Binary Mutation Analysis of Tests Using Reassembleable Disassembly

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Motivation

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- Software usage is increasingly common in embedded/critical systems
  - security cameras, industrial vacuum cleaners, nuclear power plants
  - 3rd party components are prevalent
- System-level integrators often rely on 3rd party binary-only libraries
- Security properties like exploitability can only be determined on final binary

Motivation

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- Software testing is important!
- Regression tests are based on bugs found in the past
- How can we know how “good” our tests are?
- Mutation introduces a small change in the program
    - Used as a proxy for real bugs
    - Need not be hard-to-find bugs
    - Want all mutations to be detected, regardless of what behavior they introduce

How does Mutation Analysis work?

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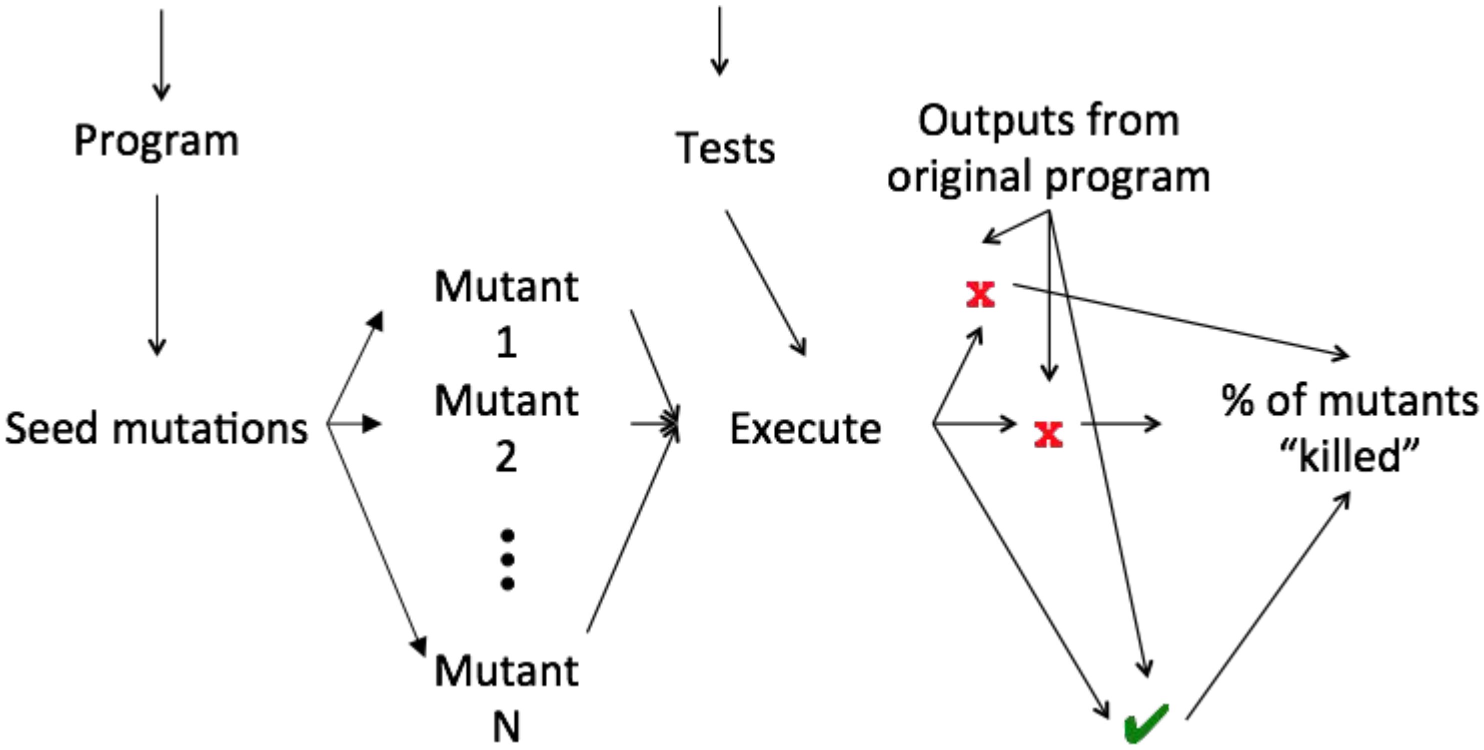

Mutation Analysis For Binaries

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- What instructions should we mutate?
  - conditional jump instructions (jCC)
  - conditional move instructions (cmovCC)
  - set byte on condition instructions (setCC)
  - add/subtract with carry/borrow (adc/sbb)

How do these mutation operators correspond to bugs?

