ESBMC-Python: A Bounded Model Checker for Python Programs

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Introduction

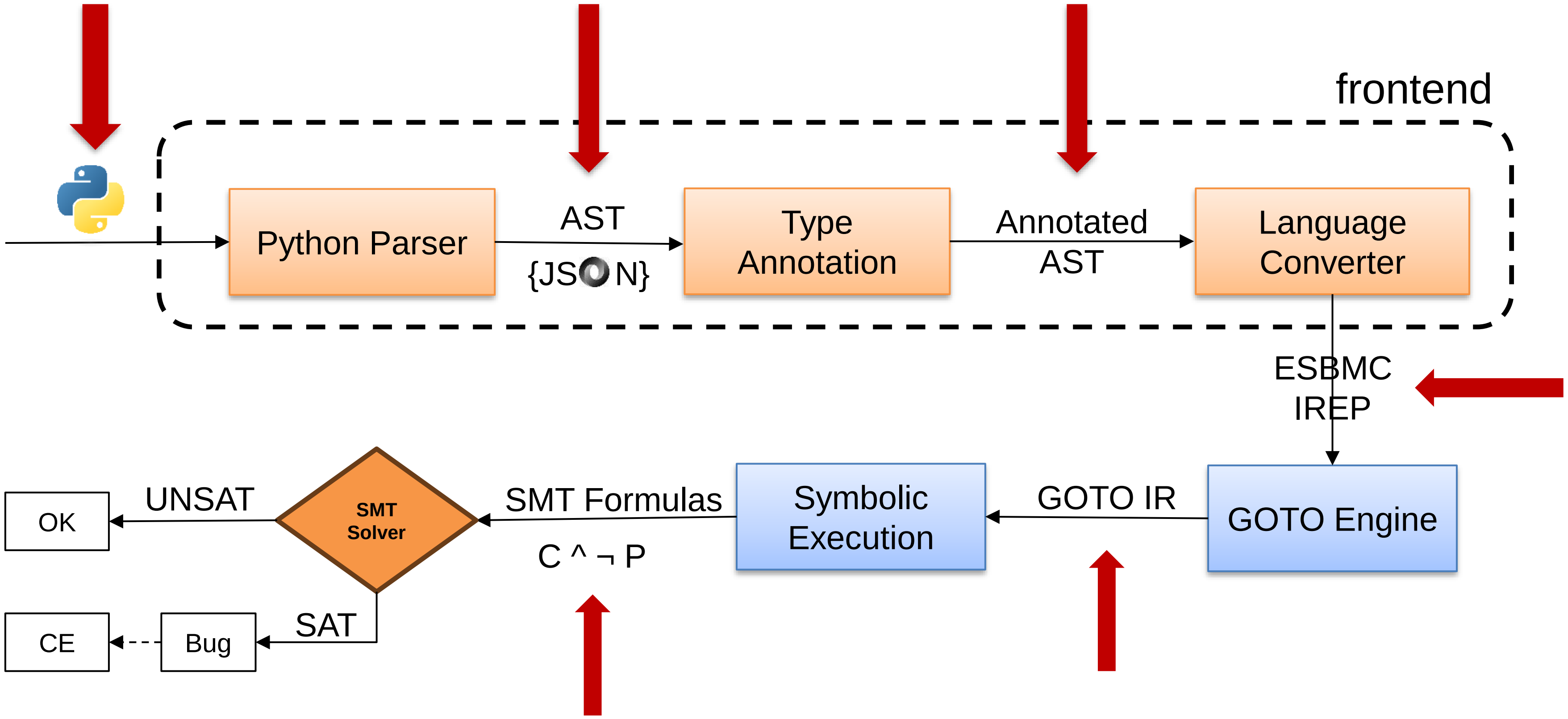
Research Problem

- **Lack of formal tools** for verifying Python program correctness.
- Main challenges: **dynamic nature** of the language and the **absence of type information**.

Approach

Develop a **frontend** for an SMT-based **Bounded Model Checker** that can infer and **add type information**, enabling exhaustive exploration of program paths to identify issues.

ESBMC-Python: Overview



Verification properties: Division-by-zero, indexing errors, arithmetic overflow, and user-defined assertions.

