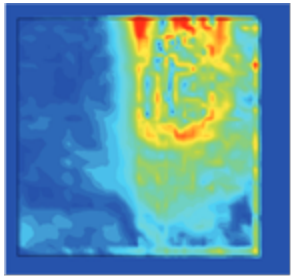
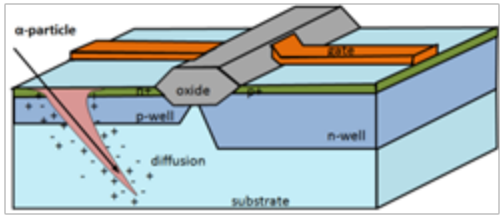
LLFI: An Intermediate Code-Level Fault Injection Tool for Hardware Faults

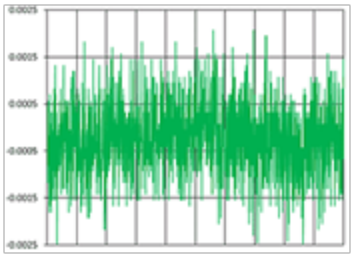
Qining Lu, Mostafa Farahani,
Jiesheng Wei, Anna Thomas, and
Karthik Pattabiraman

Department of Electrical and Computer Engineering,
University of British Columbia

Motivation







- Hardware faults' frequency is increasing [Borkar'11][Constantinescu'08]
  - Temperature variations
  - Soft errors due to particle strikes
  - Manufacturing defects

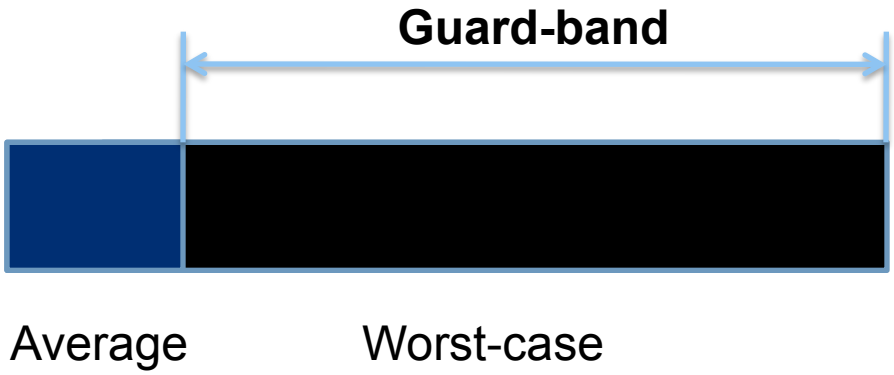
Hardware Errors: Traditional "Solutions"

- **Guard-banding**

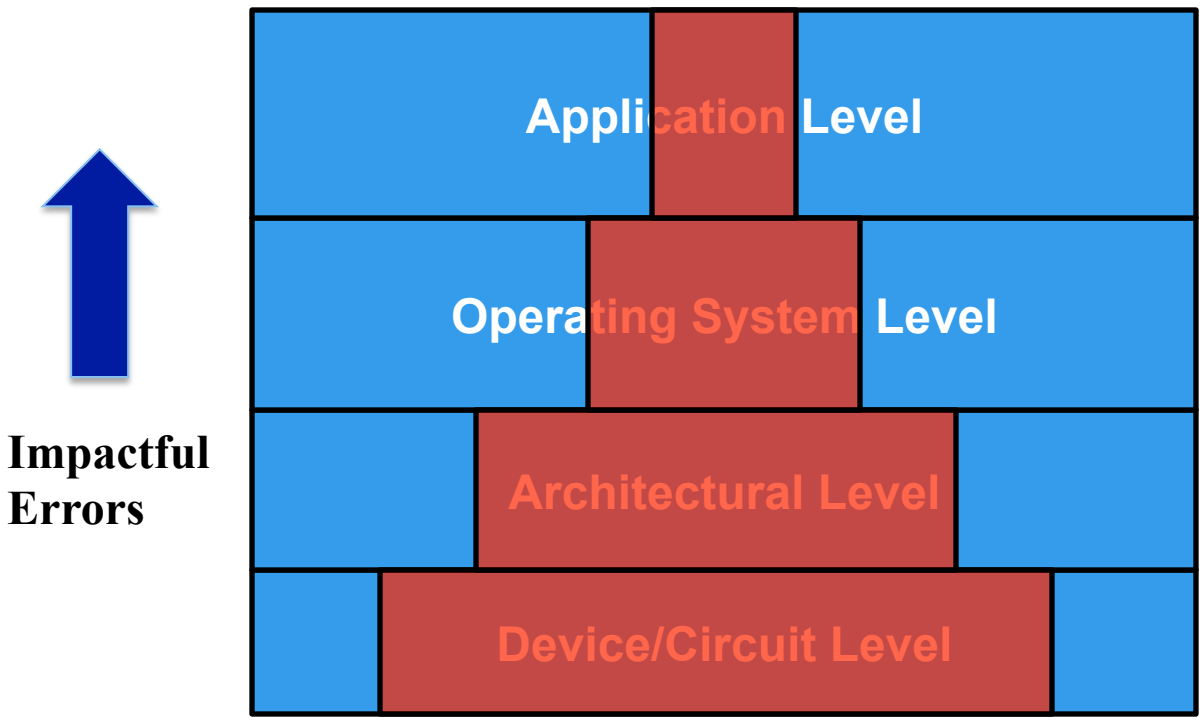
  Guard-banding wastes power as gap between average and worst-case widens due to variations