Mutation Example (jCC)

```
static int duplicate_decls (
    tree newdecl, tree olddecl, int different_binding_level)
{
    ...
    /* begin added code */
    else if (TYPE_ARG_TYPES (oldtype) == NULL
                && TYPE_ARG_TYPES (newtype) != NULL) {
        ...
    } /* end added code */
    ...
}
```

Mutation Example (jCC)

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```
. . .
805c9c5: mov  0x18(%esp),%eax
805c9c9: mov  0xc(%eax),%ecx
805c9cc: test %ecx,%ecx
; TYPE_ARG_TYPES (oldtype) == NULL
805c9ce: jne  805bda4 <duplicate_decls+0x134>
805c9d4: mov  0xc(%edi),%eax
805c9d7: test %eax,%eax
; TYPE_ARG_TYPES (newtype) != NULL
805c9d9: je   805bda4 <duplicate_decls+0x134>
. . .
```

Mutation Example (jCC)

Mutating this jne to a unconditional jump reverts the patch

```
. . .
805c9c5: mov  0x18(%esp),%eax
805c9c9: mov  0xc(%eax),%ecx
805c9cc: test %ecx,%ecx
; TYPE_ARG_TYPES (oldtype) == NULL
805c9ce: jne  805bda4 <duplicate_decls+0x134>
805c9d4: mov  0xc(%edi),%eax
805c9d7: test %eax,%eax
; TYPE_ARG_TYPES (newtype) != NULL
805c9d9: je   805bda4 <duplicate_decls+0x134>
. . .
```

How do we construct binary mutants?

On Binary Rewriting

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- In place instruction rewriting
