Lapse

Automatic, Formal Fault-Tolerant Correctness Proofs for Native Code

Charles Averill, Ilan Buzzetti, Alex Bellon, Kevin Hamlen

The University of Texas at Dallas
UC San Diego

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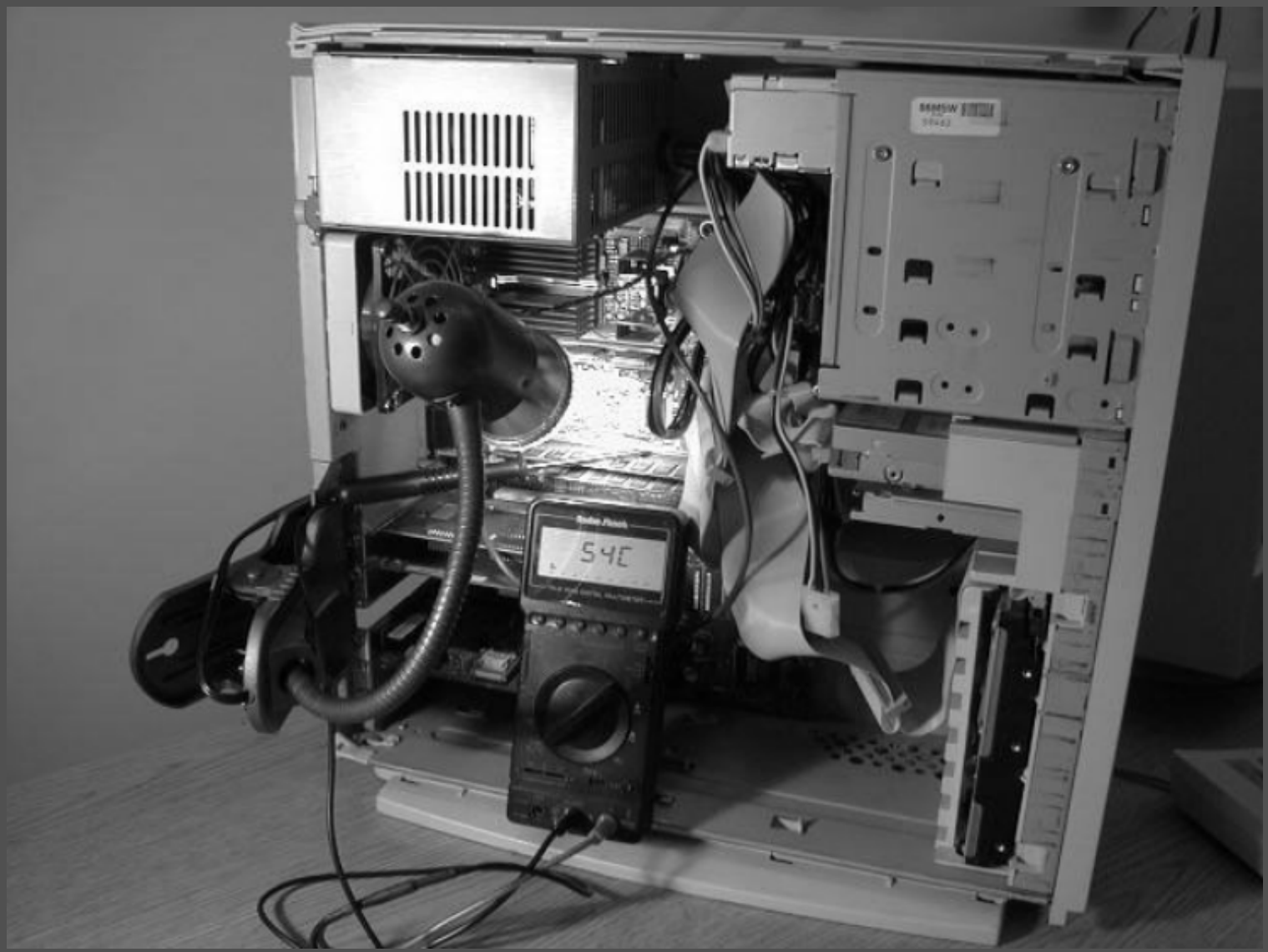
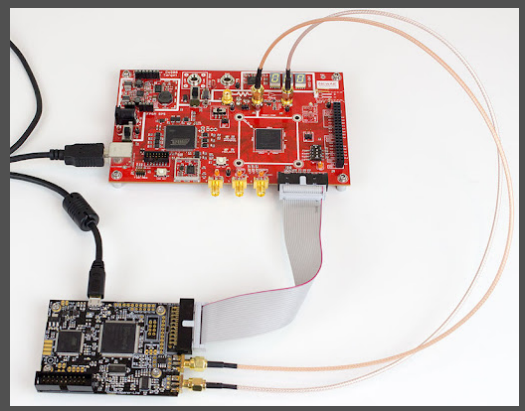
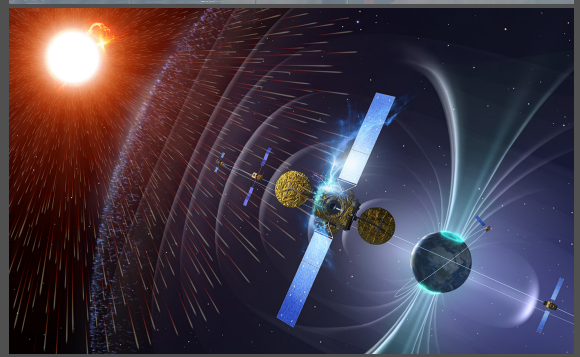
“Using Memory Errors to Attack a Virtual Machine”