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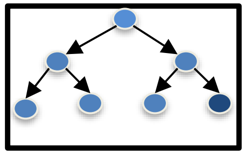
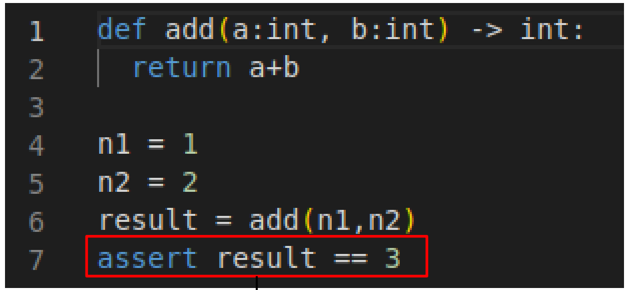
Code Representation Transformation



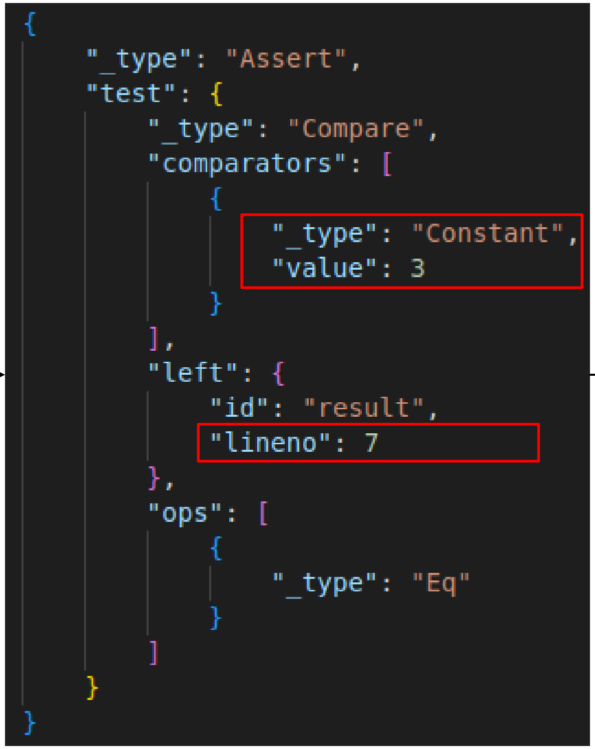
{JSON}

ESBMC IREP

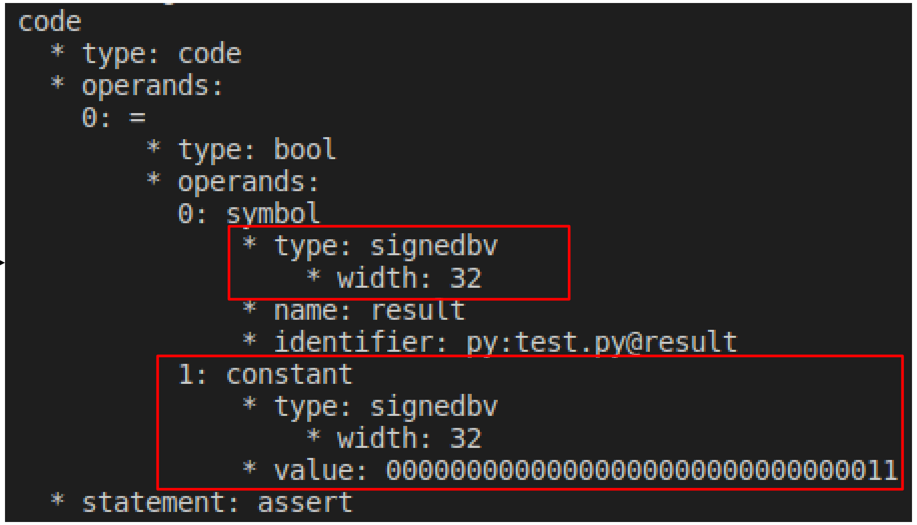


```python
def add(a:int, b:int) -> int:
    return a+b

n1 = 1
n2 = 2
result = add(n1,n2)
assert result == 3
```



```json
{
    "_type": "Assert",
    "test": {
        "_type": "Compare",
        "comparators": [
            {
                "_type": "Constant",
                "value": 3
            }
        ],
        "left": {
            "id": "result",
            "lineno": 7
        },
        "ops": [
            {
                "_type": "Eq"
            }
        ]
    }
}
```



```
code
  * type: code
  * operands:
    0: =
        * type: bool
        * operands:
          0: symbol
            * type: signedbv
                * width: 32
            * name: result
            * identifier: py:test.py@result
          1: constant
            * type: signedbv
                * width: 32
            * value: 00000000000000000000000000000011
  * statement: assert
```

