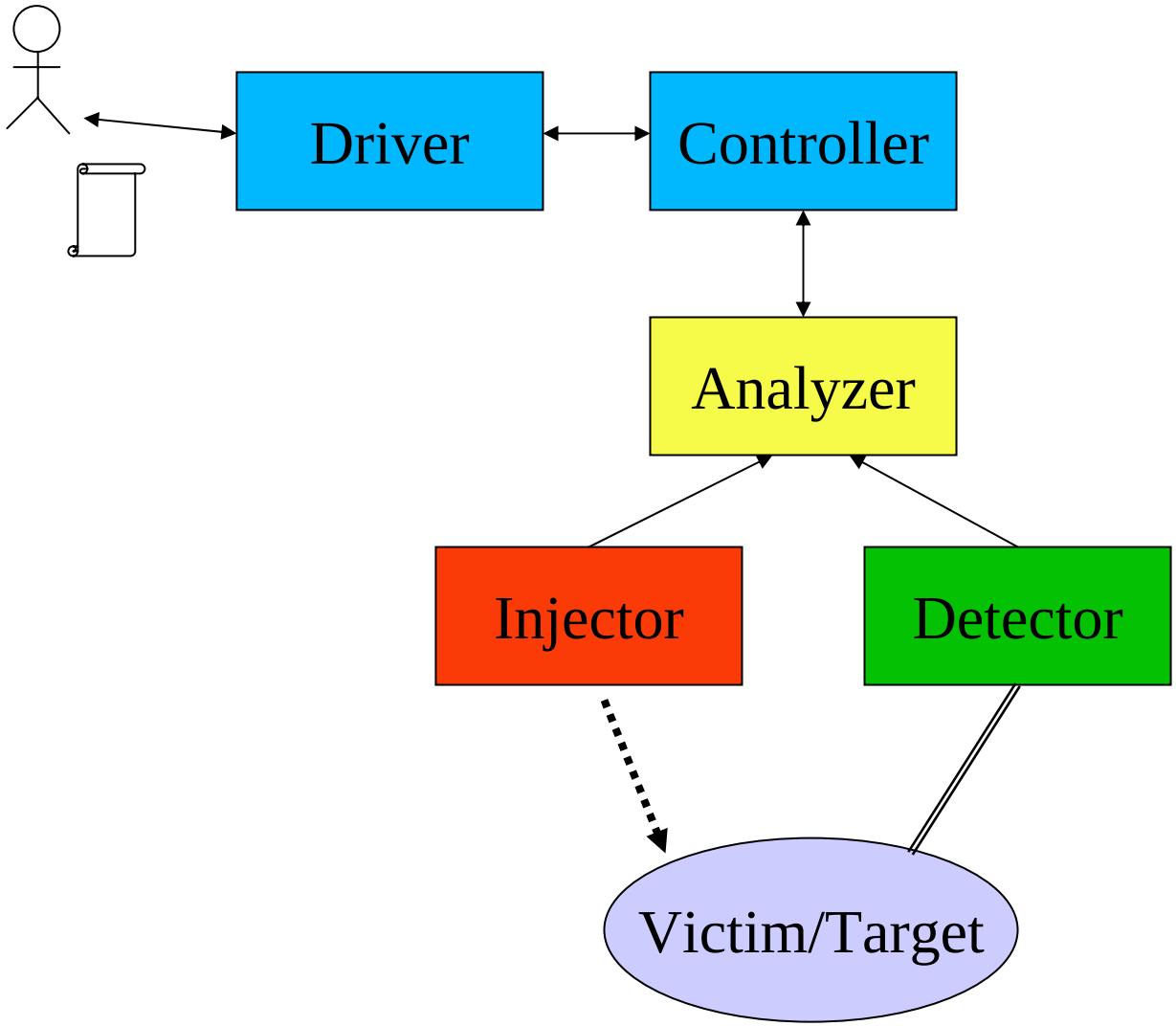
# Basic Criteria for FI Framework

- **Simplicity**
  - **Easy to setup, define and perform FI experiments**
- **Versatility**
  - **Support experiments at different levels of software stack**
    - **User and Kernel level**
- **Reproducibility**
  - **Framework should allow for reproducible experiments**
- **Distributed environments**
  - **Experiments on local & remote nodes; physical & virtual machines**

# Fault Injection Architecture

- **Driver**
  - **Interface between user and framework**
- **Controller**
  - **Manages life-cycle of components (create, run, terminate)**
- **Analyzer**
  - **Responsible for collating/processing experiment info**
  - **Interprets events for a given detector/injector configuration**
- **Injector**
  - **Generates a fault (error) in a given victim/target**
- **Detector**
  - **Detects a failure in a given victim/target**

# Fault Injection Architecture



# Evaluation

- **Initial framework implementation**
  - **Prototype called *finject***
- **Preliminary evaluation**
  - **Memory/register based fault injection**
- **Two experiments**
  - **Experiment I: ptrace based injector**
  - **Experiment II: Linux-FI based injector**

