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ESBMC v7.4: Harnessing the Power of Intervals

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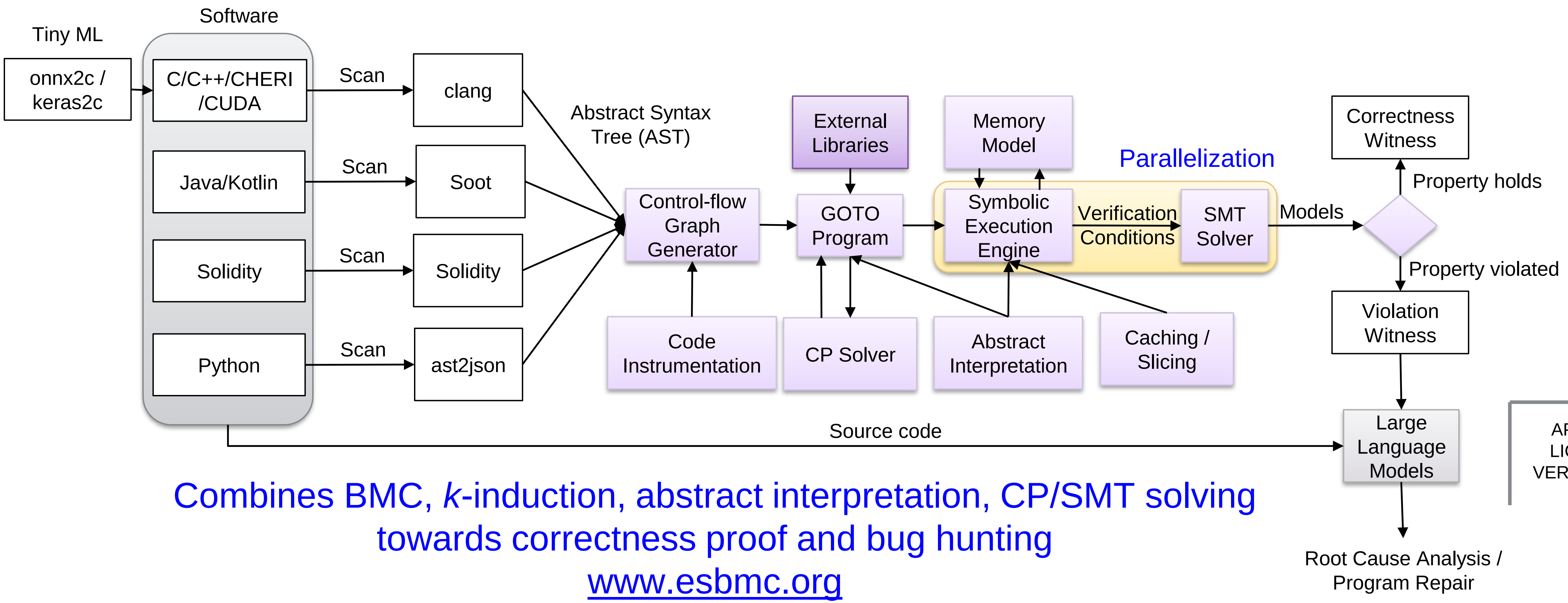
Project

- ESBMC is a verification engine capable of verifying C programs by relying on BMC, k-Induction and SMT.
- It is a joint project with the Federal University of Amazonas (Brazil), University of Southampton (UK), University of Manchester (UK), and University of Stellenbosch (South Africa).

ESBMC architecture



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Combines BMC, *k*-induction, abstract interpretation, CP/SMT solving towards correctness proof and bug hunting

www.esbmc.org

Interval Analysis

Interval Analysis

- The interval analysis consists of computing all values the variables *might* assume at each statement.
- The analysis can be used to infer properties regarding the program states and flow.

```c
1 int main() {
2   int a = *;
3   while(a <= 100)
4     a++;
5   assert(a > 10);
6   return 0;
7 }
```

Line	*Interval for "a"*
3	$(-\infty, +\infty)$
4	$(-\infty, 100]$
5	$(100, +\infty)$

Interval Analysis in BMC

- Interval analysis can help BMC by removing unreachable instructions:

```
int main() 0 ref
{
  int a; 2 refs
  if(a < 0 && a > 0)
    while(1) assert(0);
  return 0;
}
```