JSON-Based Type Annotation

Constant Values

x = 10 → x:**int** = 10

Referred Variables

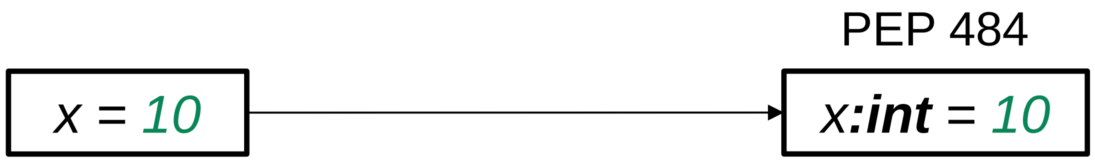
y = *x* → *y*:***int*** = *x*

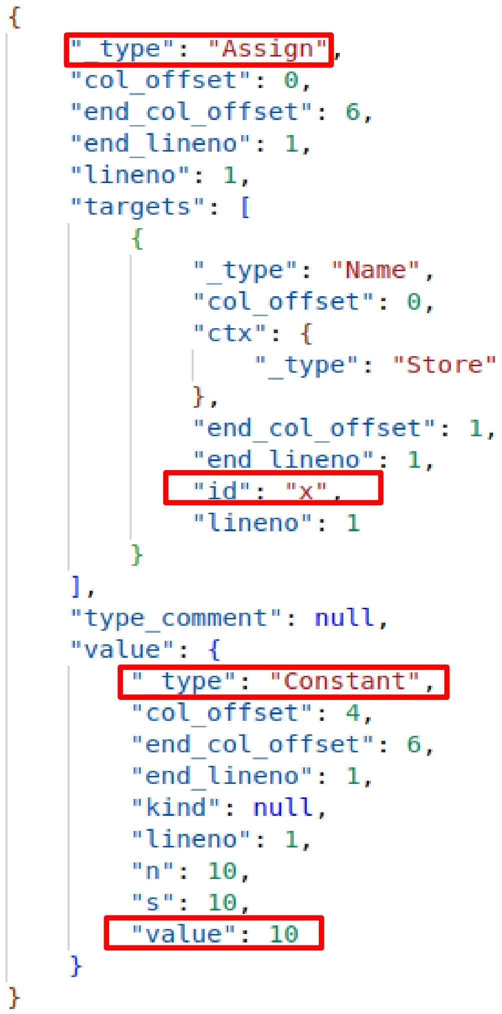
Class Instances

z = *MyClass()*

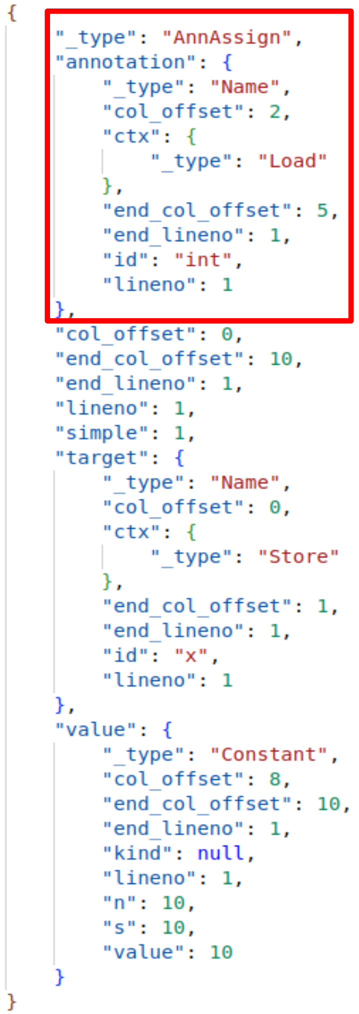
Function Calls

def foo() : return 1
x = *foo()* → *x*:***int*** = *foo()*





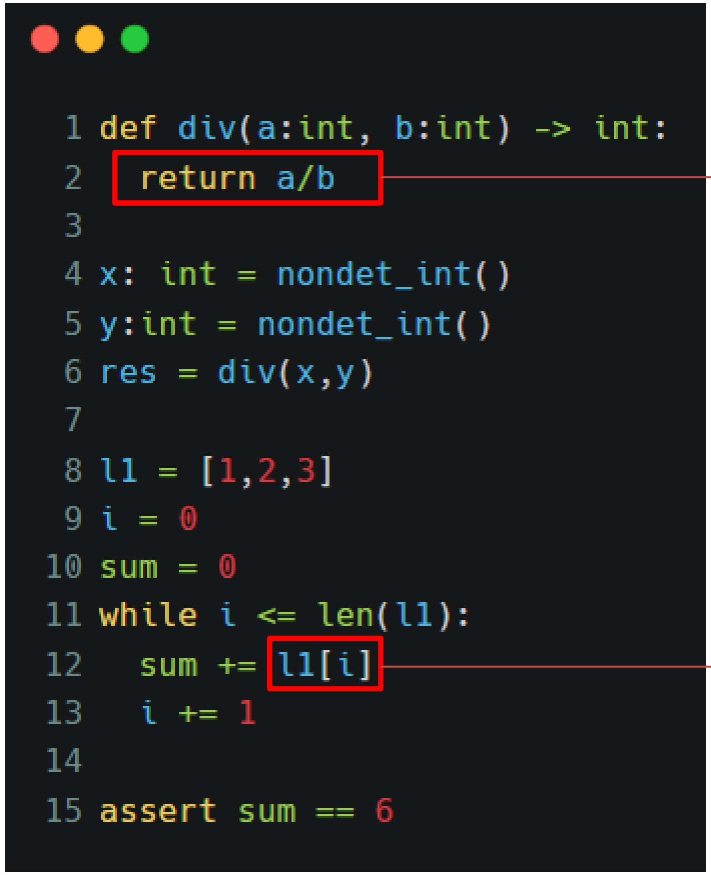
```
{
    "_type": "Assign",
    "col_offset": 0,
    "end_col_offset": 6,
    "end_lineno": 1,
    "lineno": 1,
    "targets": [
        {
            "_type": "Name",
            "col_offset": 0,
            "ctx": {
                "_type": "Store"
            },
            "end_col_offset": 1,
            "end_lineno": 1,
            "id": "x",
            "lineno": 1
        }
    ],
    "type_comment": null,
    "value": {
        "_type": "Constant",
        "col_offset": 4,
        "end_col_offset": 6,
        "end_lineno": 1,
        "kind": null,