  - Challenging when the new instruction is longer
- Dynamic instruction rewriting
  - Test suite runtime overhead
- Reassembleable Disassembly
  - Reusable tool translates binary into assembly
  - Make changes statically to the assembly
  - Reassemble to binary
  - Run test suite without runtime overhead

Reassembleable Disassembly

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- Two available open-source projects:
  - Uroboros [USENIX'15]
    - `https://github.com/s3team/uroboros`
  - Ramblr [NDSS'17]
    - `https://github.com/angr/patcherex`
- Uroboros worked fine on most of our binaries
  - Some reliability issues on 2 larger binaries
- Gave Ramblr a shot
  - No success on non-CGC binaries

Binary Mutation Analysis Workflow

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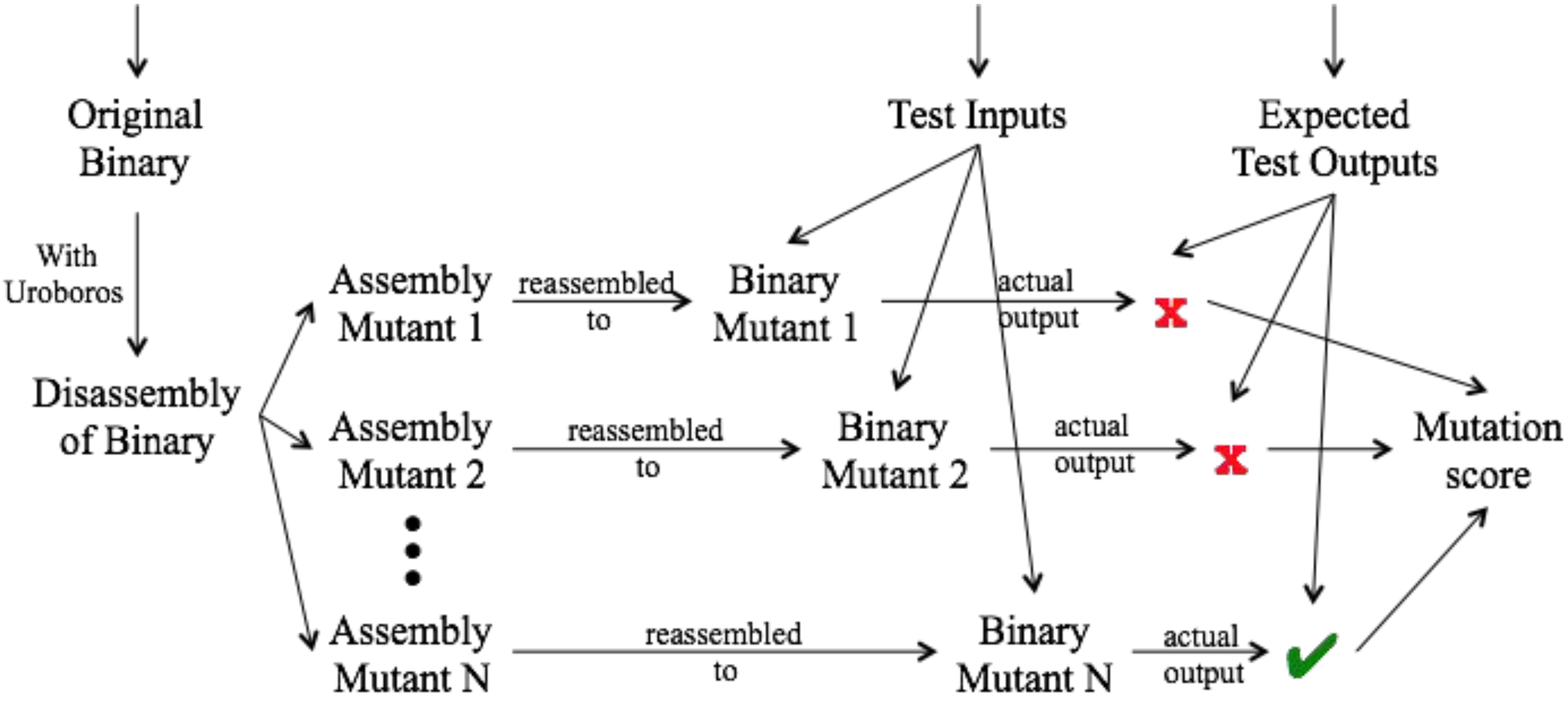

Mutant Categories

- Mutants differ from the original binary only in mutated instruction
- Based on the result of mutant execution
  - **Killed**: mutants that does not produce test's expected output
  - **Live**: mutants that produced the expected test's output
  - **Trivial**: mutants that fail on any input (excluded from killed)