Contradiction

Unreachable

Interval Analysis in *k-induction*

- *k-induction* algorithm hijacks loop conditions to nondeterministic values, thus computing intervals become essential

```c
int main()
{
  unsigned int a = 10;
  unsigned int b = 1;

  while(a < 50 && *)
  {
    a++;
    b = a*2;
  }

  assert(b >= a);
}
```

```c
int main()
{
  unsigned int a = 10;
  unsigned int b = 1;

  a = *; b=*;
  while(a < 50 && *)
  {
    a++;
    b = a*2;
  }

  __ESBMC_assume(a < 50);
  assert((a*2) >= a);
}
```

Contracting Intervals

- The restrictions can be computed by using contractors (Forward/Backward)

```
int main()
{
  int a = * ? 1 : 11; // [1,11]
  int b = * ? 2 : 9; // [2,9]
  if(a < b) {
    // ...
  }
}
```

We can apply contractor algorithms to contract ”a” in terms of “b”:

Forward: $y = a - b \rightarrow [y] = ([a] - [b]) \cap (-infinity, 0]$

Backwards:

$$[a] = [a] \cap ([b] + [y])$$
$$[b] = [b] \cap ([a] - [y])$$

Forward: $[y]$ = [1,11]-[2,9] $\cap$ $(-infinity, 0]$ = = [-8,0]

Backwards:

$$[a] = [1{,}11] \cap ([2{,}9] + [-8{,}0]) = [1{,}9]$$
$$[b] = [2{,}9] \cap ([1{,}9] - [-8{,}0]) = [2{,}9]$$

ESBMC has support for other contractors by relying on ibex: a C++ numerical library based on **interval arithmetic** and **constraint programming.**

Computing Intervals

- For non-loop sequences:
  1. Initialize variable interval to $[(-\infty, \infty)]$;
  2. Use conditionals to restrict the interval;
  3. Merge intervals after conditionals;

```c
int main()
{
  int a;
  if(a < 50) {
    // ...
    a = 3;
  }
  else {
    // ...
    a = 5;
  }
  // ...
}
```

Computing Intervals (contractor)

- Restrictions are computed through the use of contractors:
  - $[a] = [-infinity, 49]$
  - $[a] = [50, infinity]$
- Merging is computed with the Hull operation:

$$[3,3] \sqcup [5,5] = [3,5]$$

```c
int main()
{
  int a;
  if(a < 50) {
    // ...
    a = 3;
  }
  else {
    // ...
    a = 5;
  }
  // ...
}
```

Computing Intervals

- For non-loop sequences:
  1. Initialize variable interval to $[(-\infty, \infty)]$.
  2. Use conditionals to restrict the interval.
  3. Merge intervals after conditionals.

Line	*Interval for "a"*
4	$(-\infty, +\infty)$
5	$(-\infty, 50)$
7	$[3,3]$
9	$[50, +\infty)$
11	$[5,5]$
12	$[3,5]$

```
1 int main()
2 {
3   int a;
4   if(a < 50) {
5     // ...
6     a = 3;
7   }
8   else {
9     // ...
10    a = 5;
11  }
12  // ...
13 }
```