- **Duplication**

  Hardware duplication (DMR) can result in 2X slowdown and/or energy consumption

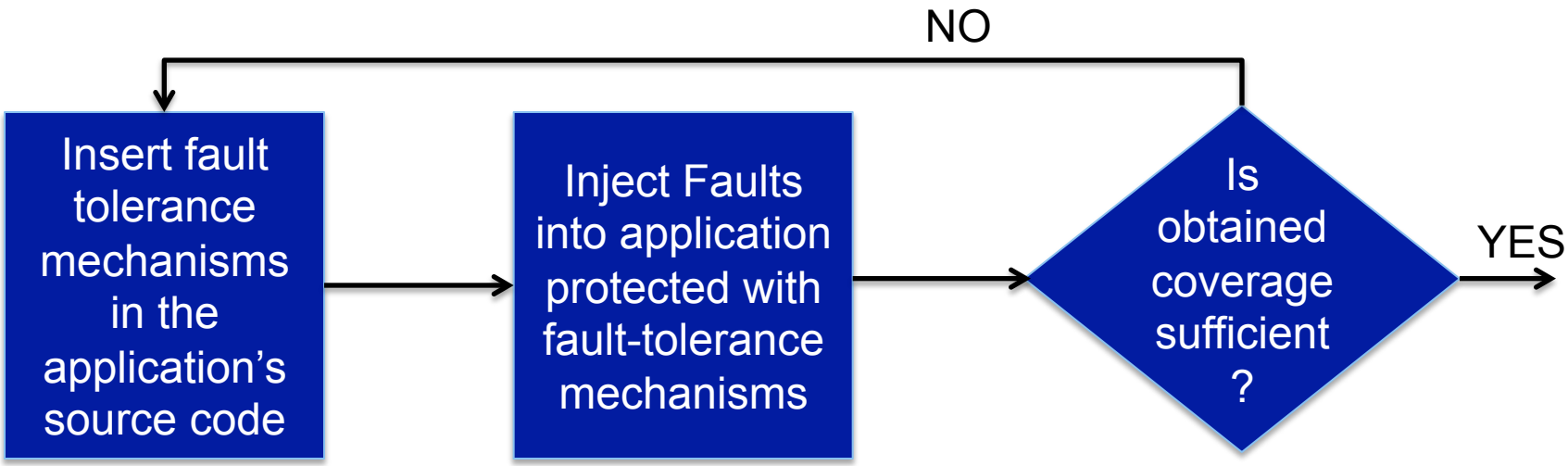


Application-level techniques

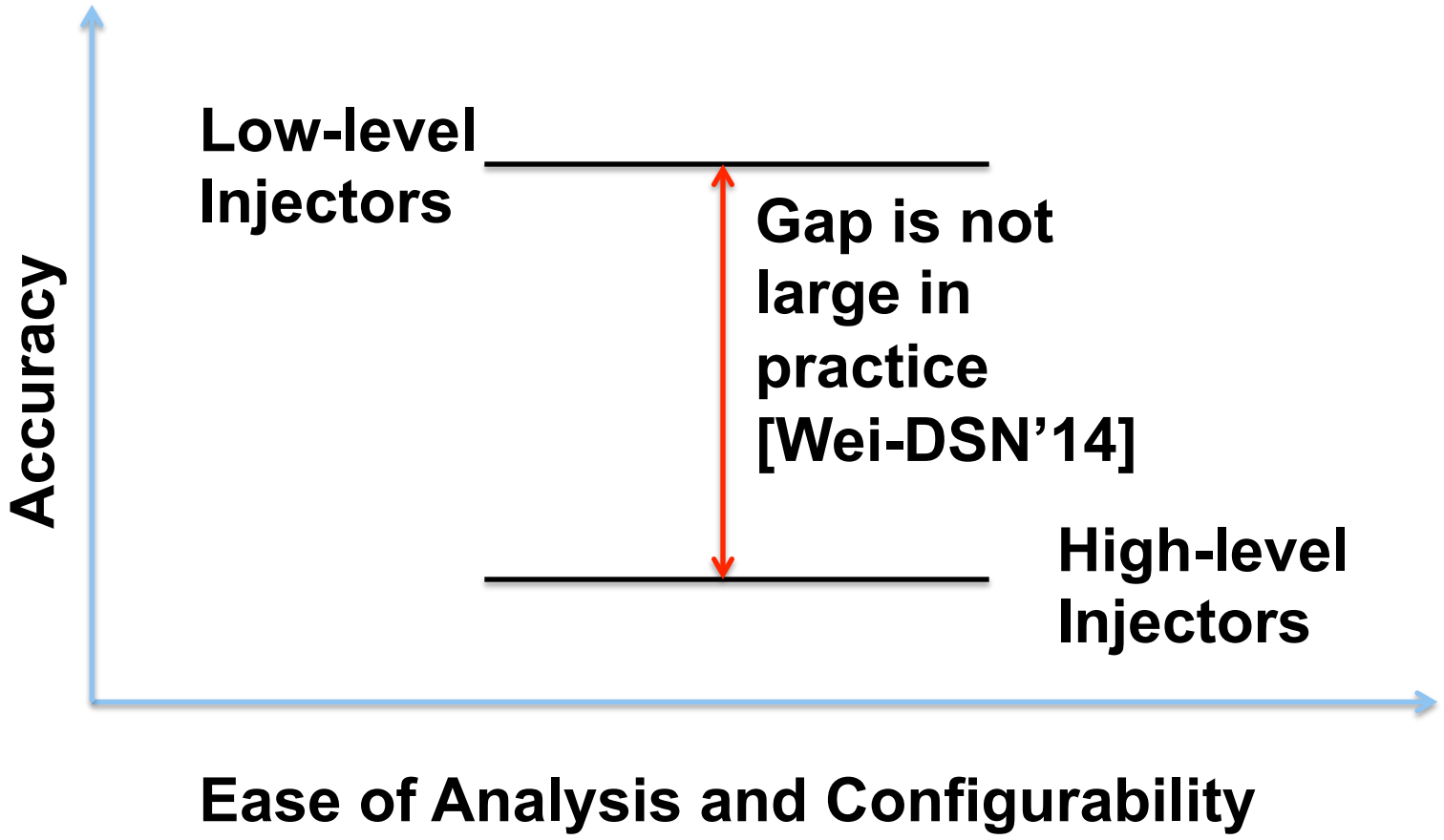


Fault Injection

- To obtain coverage estimates for applications
- Iteratively improve coverage based on the errors missed by fault tolerance mechanisms
  - Analyze the errors that are missed by the FTMs



