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Semantic Equivalence Checking of Decompiled Binaries

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Will Klieber
Software Security Researcher

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Introduction

- Goal: Increase software assurance of binary components.
  - Enable the DoD to find and fix potential vulnerabilities
- We estimate that the equivalent of at least 100 million LOC of binary-only software is in use by DoD.
  - Old legacy code
  - Code from contractors
- Protect against cyberattacks that hijack the build process (e.g., SolarWinds attack).
  - Analysis of the binary executable can find injected malware not present in the source code.
- It’s much easier to work with decompiled code than machine code.
- But can the decompilation be trusted? We investigate!

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Overview

- Main technical challenge: Determine which functions in a binary are decompiled to a semantically equivalent form.
- We work with an existing open-source decompiler (Ghidra):
  - Existing decompilers were developed for aiding manual reverse engineering.
  - They were not designed to produce recompilable code.
  - Gap: Decompiled code often has semantic inaccuracies and syntactic errors.
- By "semantically equivalent", we mean: On all possible executions, if the two functions (original and decompiled) are given the same input, they produce the same output and side effects.
- Two ways of evaluating semantic equivalence:
  - Randomized testing (works for all functions, but can miss counterexamples)
  - Formal verification with SeaHorn (cannot handle certain constructs, e.g., floating-point comparisons)

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Previous State of the Art

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- Zhibo Liu and Shuai Wang. "How far we have come: testing decompilation correctness of C decompilers." *ACM Int'l Symposium on Software Testing & Analysis (ISSTA),* July 2020.
  - Out of 2504 test cases, 93% were correctly decompiled by Ghidra.
  - Tested **synthetic** test cases **without input or nondeterminism,** averaging 243 LoC each.
  - Only **unoptimized** code. No structs, unions, arrays, or pointers.

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Pipeline for Measurement and Evaluation

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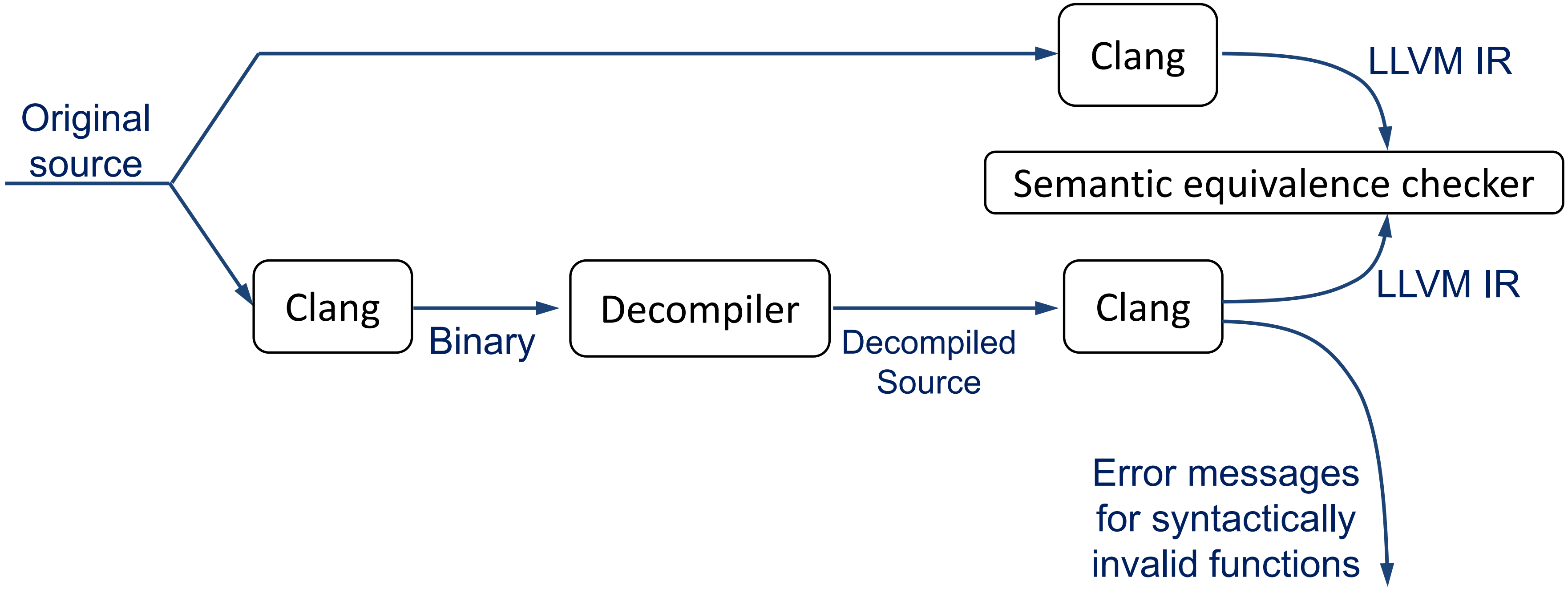