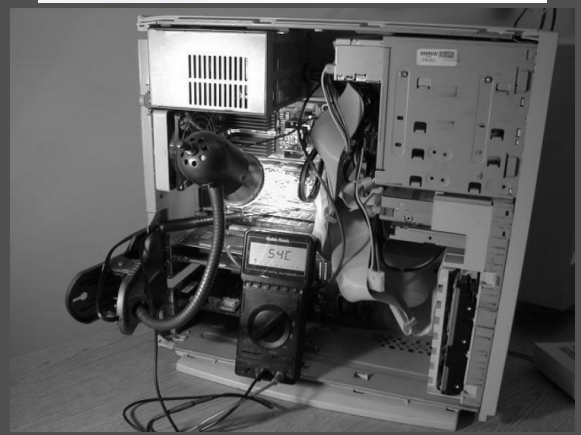


Contract Violations

- Hardware invariants can be invalidated without proper protection, either by harsh or unsuitable environments, or by an adversary
- Many adverse effects: memory corruption, register corruption, **instruction skips**, decoding pipeline corruption, etc.

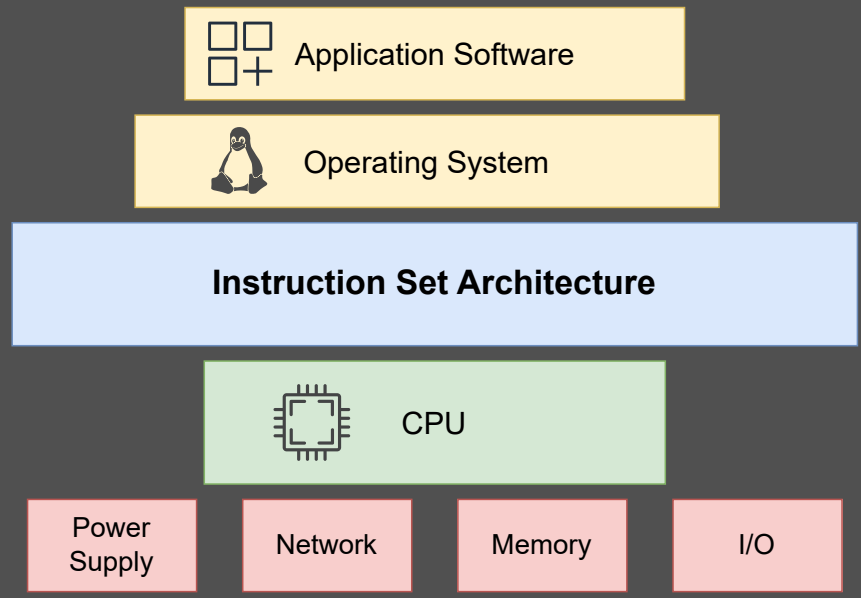






Hardware-Software Contract

- Software developers expect a *contract* between HW/SW
- Contract is "hardware usually tries to behave correctly," not "hardware always behaves"
- Devs have a responsibility to work within these limits
- CPU developers design with *hardware invariants* in mind, properties of the physical system that must be constant or within bounds over time



Standard Approaches

Software for critical systems must handle contract violations:

- **Control duplication**[1]: run code multiple times
- **Data duplication**[2]: store multiple copies of sensitive data
- **Runtime checks**[3] of invariants, state consistency, etc.