High-Level Vs. Low-Level Injectors



Outline

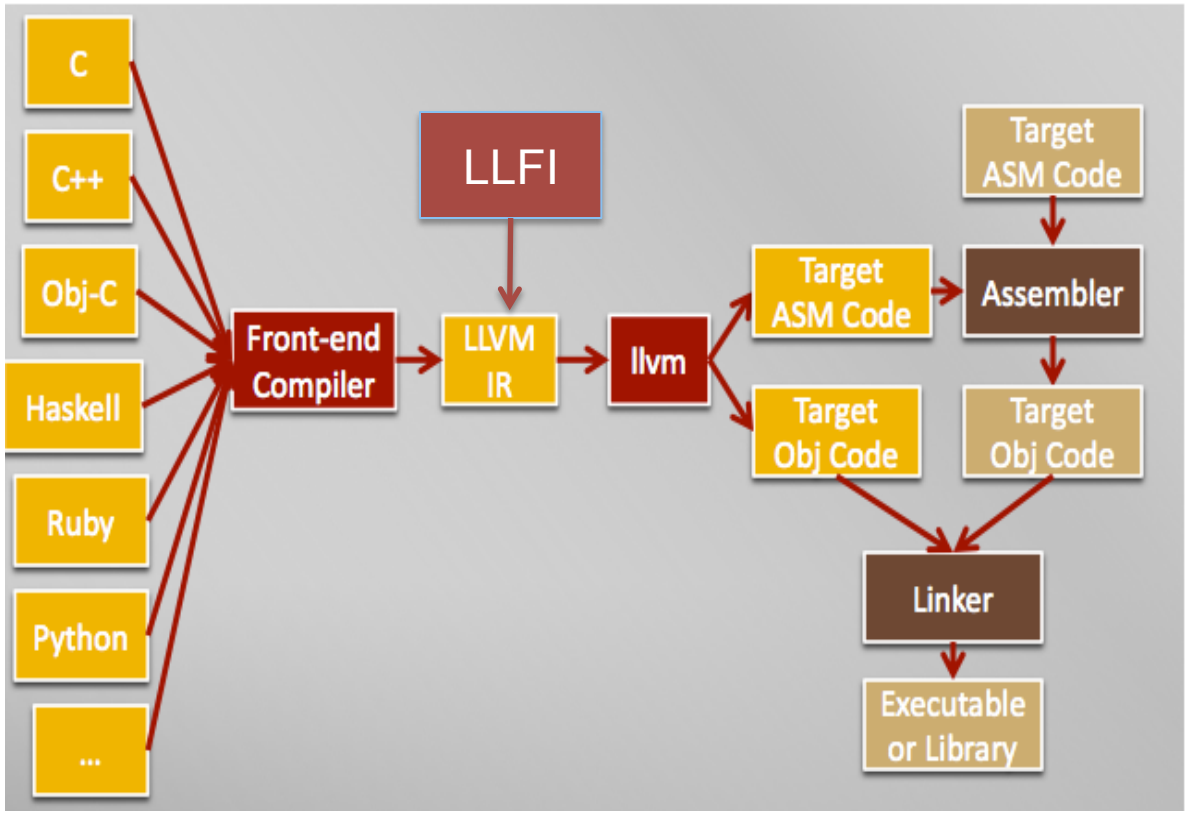
- Motivation
- LLFI: High Level Fault Injector
- Experimental Setup and Results
- Conclusion

LLFI: High-Level Fault Injector

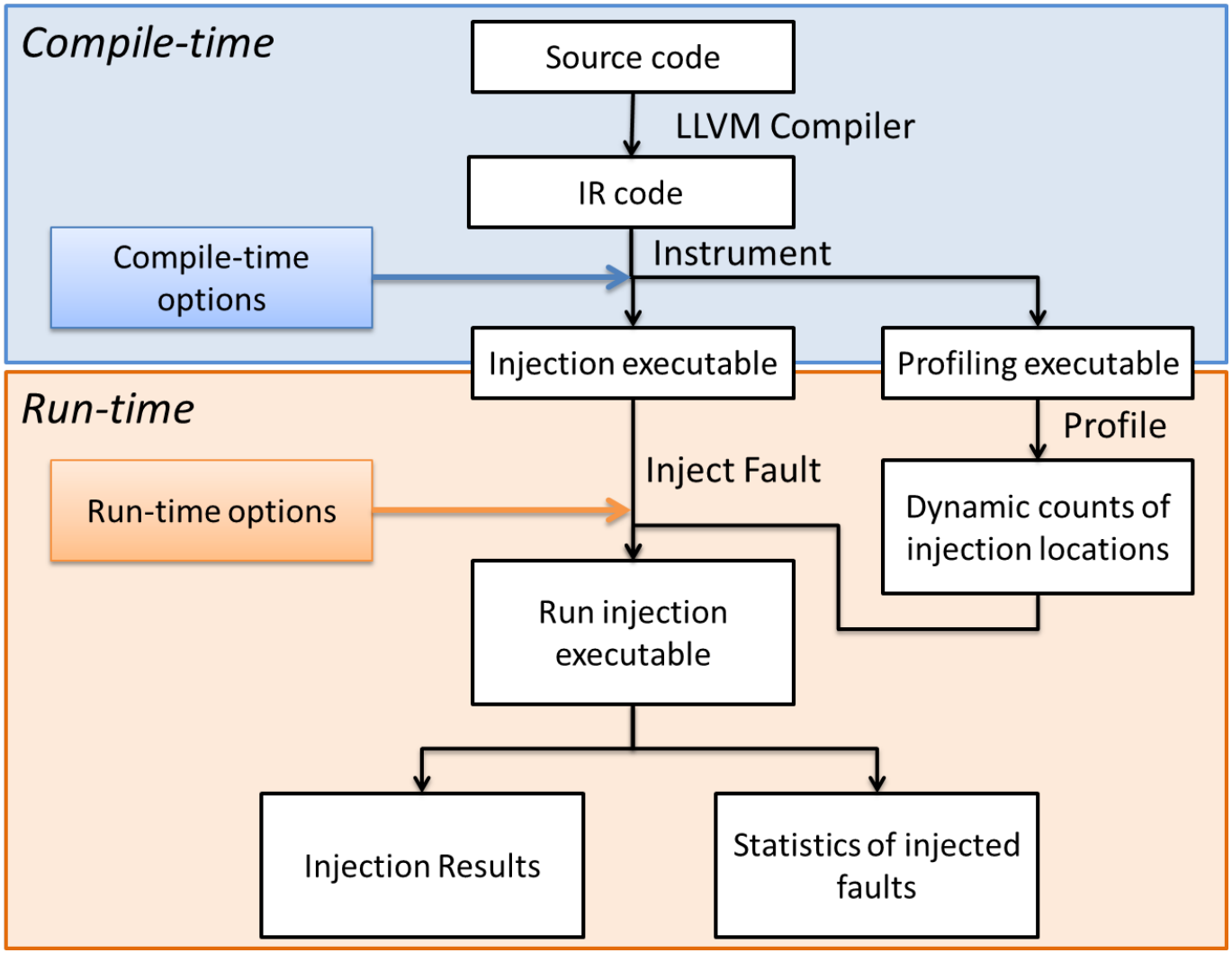
- **A fault injector based on LLVM**
  - Intermediate representation (IR) level injection
- **Features**
  - **Easy to customize the fault injection**
  - Easy to analyze fault propagation
  - Easy to use by developers