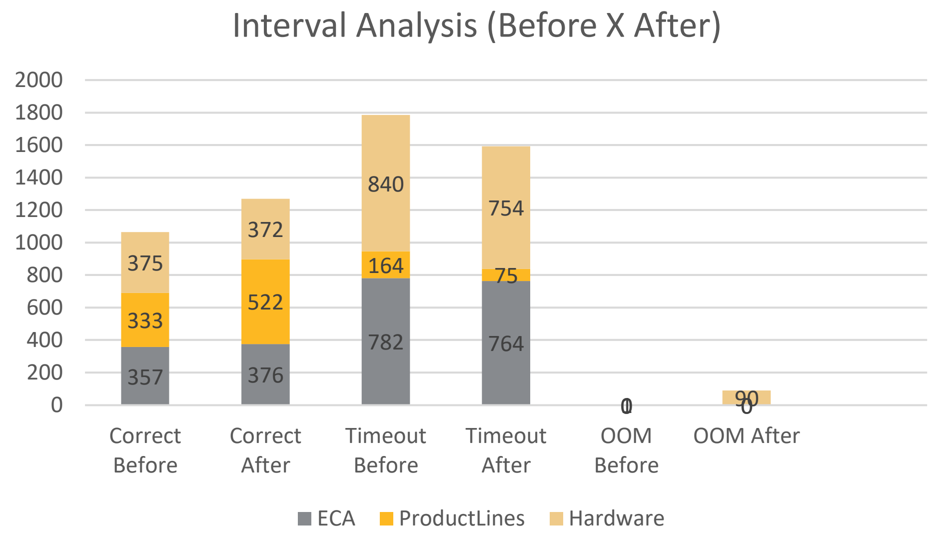
Computing Intervals

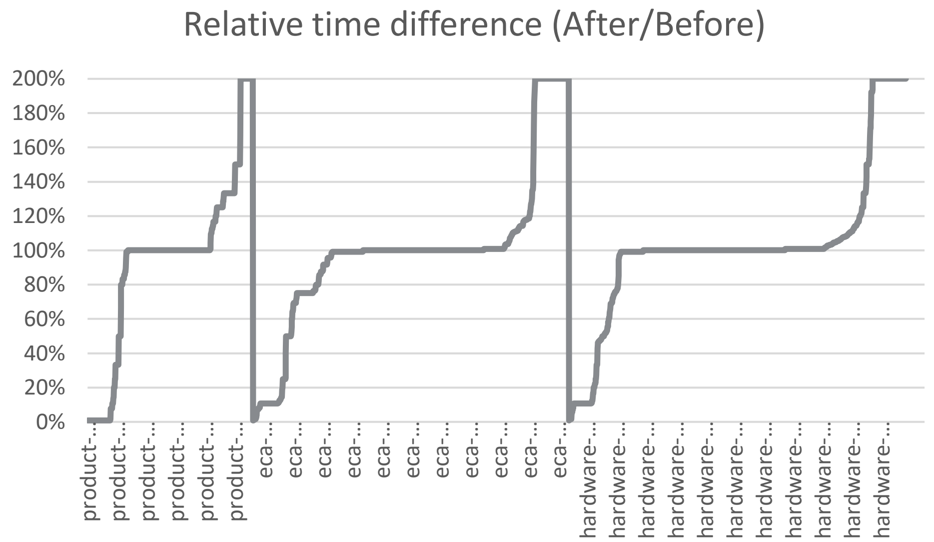
```c
int main()
{
  int a;
  if(a < 50) {
    // ...
    a = 3;
  }
  else {
    // ...
    a = 5;
  }
  // ...
}
```

```c
int main()
{
  int a;
  if(a < 50) {
    __ESBMC_assume(a < 50);
    // ...
    a = 3;
  }
  else {
    __ESBMC_assume(a >= 50);
    // ...
    a = 5;
  }
  __ESBMC_assume(a >= 3 && a <= 5);
  // ...
}
```

Results

- ✓ The instrumentation and optimizations helped the verification of unique tasks.
- × The preprocessing takes a toll in the hardware benchmarks.





Memory Leaks

Memtrack

- ESBMC employs a refined check for the valid-memtrack property.

1. At the end of an execution, for each memory object, add an assertion that it was deallocated correctly.
2. Add a guard into the assertion that there is no pointer currently referring to that memory object.

Memcleanup

- The new algorithm leverages the existing one tracking the lifetime of allocations for the valid-memcleanup property, but it specifically excludes still-reachable objects from the check.

Memory Object
Obj1
…
ObjN

Mem-cleanup checks if at the end of the execution, every memory object was freed.

Memcleanup

- The new algorithm leverages the existing one tracking the lifetime of allocations for the valid-memcleanup property, but it specifically excludes still-reachable objects from the check.