# FInject Input File

- **Experiment file: "*experiment.txt*"**
  - **Used to express type of failure & experiment parameters**
  - **One experiment per line**

```
# finject experiments
# Format:
# fault_type : fault_mode : fault_args : victim_host : flags
memory : intermittent : app='/tmp/fileptr‘ : ubuntu-vm : finject='kern-memory',dargs='50'
register : permanent : app='/tmp/loopnest-forever‘ : localhost : finject='user-memory'
```

**** Note, currently only minimal subset of input fields are supported***

- **Usage**

**./finject --file experiment.txt**

# FInject Config File

- **Framework config file: "*finject.conf*"**
  - **Used to group compatible injectors-detectors-analyzers**
  - **Determines backend modules used by framework for experiments**

```
# finject experiment settings
[user-memory]
    injector=injectors/frob-reg-injector
    detector=detectors/child-watcher
    analyzer=analyzers/basic-counter
```

# Experiment I: Ptrace based injector

- **Injects CPU register errors (bit-flips) via `ptrace()`**
- **Finject Components**
  - **Target: "*loopnest-forever*"**
    - **App that runs infinite loop printing PID & counter**
  - **Analyzer: "*basic-counter*"**
    - **Counts labeled events from Detector & Injector**
  - **Detector: "*child-watcher*"**
    - **Starts app & watches/reports child exit status to Analyzer**
  - **Injector: "*frob-reg-injector*"**
    - **Injects bit-flip in register value for an app (PID) & notifies Analyzer**

# Experiment I (cont.)

- **On average the dummy application failed after sending approximately 22 faults (register bit-flips)**
- **As expected the application spent almost all time in a library write routine printing the output, which wasn't esp. sensitive to the register based errors**

| Field | Value | Description |
|---|---|---|
| Count (victims) | 100 | Number of victim application instances |
| Total (injections) | 2197 | Number of injected failures for all runs |
| Minimum | 1 | Number of injections to victim failure |
| Maximum | 98 | Number of injections to victim failure |
| Mean | 21.97 | Number of injections to victim failure |
| Median | 17 | Number of injections to victim failure |
| Mode | 4 | Number of injections to victim failure |
| Std.Dev. | 21.419 | Number of injections to victim failure |

Table 1: Statistics associated with Experiment-I (register bit-flip)

# Experiment II: Background on Memory

- **Linux memory allocation**
  - **Generic pages**
  - **Object cache (SLAB)**
- **SLAB**
  - **Cache of typed memory objects**
  - **Reuse freed memory objects (performance)**
  - **Listing of object types & statistics via `/proc/slabinfo`**
- **Example**
  - **Maintain cache of file pointer ("filp") objects**

```
#include <stdio.h>
FILE *tmpfile(void);
```

# Experiment II: Linux-FI based injector

- **Injects memory allocation errors for 'filp' SLAB objects via Linux-FI**
- **Finject Components**
  - **Target: "*fileptr*"**
    - Creates temporary file(s) & handle via `tmpfile()`
  - **Analyzer: "*basic-counter*"**
    - **Counts labeled events from Detector & Injector**
  - **Detector: "*fileptr-watcher*"**
    - **Starts app & watches child STDOUT and exit status, notifies Analyzer**
  - **Injector: "*linux-fi-injector*"**
    - **Just report kernel generated faults to Analyzer**
    - **Actual injector is the Linux-FI subsystem**

# Future Work

- **Finalize initial finject prototype**
  - **Framework itself**
  - **Injector/Detectors: Linux-FI (SLAB) & ptrace**
- **Fault types/methods**
  - **Identify representative failures for HPC systems**
  - **Determine how best to perform injection/detection**
- **Anomaly analysis**
  - **Combine tool with current anomaly analysis prototype**
  - **Investigate anomaly/failure correlation**

# Conclusion

- **Resilience research needs platforms/tools for repeatable experimentation**
- **Fault injection provides a useful mechanism to perform repeatable testing and development**
- **Proposed fault injection framework provides basis for building resilience testbeds/environments**
- **Prototype leveraged ptrace(2) and Linux-FI**
  - **CPU register bit flips**
  - **Linux SLAB allocation errors (type ‘filp’)**

# Resources

**http://www.csm.ornl.gov/srt**

# Flow of FInject Experiment

1. Driver: reads and processes list of experiments
2. Driver: invokes Controller with an experiment
3. Controller: reads framework conguration (policy) settings
4. Controller: redirects STDERR for children
5. Controller: starts Analyzer
6. Analyzer: routes Detector/Injector STDOUT to Analyzer STDIN
7. Analyzer: starts Detector
8. Detector: starts victim App, watches/reports to Analyzer
9. Analyzer: starts Injector
10. Injector: victimizes App, reports to Analyzer
11. Analyzer: waits on Detector/Injector
12. Analyzer: sends results to Controller
13. Controller: prints results and returns to Driver