LLFI: Structure

Works at LLVM compiler's intermediate (IR) code level [Lattner'05] –widely used in industry



LLFI: Workflow

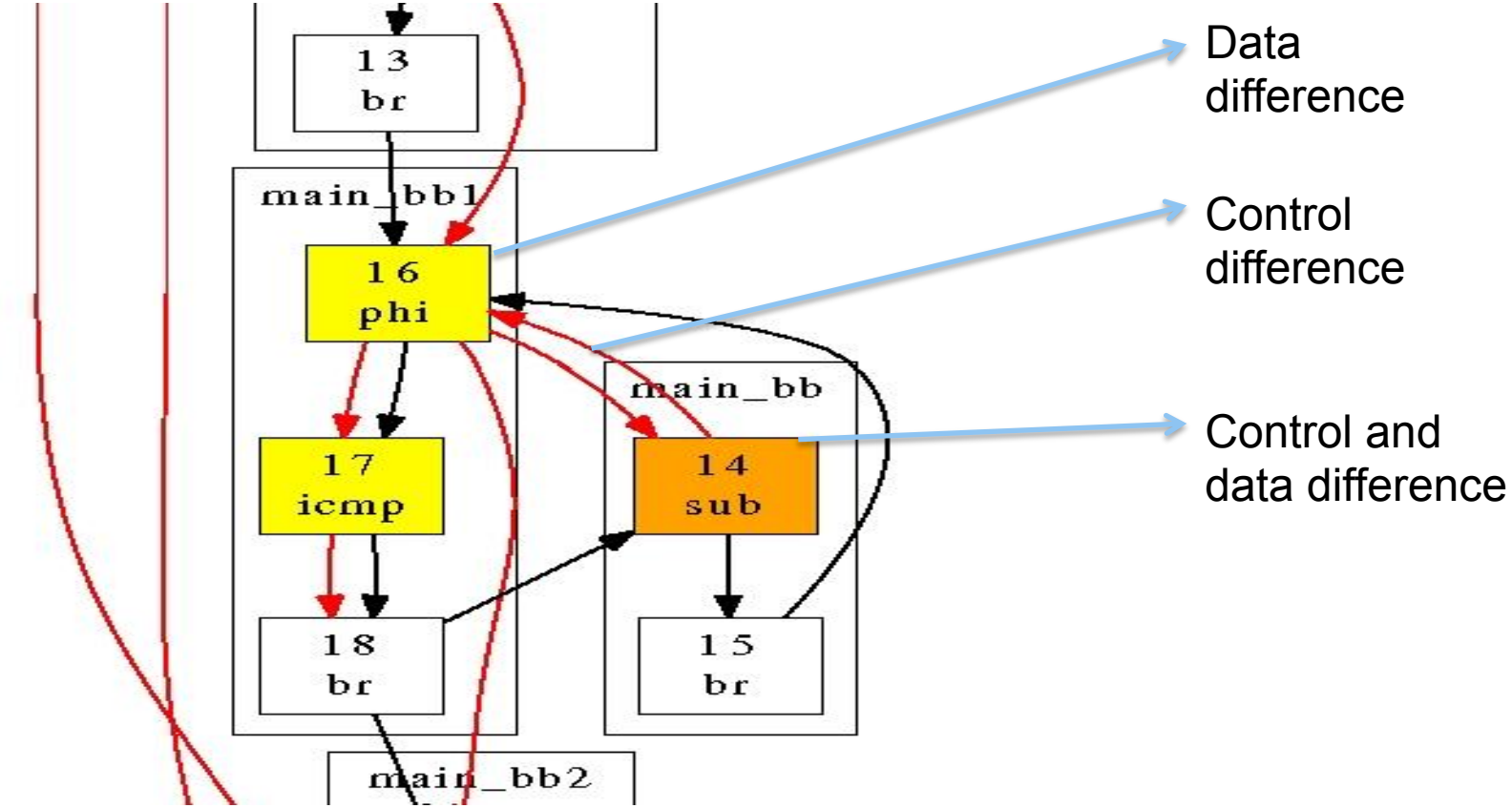


LLFI: Easy to Customize

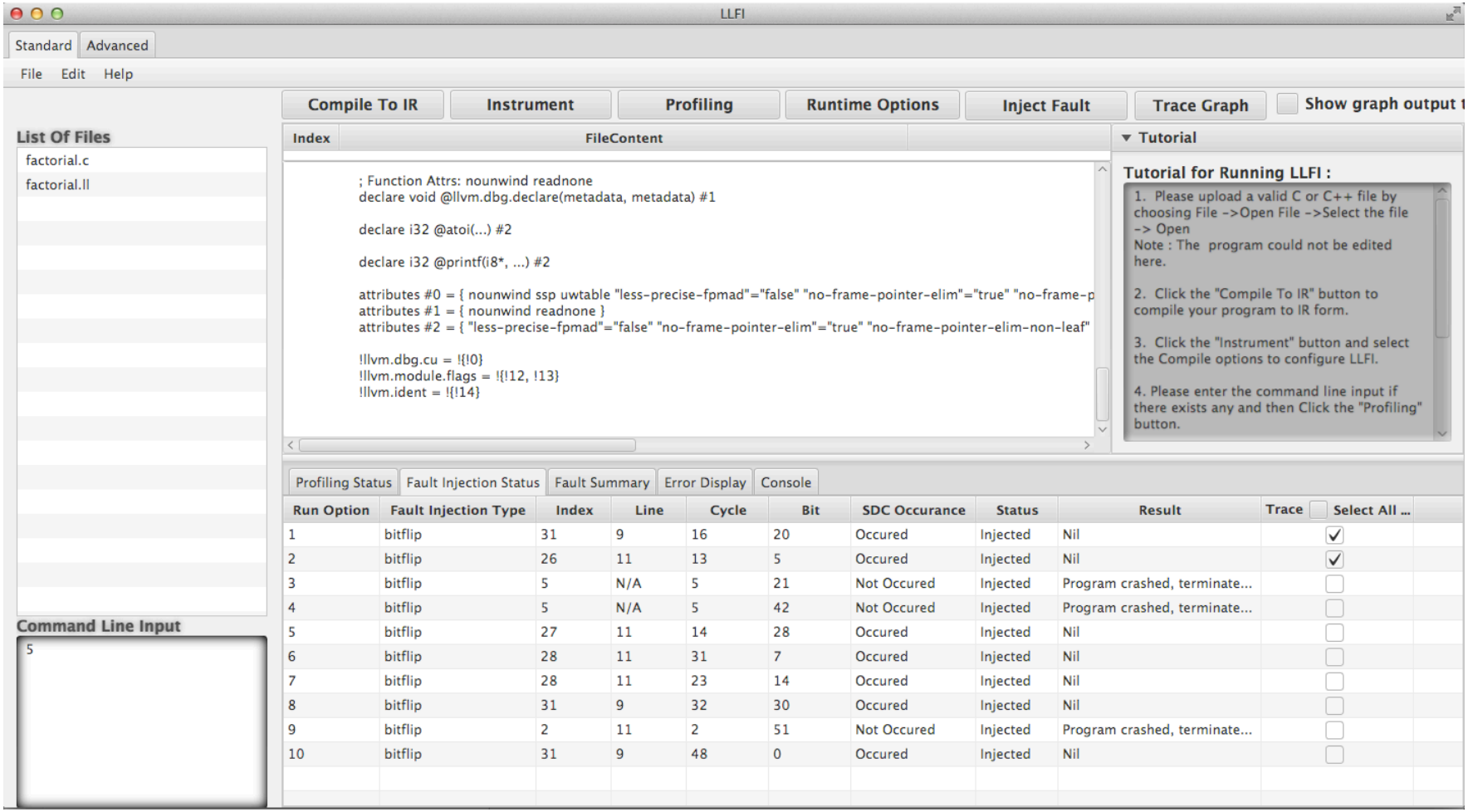
- **Fault injection instruction selector**
  - Based on instruction type (LLVM IR)
    - Include: add + cmp
    - Exclude: load
  - Based on register target (source/destination)
  - Can choose type of fault to inject (single/ double bit flip, stuck at fault etc.)

LLFI: Easy to Analyze

- Graphical output of trace differences



LLFI: Easy to Use



Outline

- Motivation
- LLFI: High Level Fault Injector
- Experimental Setup and Results
- Conclusion