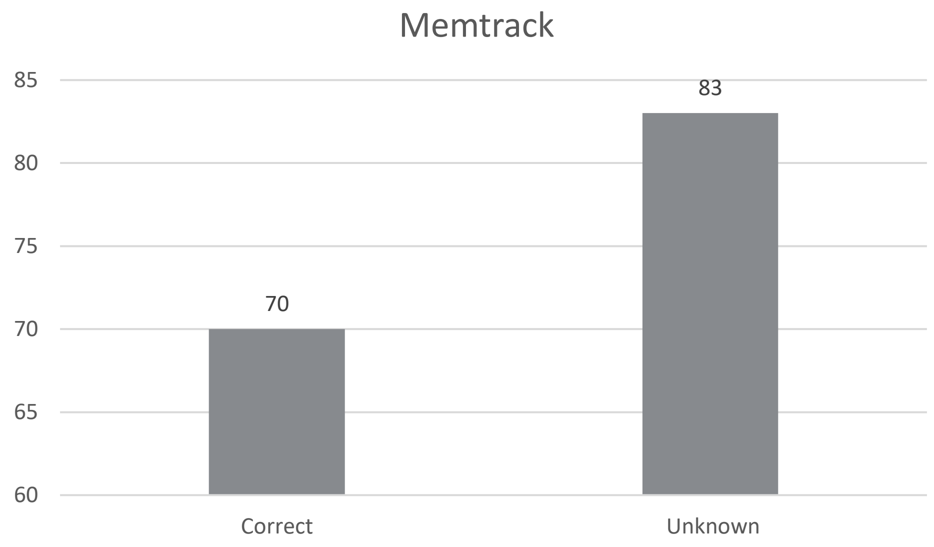
Memory Object
Obj1
…
ObjN

Pointer	Target
Ptr1	Obj1
…	…
PtrM	NULL

→ Obj1 check is removed!

Results

- The new algorithm to verify valid-memtrack benchmarks.
- There is a weakness in the current implementation concerning dynamic allocations only reachable through pointers stored in arrays of statically unknown size.
- We will address this weakness and submit suitable tasks for this property to SV-COMP in the future.



Math Operational Models

math.h

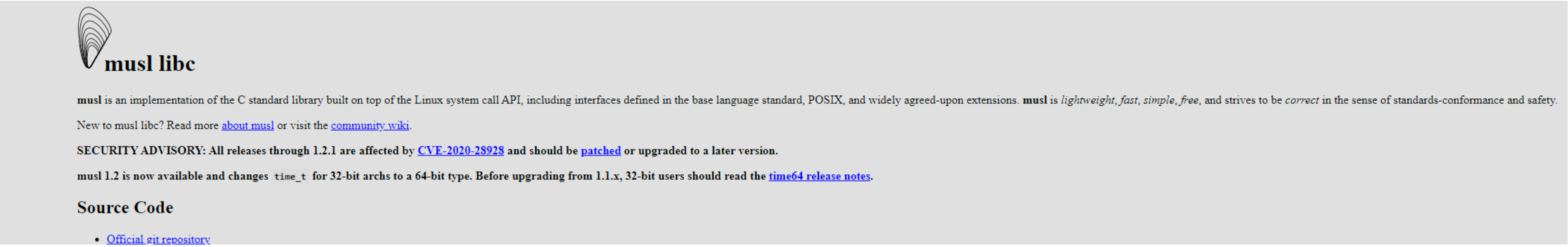
- ESBMC did not have precise OM for float operations. This used to be enough.
- The neural network benchmarks relies on 32-bit floats, which leaded to incorrect results.
- As a tradeoff between precision and verification speed, ESBMC now features a two-pronged design: precise and approximated.

math.h

- The IEEE 754 standard mandates bit-precise semantics for a small subset of the math.h library only (it includes: addition, multiplication, division, sqrt, fma, and other support functions such as remquo).
- In contrast, the behavior of most transcendental functions (e.g., sin, cos, exp, log) is platform-specific. Still, the standard recommends implementing the correct rounding whenever possible.

math.h

- For the most commonly-used float functions, we borrow the MUSL plain-C implementation of numerical algorithms.



math.h

- For the corresponding double functions, we employ less complex algorithms with approximate behavior.
  - For example, the exponential was approximated by Taylor series.