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Syntactic Validity of Decompiled Code – SPEC2006

Codebase	Source Functions	Recompilation Success Rate
lbm	21	71%
mcf	24	88%
libquantum	94	52%
bzip2	120	84%
sjeng	144	67%
milc	235	78%
sphinx3	370	65%
hmmer	657	61%
gobmk	2,693	76%
Average		**71%**

This table shows the percentage of decompiled functions that are recompilable (i.e., syntactically valid) C code.

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Semantic Equivalence Checking of Ghidra on SPEC2006

- Tested 1157 functions from SPEC2006 that decompiled to syntactically valid code.
  - Excludes 1500 autogenerated functions from gobmk
  - Excludes functions that were non-testable:
    - Multiple functions with the same name.
- Ran 1000 trials of each function.
- Results:
  - 35% of functions behaved equivalently on all runs.
  - 30% of functions behaved non-equivalently on all runs.
  - 31% of functions had some runs that behaved equivalently and some that didn't.
    (Of course, a single non-equivalent run suffices to prove that the functions aren't equivalent.)
  - On 3% functions, our tool failed on at least one run.
    - Failure in loop bounding

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Semantic Equivalence – Results by Benchmark Suite

	All equiv	All differ	Mixed	Tool fail
libquantum	54%	34%	9%	3%
milc	49%	33%	16%	6%
sphinx3	48%	31%	19%	2%
bzip2	43%	30%	25%	4%
lbm	40%	47%	7%	7%
sjeng	29%	48%	14%	10%
mcf	26%	47%	21%	5%
gobmk	26%	15%	56%	1%
hmmer	22%	61%	13%	4%
OVERALL	**35%**	**30%**	**31%**	**3%**

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Pipeline for Use on Binaries without Original Source

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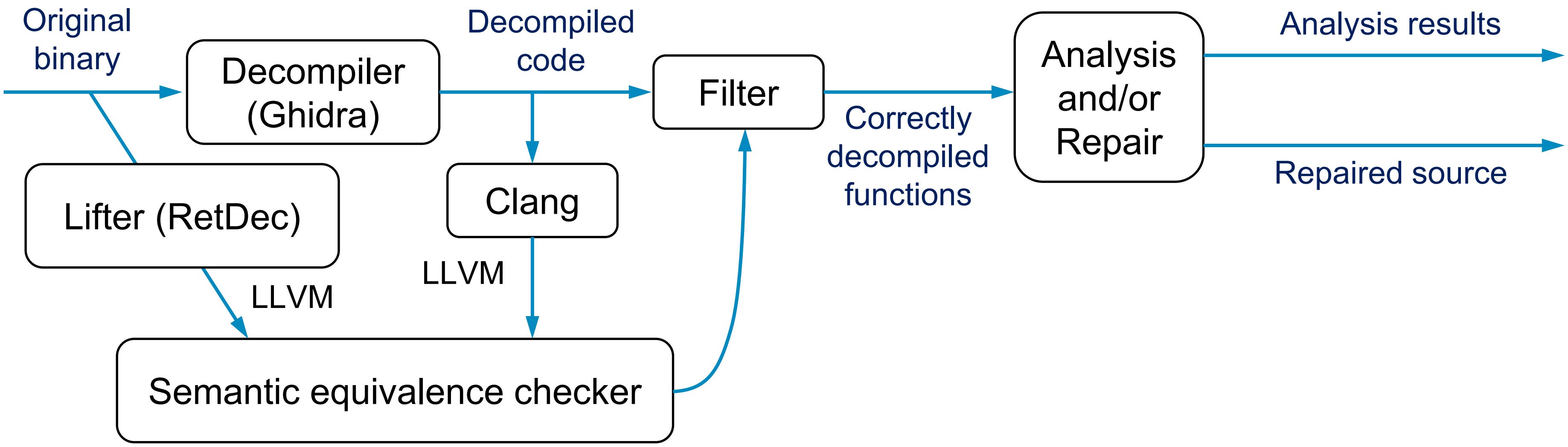