        "lineno": 1,
        "n": 10,
        "s": 10,
        "value": 10
    }
}
```



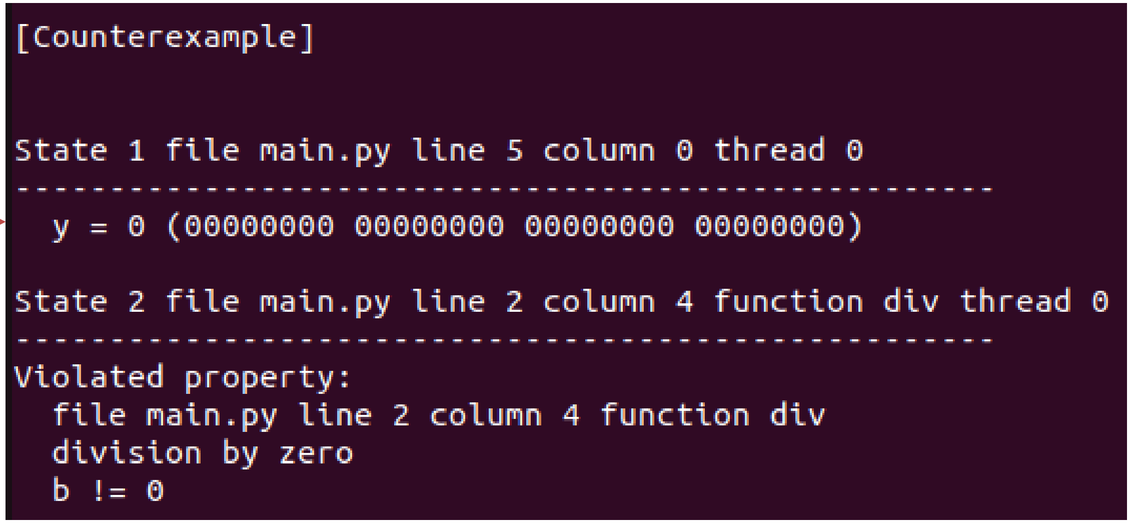
```
{
    "_type": "AnnAssign",
    "annotation": {
        "_type": "Name",
        "col_offset": 2,
        "ctx": {
            "_type": "Load"
        },
        "end_col_offset": 5,
        "end_lineno": 1,
        "id": "int",
        "lineno": 1
    },
    "col_offset": 0,
    "end_col_offset": 10,
    "end_lineno": 1,
    "lineno": 1,
    "simple": 1,
    "target": {
        "_type": "Name",
        "col_offset": 0,
        "ctx": {
            "_type": "Store"
        },
        "end_col_offset": 1,
        "end_lineno": 1,
        "id": "x",
        "lineno": 1
    },
    "value": {
        "_type": "Constant",
        "col_offset": 8,
        "end_col_offset": 10,
        "end_lineno": 1,
        "kind": null,
        "lineno": 1,
        "n": 10,
        "s": 10,
        "value": 10
    }
}
```