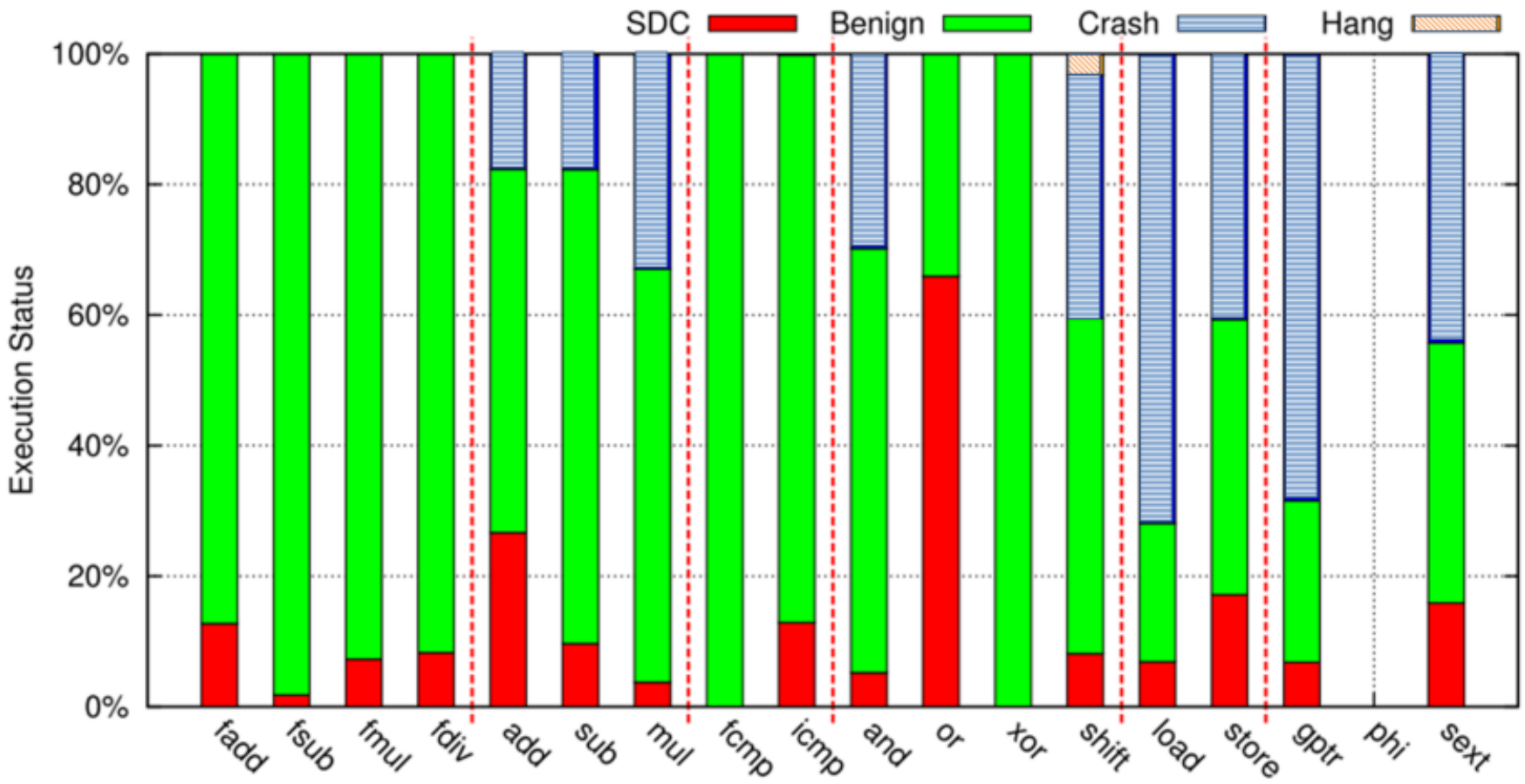
Research Questions

- RQ1: Effect of injecting faults into different types of instructions in the program
- RQ2: Effect of injecting faults into different kinds of registers (source or destination)
- RQ3: Effect of single bit flip vs. double bit flip fault type, and ‘distance’ between them

Experimental Setup

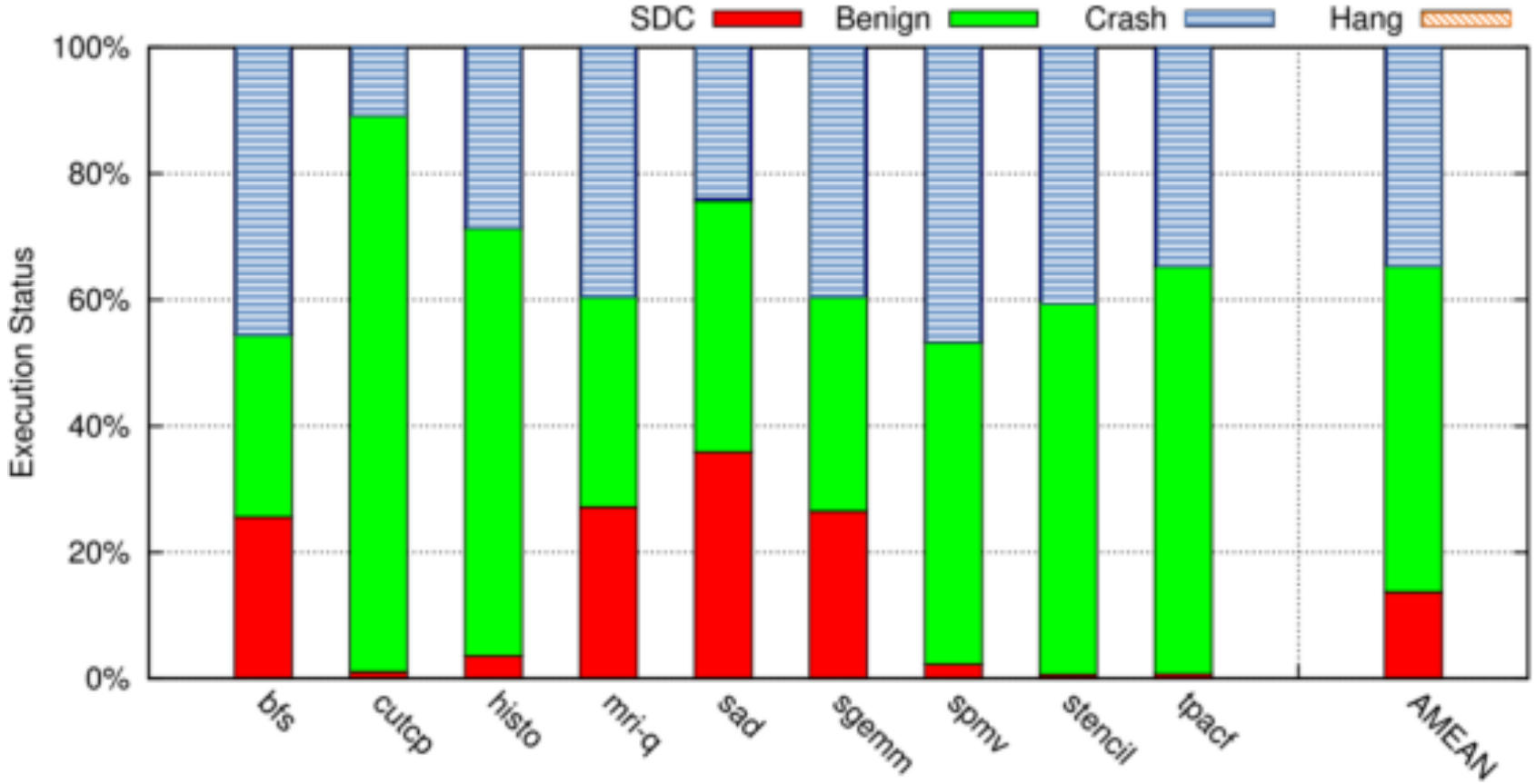
- **Benchmarks:**
  - *PARBOIL* benchmark suite for CPUs
- **Method:**
  - 1000 fault injections per benchmark per experiment
  - One fault per run (singe bit flip)
- **Outcomes:**
  - Crash, Hang, Silent Data Corruption (SDCs) or Benign