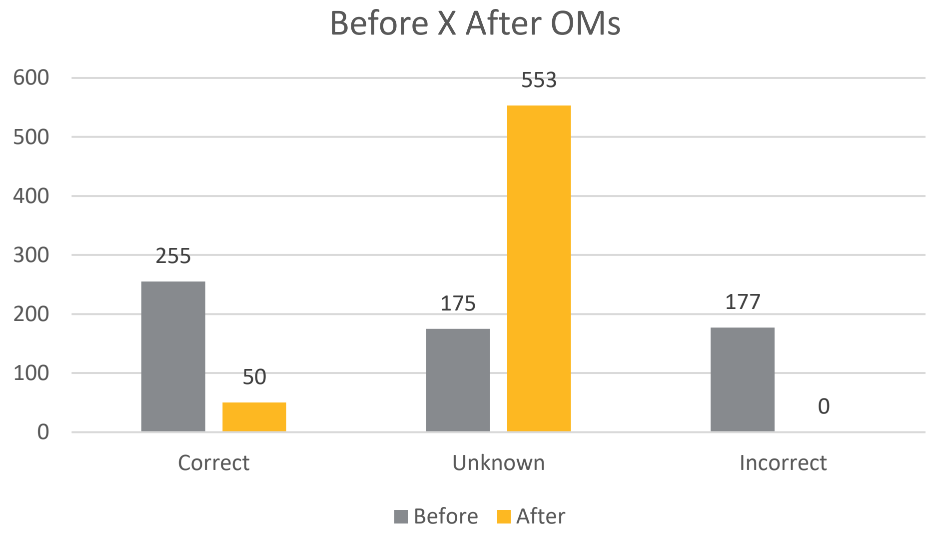
```c
double expm1(double x) /* exp(x) - 1 */
{
  switch(fpclassify(x))
  {
  case FP_NAN:
  case FP_ZERO:
    return x;
  case FP_INFINITE:
    return signbit(x) ? -1.0 : x;
  case FP_SUBNORMAL:
  case FP_NORMAL:
    break;
  }

  /* Taylor series converges everywhere, but the rate of convergence
   * is pretty bad; below we do a simple range reduction for larger |x|.
   */
  if(fabs(x) < 0x1p-3)
    return expm1_taylor(x);

  /* range reduction: exp(xm * 2^xe) = exp(xm) ^ (2^xe) */
  int xe;
  double xm = frexp(x, &xe); // |xm| in [2^-1,2^-0)
  xm *= 0x1p-3;
  xe += 3;                          // |xm| in [2^-4,2^-3)
  double r = expm1_taylor(xm) + 1; // r = exp(xm)
  /* xe is > 0 and xe < 1025+3, square xe times to account for 2^xe */
  for(int i = 0; i < xe; i++)
    r *= r;
  return r - 1;
}
```

Results

- Without operational models of the math.h library, ESBMC would assign non-deterministic results, which may cause incorrect counterexamples to be returned.
- Providing explicit operational models for many common functions in math.h improved the results



Data Races

Data Race Instrumentation

- ESBMC can detect data-races by instrumenting explicit assertions in the program.
- The instrumentation consists in setting an intermediate boolean for the assigned variable to true and then setting it back to false after the write is finished.
- The check consists in verifying whether there is a read while the write has not finished.
- The GOTO approach can increase the number of interleavings and has partial support for benchmarks that rely on pointer dereference.

Data Race Instrumentation

```
int foo() {
  global_var = 2;
}

int bar() {
  int tmp = global_var + 1;
  global_var = tmp;
}
```

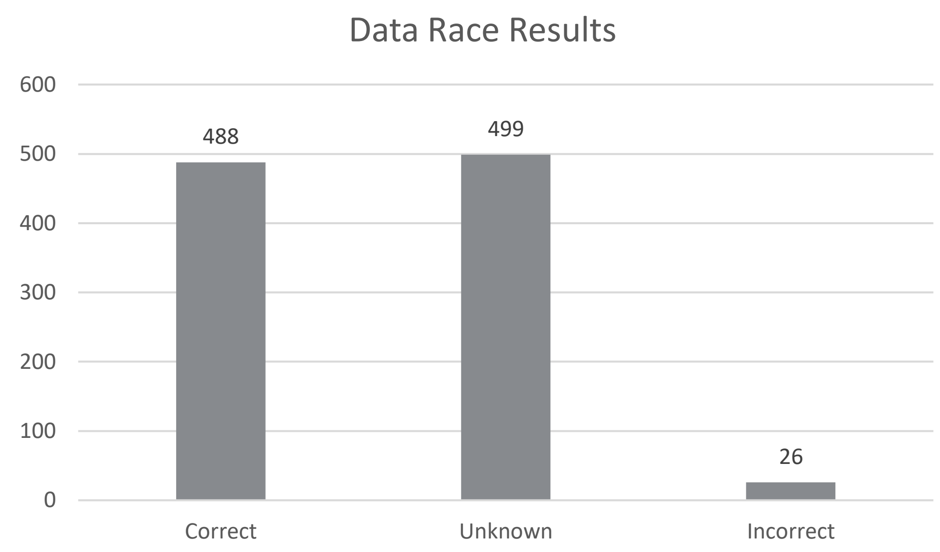
```
int foo() {
  global_var_writing = 1;
  global_var = 2;
  global_var_writing = 0;
}

int bar() {
  assert(!global_var_writing);
  int tmp = global_var + 1;
  global_var = tmp;
}
```

- Assuming that **foo** and **bar** are running in different threads, the assertion will check whether there is an interleaving where a read will happen before the assignment happens.

Symbolic Execution

- To improve the analysis, the property is now hybrid.
- The incorrect verdicts are mostly due to still missing support for detecting data races during dereferences of pointers to compound types.



Thanks for watching!