- **N-version programming**[4]: multiple unique implementations
- Fail-stops, state rollbacks, ASLR, ...

How well does any of this work?

[1] Soft N-Modular Redundancy - Kim, Shanbhag

[2] Redundancy in Data Structures: Improving Software Fault Tolerance - Taylor, Morgan, and Black

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Limitations

Common issues with each approach:

- **Complexity**: more program complexity $\propto$ more bugs
- **Probability**: assume random events (e.g., cosmic ray bit flips) will have random global behavior
- *No Guarantees*: we wanted assurance + safety, we already have FM, none of the approaches give formal guarantees!

How do we get formal assurances for fault-capable environments?

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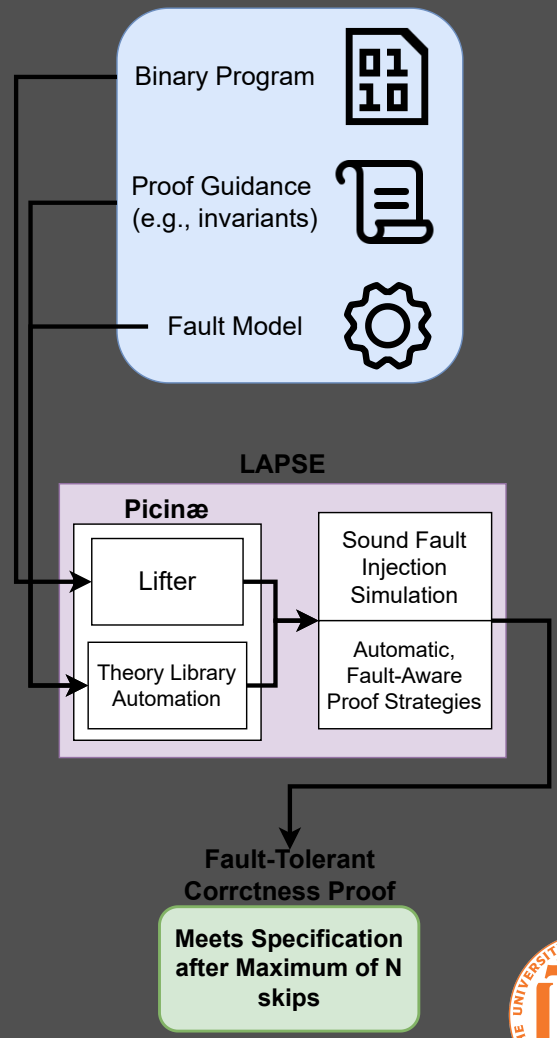
Formal Assurances for Faulty Environments

Introducing LAPSE[a], the first proof framework for developing machine-checked, fault-tolerant proofs of correctness.