Results: RQ1 (Instruction Types)



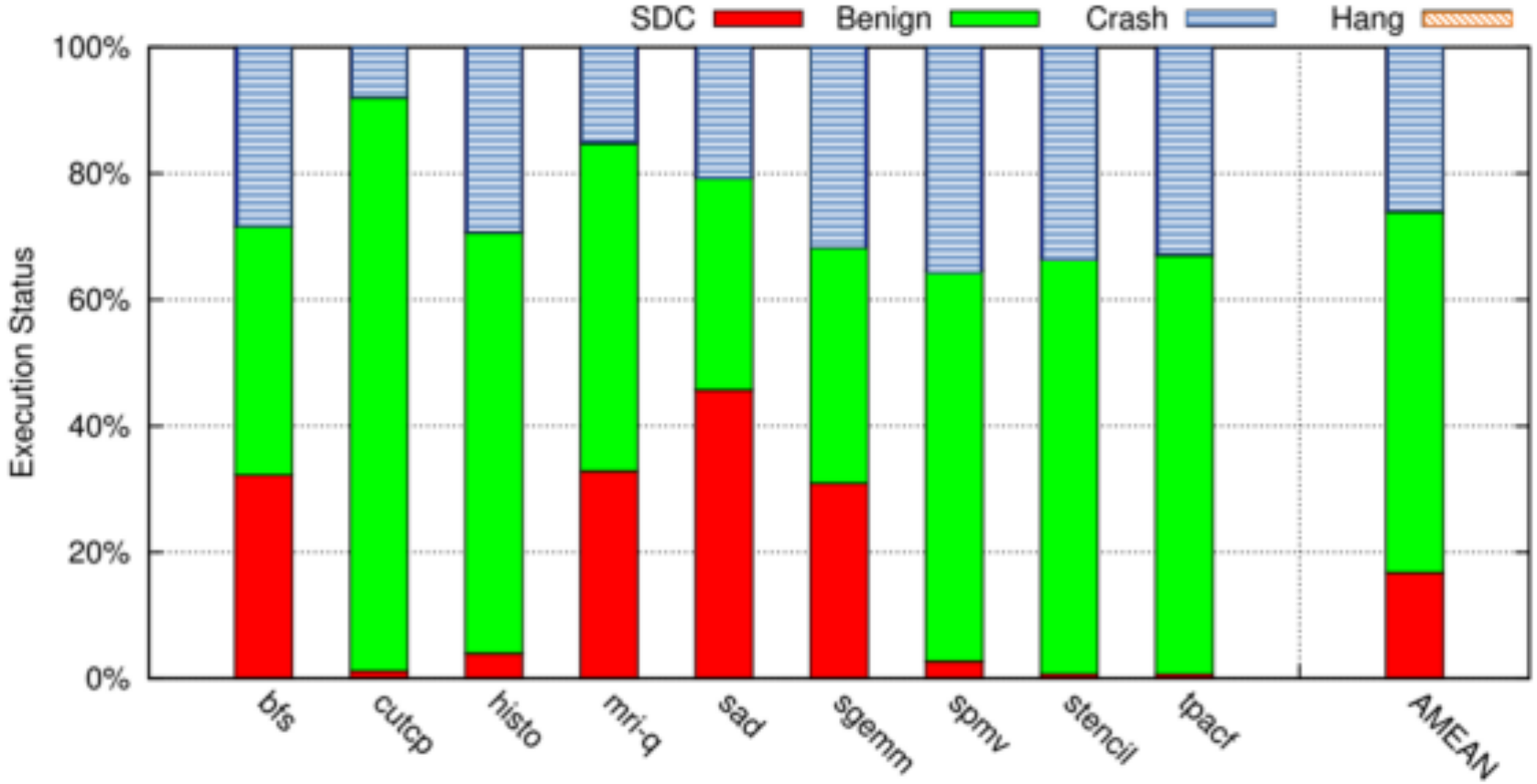
Failure distribution of injecting different instruction types

Results: RQ2 (Register Types)



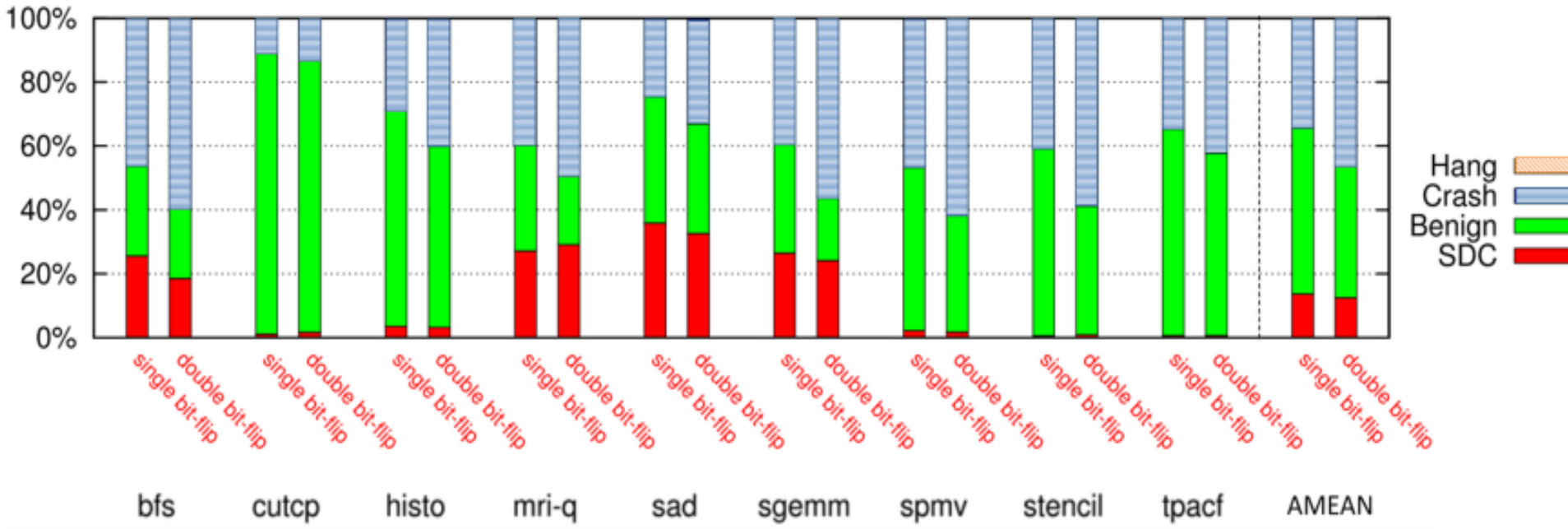
Failure distribution of injecting into source register