Measuring the Test Quality

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- Mutation Score
  - #(killed mutants) / #(total mutants)
- Mutant coverage
  - Killed mutants are covered by test input
  - Live mutants may or may not be covered
    - Input may reach the mutated instruction
      - But is not reflected in the output
    - An example of one such mutant is provided in the paper

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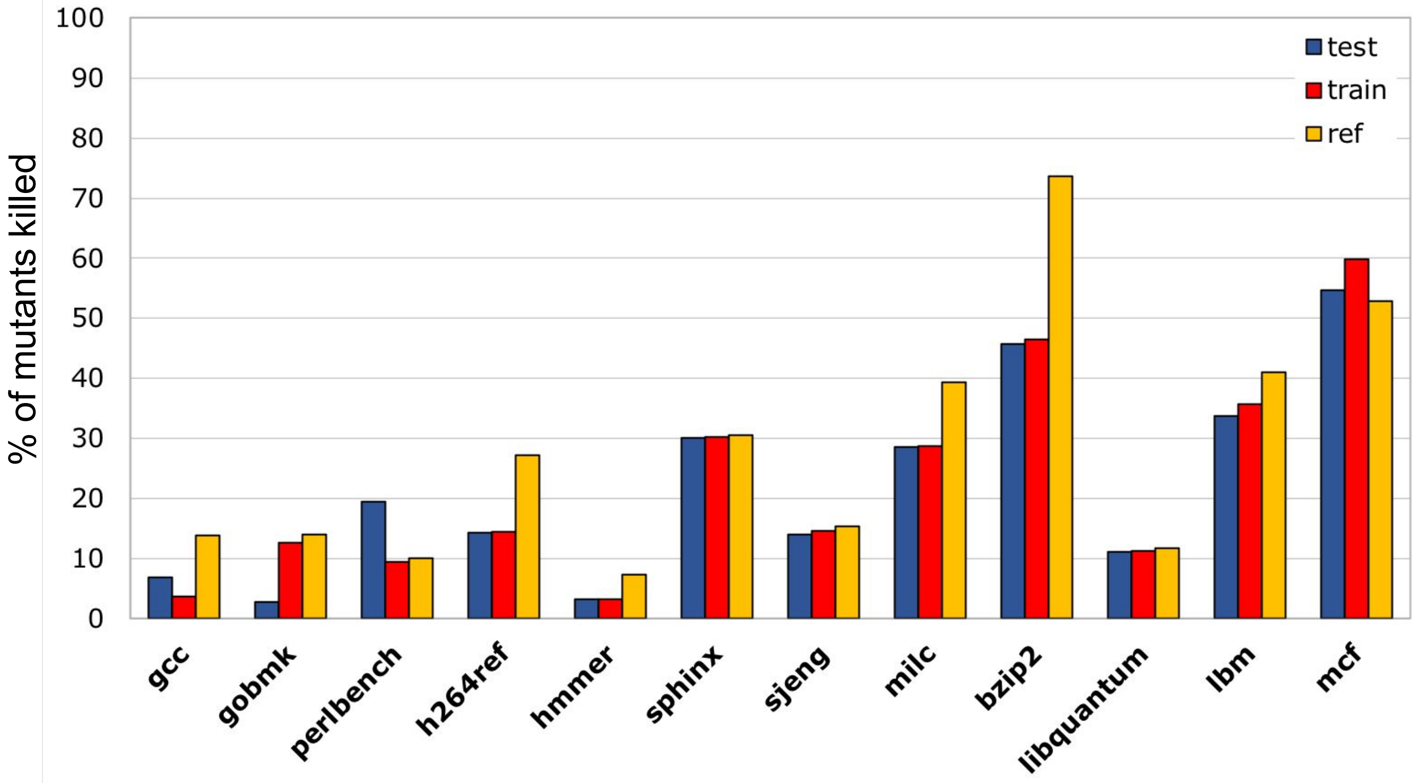
Evaluation

SPEC 2006

- 12 benchmarks in C
- 3 different input sets
  - **test**: to confirm the binary is functional
  - **train**: used for feedback-driven optimization
  - **ref**: the actual workload
- Generated as many mutants as possible
  - Select 1000 randomly for each binary
  - For *lbm* and *mcf*: 166 and 480 mutants respectively

SPEC 2006 - Mutation Score



SPEC 2006 - Categorized Mutants*

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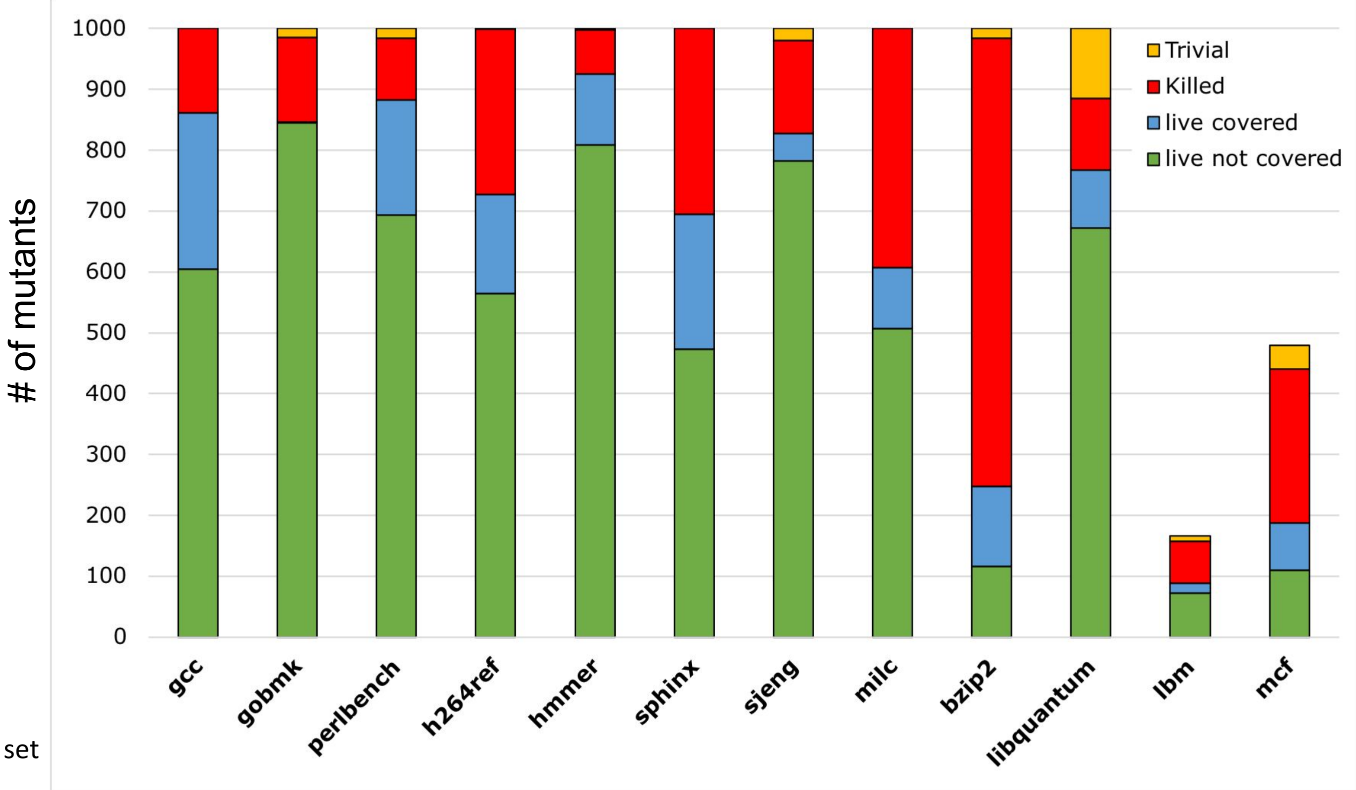

*on **ref** input set

Embedded-Control Binaries

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- Selected 5 safety-critical binaries
  - Docking approach application
  - Cruise controller
  - Infusion pump
  - Microwave control logic (two versions)
- The test input generated automatically using a coverage-guided test generation technique [1]

1. T. Byun, V. Sharma, S. Rayadurgam, S. McCamant, and M. P. E. Heimdahl, “Toward rigorous object-code coverage criteria,” in 2017 IEEE 28th International Symposium on Software Reliability Engineering (ISSRE), Oct 2017, pp. 328–338.

Mutation Results

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Embedded Binary	Trivial Mutants	Killed Mutants	Live Mutants	Binary Mutation Score	Source-level Mutation Score
Docking Approach	0	1154	1854	38.4%	26.9%
Infusion Pump	0	525	723	42.1%	25.0%
Cruise Controller	25	594	277	68.1%	73.6%
Microwave (auto)	22	390	150	72.2%	67.8%
Microwave (manual)	1	86	11	88.6%	67.8%

Future Work

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- Improve the variety of mutation operators
  - Make binary mutants more representative of the source-level mutants
- Explore practicality of in-place binary rewriting for mutant generation
- Perform a comprehensive comparison between source-level and binary-level mutation

Q/A

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Thank you for your attention

Check out:

`https://github.com/navidem/binarymutation`