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Semantic Fidelity of Decompilers

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Overview

- We adapt 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.
- Measurement of semantic fidelity: Percentage of decompiled functions that are semantically equivalent to the corresponding original functions.
- By “semantically equivalent”, we mean that, on all possible executions, if the two functions (original and decompiled) are given the same input, they produce the same output and side effects.
  - Randomized testing / fuzzing
  - Formal verification with SeaHorn

Example of function that doesn't decompile correctly

```
1.  int main() {
2.    char* opt_name[2] = { "Option A", "Option B" };
3.    puts("Enter 'A' or 'B' and press enter.");
4.    int input = getchar();
5.    if ((('B' - input) >> 1) != 0) {puts("Bad choice!"); exit(1);}
6.    puts( *(opt_name + (input - 'A')) );  /* same as opt_name[input - 'A'] */
7.  }
```

The problem is that the compiler (with "-O1") changes "`opt_name + (input - 'A')`" to "`(opt_name - 'A') + input`" and replaces "`(opt_name - 'A')`" with a numeric constant. Ghidra decompiles this function to:

```
...
iVar1 = getchar();
...
puts(*(char **)((long)iVar1 * 8 + 0x600bf8));  /* the size of char* is 8 bytes */
```

Incorrect types don't prevent semantic equivalence

Original Code

```
void insertion_sort(unsigned int* A, size_t len) {
    for (size_t j = 1; j < len; ++j) {
        unsigned int key = A[j];
        /* insert A[j] into the sorted sequence A[0..j-1] */
        size_t i = j - 1;
        while (i >= 0 && A[i] > key) {
            A[i + 1] = A[i];
            --i;
        }
        A[i + 1] = key;
    }
}
```

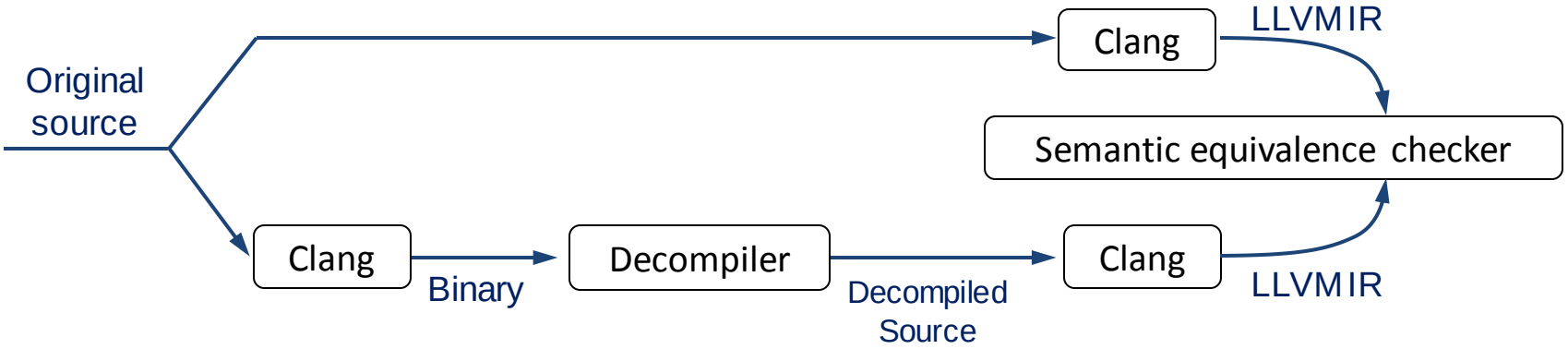
Decompiled Code

```
void insertion_sort(long param_1, ulong param_2) {
  uint uVar1; ulong uVar2;
  ulong local_18; ulong local_10;
  local_18 = 1;
  while (local_18 < param_2) {
    uVar1 = *(uint *)(param_1 + local_18 * 4);
    uVar2 = local_18;
    while (local_10 = uVar2 - 1,
           uVar1 < *(uint *)(param_1 + local_10 * 4))
    {
      *(undefined4 *)(param_1 + uVar2 * 4) =
        *(undefined4 *)(param_1 + local_10 * 4);
      uVar2 = local_10;
    }
    *(uint *)(uVar2 * 4 + param_1) = uVar1;
    local_18 = local_18 + 1;
  }
}
```