Results: RQ2 (Register Types)



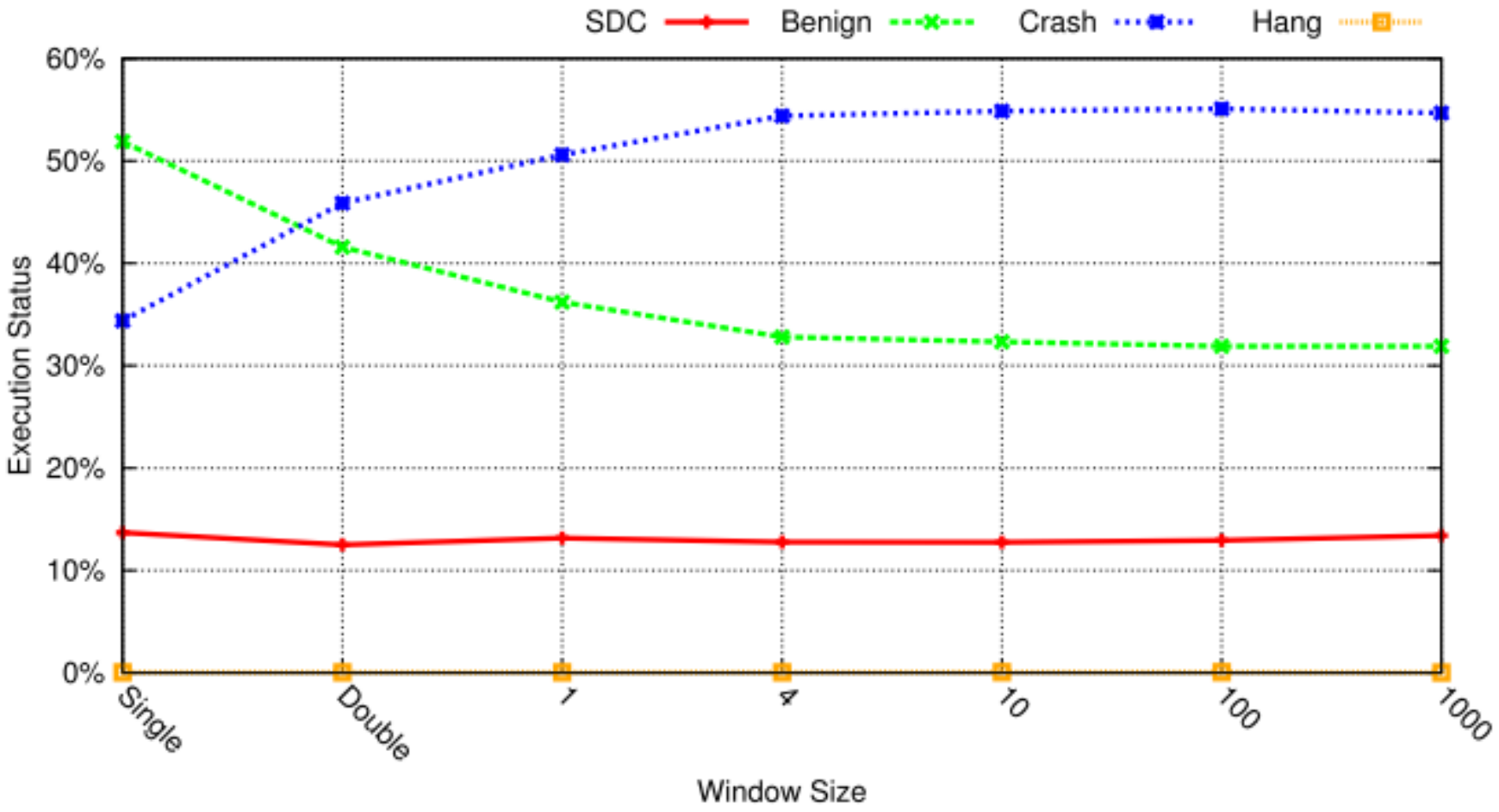
Failure distribution of injecting into destination register

Results: RQ3 (Single vs. Double Bit Flip in same Register)



Failure distribution of single bit-flip vs. double bit-flip

Results: RQ3 (Window Size)



Effect of window size for double bit flip

Outline

- Motivation
- LLFI: High Level Fault Injector
- Experimental Setup and Results
- Conclusion

Conclusion

- LLFI is a highly configurable fault injection tool that works at the LLVM IR level
- Both Instruction type and register target are highly correlated with failure outcome
- Double bit fault increases the crash rate but not the SDC rates, and that too only within a short window of <5 instructions

https://github.com/DependableSystemsLab/LLFI