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Combining Ghidra and RetDec

- **Original hypothesis:** We were expecting that a binary lifter such as RetDec would be able to serve as a reasonably good proxy for semantic ground truth.
- However, it turns out that RetDec isn’t any better than Ghidra at semantic fidelity.
- **New hypothesis:** When Ghidra and RetDec agree with each other on the semantics of a function, they are more likely to also agree with the original source.
- We successfully tested this hypothesis on the NASA Core Flight System (cFS) (https://github.com/nasa/cFS).
- Technical note: Although we use the term “equivalence,” the relation that our implementation computes actually is not symmetric:
  - If the function from RetDec returns a value but the original function does not, we still count the RetDec function as equivalent to the original source.
  - But if the original-source function returns a value, then for equivalence we require that RetDec also return the same value.

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Results on NASA cFS (total source functions: 1268)

	Ghidra	RetDec
Number of decompiled functions checkable for semantic equivalence:	520	952
Number of functions semantically equivalent to source:	124	229
Percentage of original source functions for which decompiled function is semantically equivalent:	9.8%	18.1%
Probability that a checkable decompiled function is semantically equivalent to original source:	**23.8%**	**24.1%**

Number of source functions for which both Ghidra and RetDec produce checkable decompiled functions:	519
Number of functions on which Ghidra and RetDec agree with each other:	115
Number of functions on which Ghidra and RetDec agree with each other and with the original source:	88
Probability that a checkable decompiled function is semantically equivalent to original source when Ghidra and RetDec agree on it:	**77%**

"Checkable for semantic equivalence" means: the decompiled function is syntactically valid and there is a matched function from the original source.

This analysis was performed on cFS git commit `753ed54` (Apr 25, 2022)

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Semantic Fidelity of Decompilers

Details of Technical Approach

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Problem: Semantic Equivalence with Unavailable Callees

- In the decompiled code, there might be a function call where:
  - the callee is unavailable, and
  - the callee might write to memory
- This complicates our attempts to establish an equivalence between the memories.

Example:

```
void vithist_frame_windup (vithist_t *vh, int32 frm, ...) {
    ...
    vh->frame_start[vh->n_frm] = vh->n_entry;
    ...
    vithist_lmstate_reset(vh);
    ...
}
```


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Solution: Stricter Notion of Equivalence

- Look for a *structural* equivalence:
  - Check that the sequence of **operations with side effects** is the same.
    - Memory reads, memory writes, function calls
  - Some semantically equivalent pairs are flagged.
  - But every semantically non-equivalent pair is flagged.
- Replace memory reads, memory writes, and function calls with logging.
  - Reads and function calls return a nondeterministic value.
    (Same order of nondeterministic values for original and decompiled)
  - Also log the return value of the original and decompiled functions.
- Execute original and decompiled functions and compare their logs for equivalence.

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Transformation to Test for Structural Equivalence


```
ulong lmclass_get_nclass(long *param_1) {
  long lVar1;
  ulong uVar2;

  lVar1 = *param_1;
  uVar2 = 0;
  while (lVar1 != 0) {
    uVar2 = (ulong)((int)uVar2 + 1);
    lVar1 = *(long *)(lVar1 + 0x10);
  }
  return uVar2;
}
```

```
ulong lmclass_get_nclass(long *param_1) {
  long lVar1;
  ulong uVar2;

  lVar1 = read_mem_long(param_1);
  uVar2 = 0;
  while (lVar1 != 0) {
    uVar2 = (ulong)((int)uVar2 + 1);
    lVar1 = read_mem_long((long *)(lVar1 + 0x10));
  }
  return retval_ul(uVar2);
}
```


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Example of Log

Original

```
static void setExit ( Int32 v )
{
    if (v > exitValue) exitValue = v;
}
```

Decompiled

```
void setExit(int param_1)
{
  if (exitValue < param_1) {
    exitValue = param_1;
  }
  return;
}
```

```
ORIGINAL                  | DECOMPILED
READ  ADDR  0000270f      | READ  ADDR  0000270f
WRITE ADDR  0000270f      | WRITE ADDR  0000270f
WRITE VALUE 0000008d      | WRITE VALUE 0000008d
PASS
```


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Bounded Semantic Equivalence Checking with Logging

- Comparing the logs is impractical for existing verification tools in the unbounded case.
  - (at least for the straightforward approach of non-interleaved execution)
- Bound the number of execution steps:
  - Unroll loops for a fixed number of iterations.
  - Problem: Loops can potentially be structured differently in decompiled vs. the original ==> can give false counterexamples to equivalence.