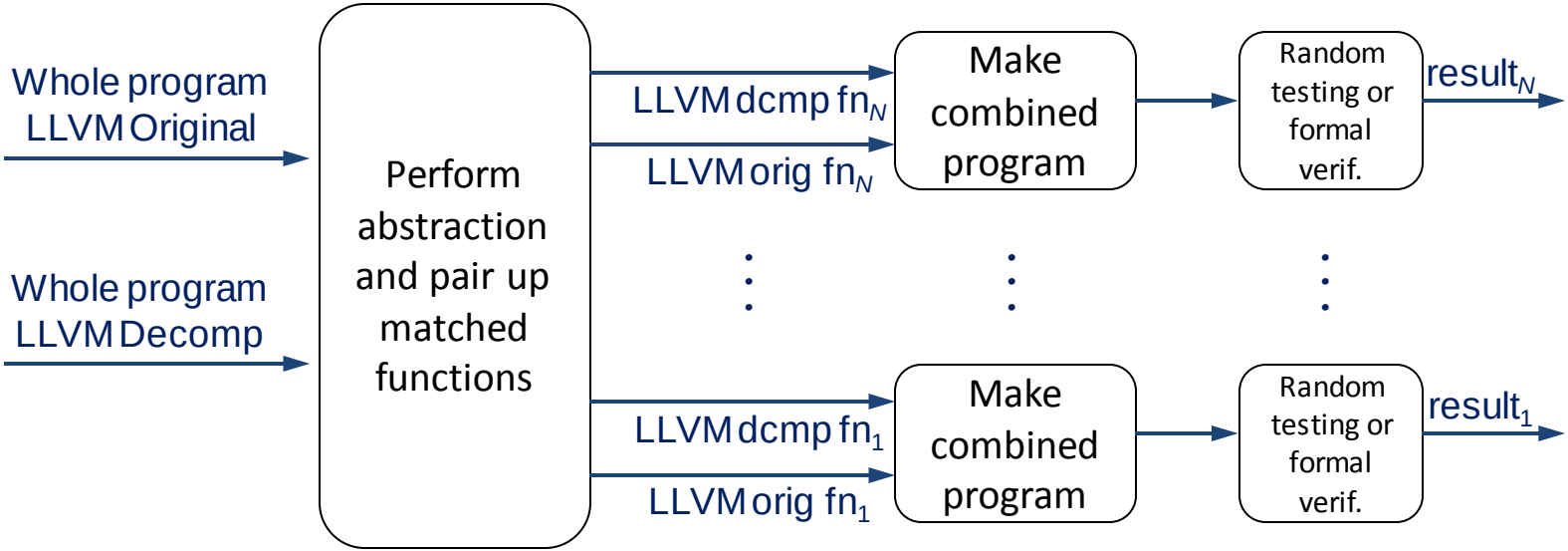
Previous State of the Art

- 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.
  - Tested **synthetic** test cases **without input or nondeterminism,** averaging 243 LoC each.
  - Only **unoptimized** code. No structs, unions, arrays, or pointers.
  - Out of 2504 test cases, 93% were correctly decompiled.
- Existing research in checking semantic equivalence at the machine-code level has focused on checking that compiler optimizations preserve semantics.

Semantic Equivalence Pipeline



Details of semantic equivalence checker



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);
    ...
}
```

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.
  - Can produce false positives: some semantically equivalent pairs are flagged.
  - But no false negatives: every semantically non-equivalent pair is flagged.
- Replace mem reads, mem 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.

Transformation to test for structural equivalence

```
1.  ulong lmclass_get_nclass(long *param_1) {
2.    long lVar1;
3.    ulong uVar2;
4.
5.    lVar1 = *param_1;
6.    uVar2 = 0;
7.    while (lVar1 != 0) {
8.      uVar2 = (ulong)((int)uVar2 + 1);
9.      lVar1 = *(long *)(lVar1 + 0x10);
10.   }
11.   return uVar2;
12. }
```