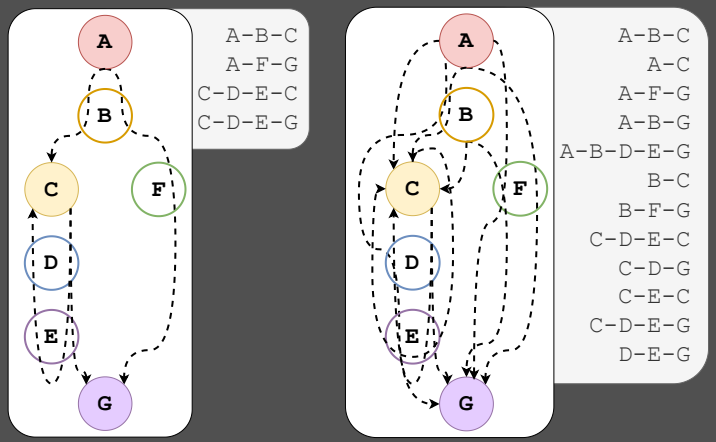
- Enables construction of machine-checked proofs *assuming a Fault Model*
- Fault model explicitly defines environmental effects
- Get guarantees that code is correct/safe/insert property here within a provided fault model

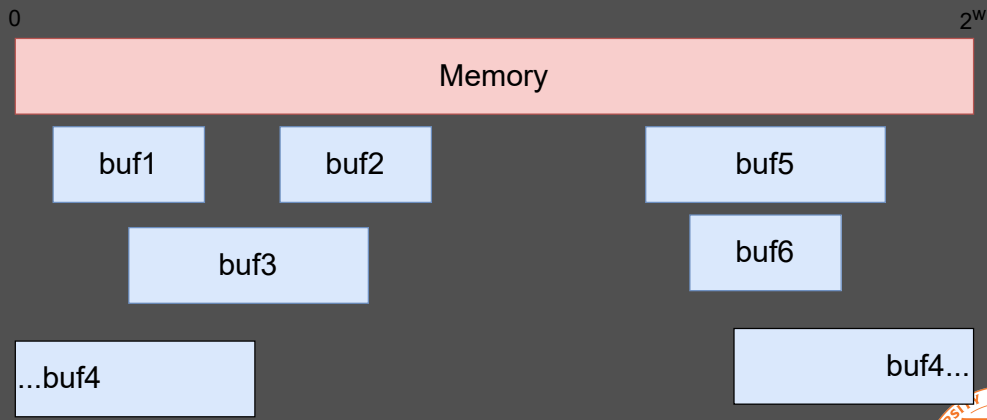


[a] "Logic for Analyzing Program Skip Effects"

Challenges in Formal Fault Tolerance

- Common in many FM approaches: *state space explosion*!
- Common in binary analysis: disassembly is undecidable, CFG recovery is undecidable, binary arithmetic needs expert analysis or SMT solvers, modeling hardware interaction...
- Expressing faults, framework modeling decisions, expressiveness of host framework, non-determinism, and so on and so on





Formal Attempts

Modern, formal FT efforts have made great strides in solving this problem:

- *PVS*: NASA HOL ITP used to verify critical systems
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Modern, formal FT efforts have made great strides in solving this problem:

- *PVS*: NASA HOL ITP used to verify critical systems - aimed at program *specifications*, not implementations
- Moro et al. formally verify a binary rewriter generating skip-tolerant ARM binaries - but only model checks the rewriter rules, rather than the rewriter tool
- Patranabis et al. verify an AES impl against fault injection attakcks - but assumes no control-flow attacks, model-checks those scenarios

Right direction, but shows that this assurance is ridiculously difficult! Still unsolved: state space explosion, sound symbolic execution, scalability, generality...

Technical Challenges

Many challenges to overcome for full proof mechanization:

- **Sound symbolic execution of machine code** to ensure all possibilities are covered
- **ISA semantics with non-determinism** to handle UB, hardware interactions, model faults
- **Flexible intermediate representation** to encode fault behaviors
- **Machine-checked proofs** at every step
- Bonus points for automation and generality (i.e., multiple ISAs)

A framework for formally verifying all control-flow paths of binary code with baked-in non-determinism, a highly flexible IR in which to encode arbitrary types of *hardware faults* that can be automated and utilized for various architectures. Sounds like a lot of work!