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Details of Semantic Equivalence Checker

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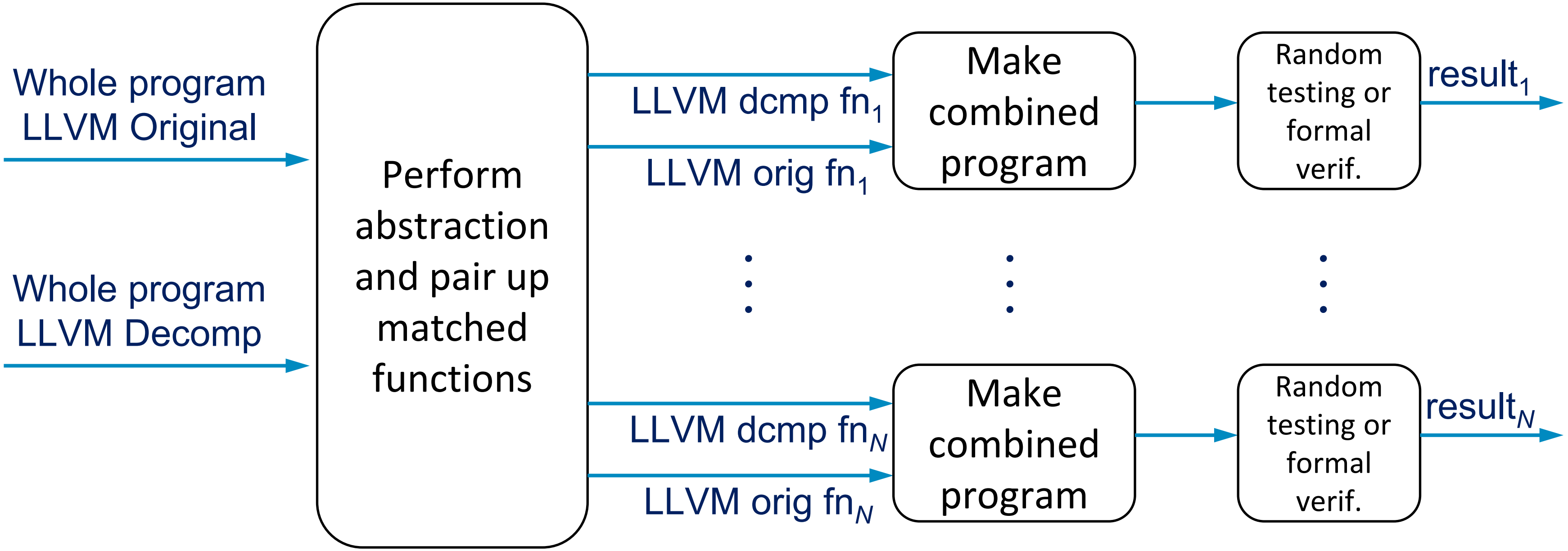

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Formal Verification and Randomized Testing

- SeaHorn can sometimes formally verify equivalence, but it can't handle some common constructs (e.g., branching on result of floating-point comparison).

- Our experiments in this project have mostly used randomized testing instead.
  - We initialize an array of random values (biased toward small values) and run both the original function and the decompiled function with this array.
  - Arguments to functions are also chosen randomly.

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Conclusion

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- Decompilers have potential to greatly help with software assurance for binary code.
- But existing decompilers often aren't semantically faithful.
- Requiring that two decompilers agree on semantics can greatly increase confidence.
  - (E.g., requiring RetDec and Ghidra to agree raises success rate from 24% to 77% on NASA cFS.)
- Our tool can also help measure improvements to decompiler semantic accuracy.
- If you are interested in trying our tool, please contact us (`info@sei.cmu.edu`).
  - Currently the tool is Distro D — it can be distributed only to DoD and contractors. But we are seeking approval to distribute it more widely.

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Team Photos





Will Klieber
Software Security Engineer

David Svoboda
Software Security Engineer

Mike McCall
Software Security Engineer

Lori Flynn
Software Security Engineer

Ruben Martins
Assistant Research Professor, CMU

Contact us at `info@sei.cmu.edu`

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