```
1.  ulong lmclass_get_nclass(long *param_1) {
2.    long lVar1;
3.    ulong uVar2;
4.
5.    lVar1 = read_mem_long(param_1);
6.    uVar2 = 0;
7.    while (lVar1 != 0) {
8.      uVar2 = (ulong)((int)uVar2 + 1);
9.      lVar1 = read_mem_long((long *)(lVar1 + 0x10));
10.   }
11.   return retval_ul(uVar2);
12. }
```

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 are sometimes structured differently in decompiled vs the original ==> can give false counterexamples to equivalence.

Current status

- We don't yet have formal verification working.
- So, we are doing 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.
- Evaluation benchmark suite: SPEC2006.
  - Selected a sample of 629 functions from SPEC2006 that decompiled to syntactically valid code.
  - Ran 1000 trials of each function.
  - Results:
    - 28% of functions behaved equivalently on all runs.
    - 48% of functions behaved non-equivalently on all runs.
    - 19% of functions had some runs that behaved equivalently and some that didn't.
    - On 6% functions, our tool crashed (due to a bug in loop bounding).

Platform Information

- 64-bit Ubuntu 18.04
- Ghidra ~~9.1.2~~ 10.1.4
- Java (openjdk 11.0.10)
- Clang 6.0

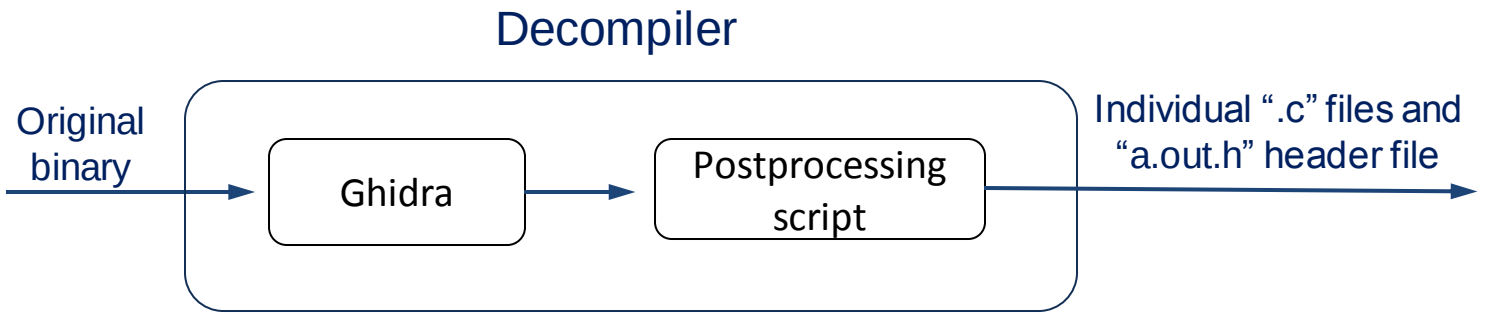
All running in a Docker container on a Mac laptop.

Postprocessing Ghidra Output

Python script, to be run after Ghidra:

- Splits **`a.out.c`** into many files, one per function
- All files go into a newly-created **`src`** directory
- Fixes simple errors
- Does not alter original input files
- Independent & Ignorant of Ghidra

Postprocessing Ghidra Output (cont.)



File	Purpose
`a.out.h`	Header file with all function declarations including all included declarations, like **`puts()`**
`a.out.c`	File with all function implementations
`a.out.sym`	File with all declared symbols

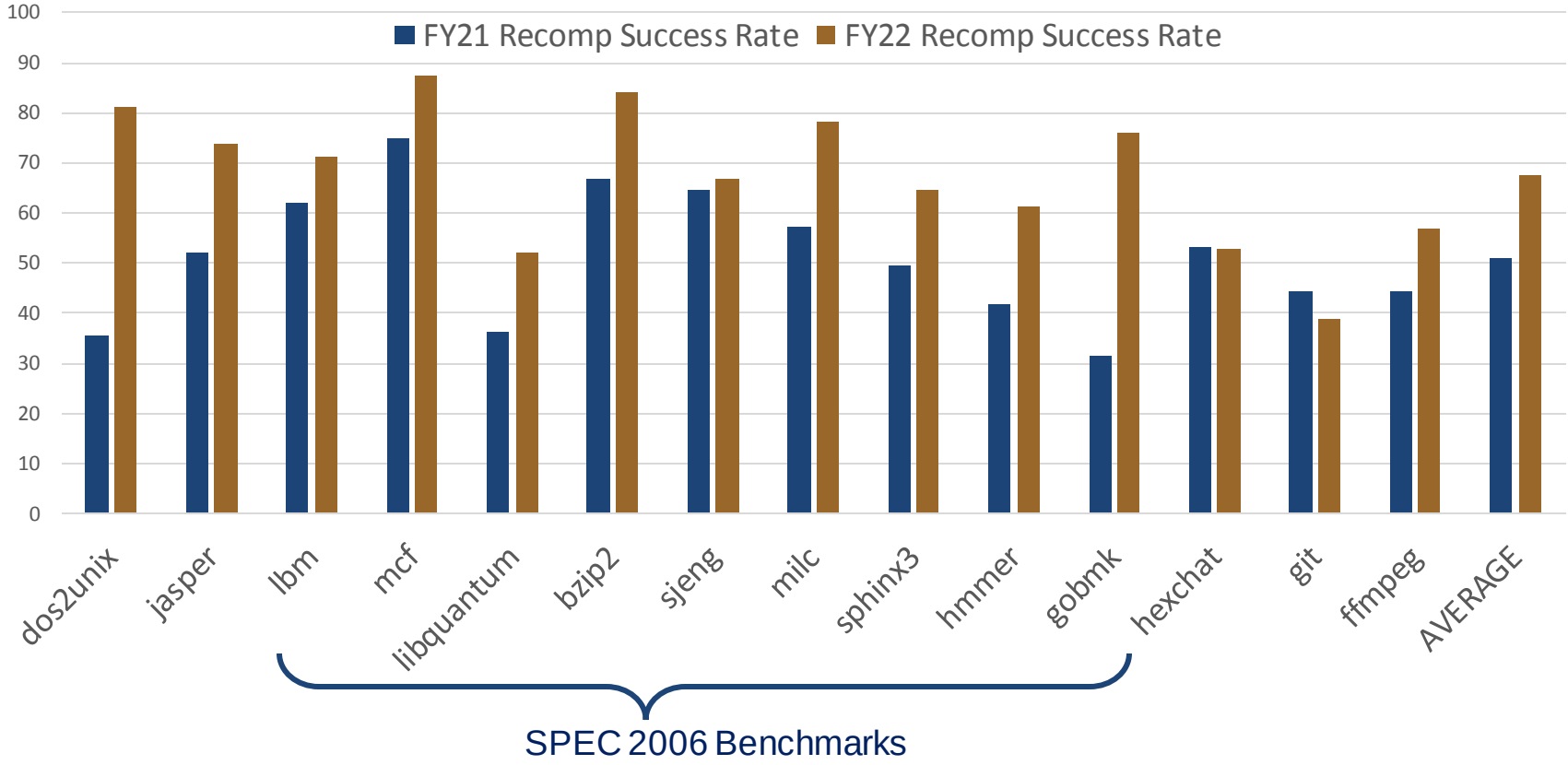
Code Recompilation

The table shows the percentage of source-code functions that are extracted as recompilable (i.e., syntactically valid) C code.

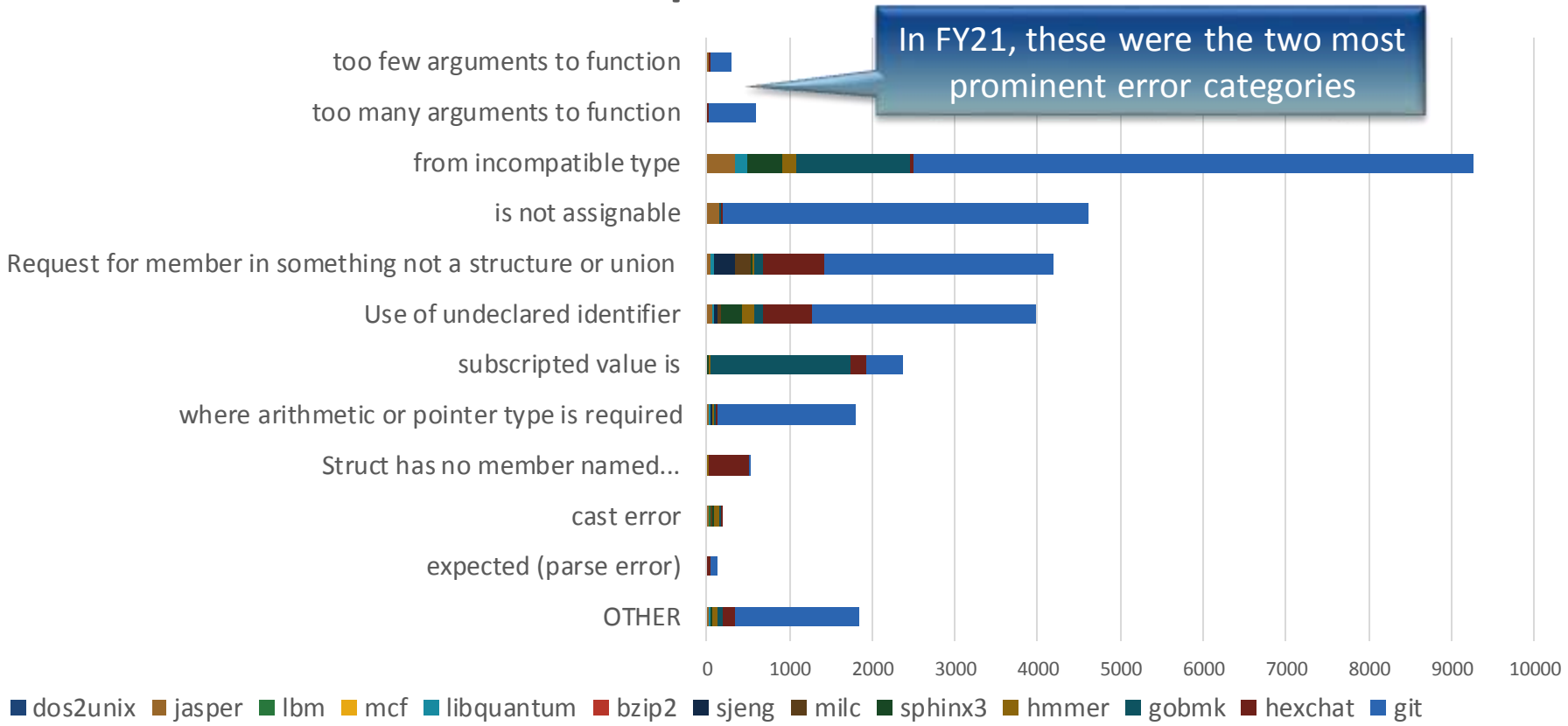
SPEC 2006 Benchmarks

Project	Source Functions	FY21 Recomp Success Rate	FY22 Recomp Success Rate
dos2unix	48	35%	81%
jasper	725	52%	74%
lbm	21	62%	71%
mcf	24	75%	88%
libquantum	94	36%	52%
bzip2	120	67%	84%
sjeng	144	65%	67%
milc	235	57%	78%
sphinx3	370	49%	65%
hmmer	657	42%	61%
gobmk	2,693	32%	76%
hexchat	2,076	53%	53%
git	6,832	44%	39%
ffmpeg	23,053	44%	57%
Average		**51%**	**68%**

Recompilation Improvement over Last Year



FY22 Recompilation Error Partition



Ghidra Bugs: Extra Typedefs

When Ghidra creates a struct, it also adds this line:

```
typedef struct foo foo, *Pfoo;
```

But consider the POSIX **stat(2)** function:

```
int stat(const char *restrict pathname,
         struct stat *restrict statbuf);
```

When Ghidra decompiles any code that calls this function, it produces:

```
int stat(const char*,struct stat*);  /* stat is a function */
typedef struct stat stat, *Pstat;    /* stat is a typedef  */
```

FY22: The same problem occurs with the POSIX **sigaction(2)** and **sysinfo(2)** functions/structs.

Other FY22 Postprocessor Improvements

- Turn on Ghidra's `Decompiler Parameter ID` feature
  - This fixed most of the `too few/many arguments` errors

- Force correct declaration of main():
  - `int main(int, char**, char**);`

- Ghidra produces C function names that start with digits (not valid in C)
  - Our fix: Prepend function name with `FN_`

- Remove duplicate enumeration constants