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A Lot of Work

- ISA-generic, instantiated to RISC-V
- Designed with instruction skips in mind, but extensible
- Declarative fault models
- Automation-capable
- Native embedding of non-determinism
- Built in Rocq on Picinæ (developed for DARPA V-SPELLS)

PICINAE

Lapse Proof Lifecycle

1. Expert analyzes binary, verifies program in fault-free environment
2. User defines `FaultModel` (encodes environmental effects) to generate fault tolerance proof machinery
3. Wrap lifted program in IL modification to simulate faults during symbolic execution
4. Write solvers via simple syntactic adjustment of initial proof
5. Launch symbolic execution with solvers to handle invariant sub-proofs

```
Definition inject_skips p s a :=
  match p s a with None => None
  | Some (sz, instr) =>
      Some (sz,
        If (fault_spacing < FT &&
            0 <? FC && Unknown)
        Then
          FC := FC - 1;
          FT := 0
        Else
          FT := FT + 1;
          instr) end.
```

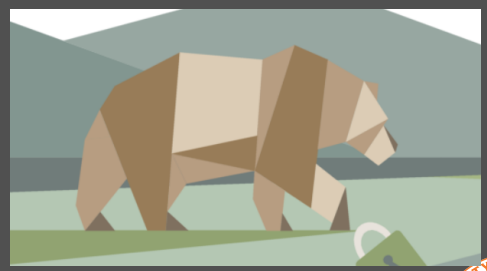
```
Module NonConsecSkips <: FaultModel.
  Definition max_faults := n.

  Definition fault_spacing := 1.
  Theorem fault_spacing_small :
    fault_spacing < 2^32.
  Proof. lia. Qed.
End NonConsecSkips.
```

Results

3 example proofs written for to show invulnerability against non-consecutive instruction skip attacks:

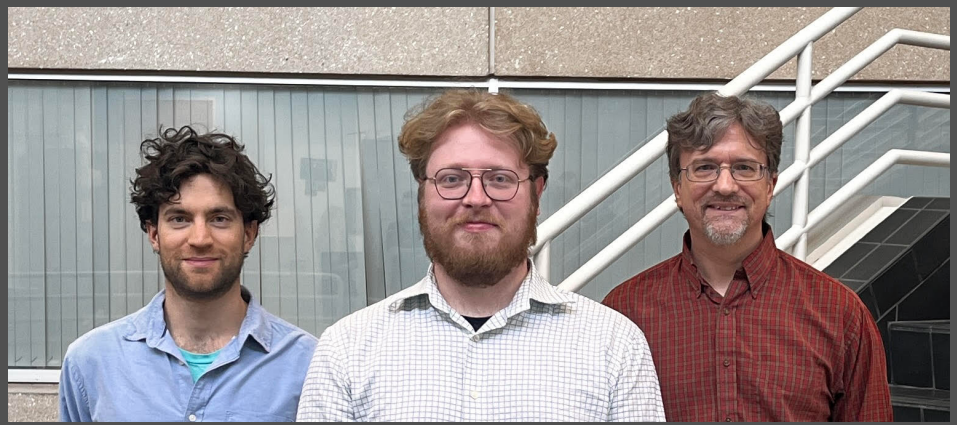
- DMR `CRYPTO_memcmp` from OpenSSL — 55LoP, ~1hr, reused
- DMR `br_ccopy` from BearSSL — 55LoP, ~15mins, reused
- Triple-Modular Redundant password checker with voting, uses `CRYPTO_memcmp` - non-standard proof structure, interprocedural, 580LoP, ~3 days, ~reused

OpenSSL
Cryptography and SSL/TLS Toolkit



Ongoing Work

- Implement memory corruption IR transformations, verify spatially-redundant programs
- Survey and simulate fault injection threat models to develop precise descriptions of their effects on software
- Expand evaluation to real-time systems, aerospace applications
- Continue to develop automation primitives for fault tolerance proofs



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