ESBMC-Python usage

$ esbmc main.py --multi-property



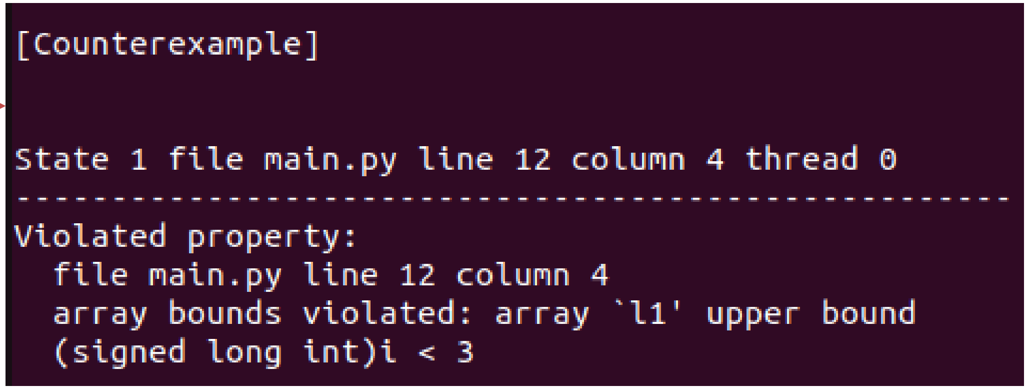
```
 1 def div(a:int, b:int) -> int:
 2   return a/b
 3
 4 x: int = nondet_int()
 5 y:int = nondet_int()
 6 res = div(x,y)
 7
 8 l1 = [1,2,3]
 9 i = 0
10 sum = 0
11 while i <= len(l1):
12   sum += l1[i]
13   i += 1
14
15 assert sum == 6
```



```
[Counterexample]


State 1 file main.py line 5 column 0 thread 0
----------------------------------------------------
  y = 0 (00000000 00000000 00000000 00000000)

State 2 file main.py line 2 column 4 function div thread 0
----------------------------------------------------
Violated property:
  file main.py line 2 column 4 function div
  division by zero
  b != 0
```



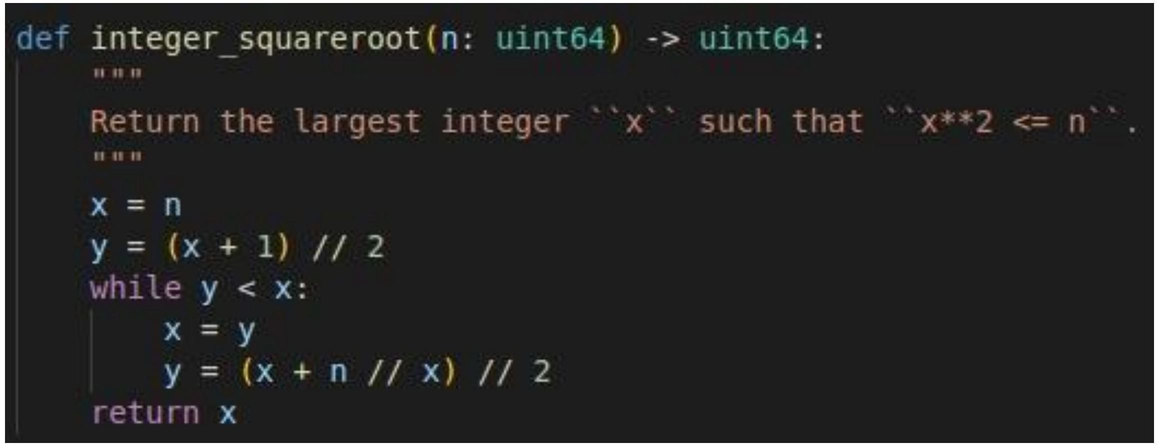
```
[Counterexample]


State 1 file main.py line 12 column 4 thread 0
----------------------------------------------------
Violated property:
  file main.py line 12 column 4
  array bounds violated: array `l1' upper bound
  (signed long int)i < 3
```

Verification of Blockchain protocol

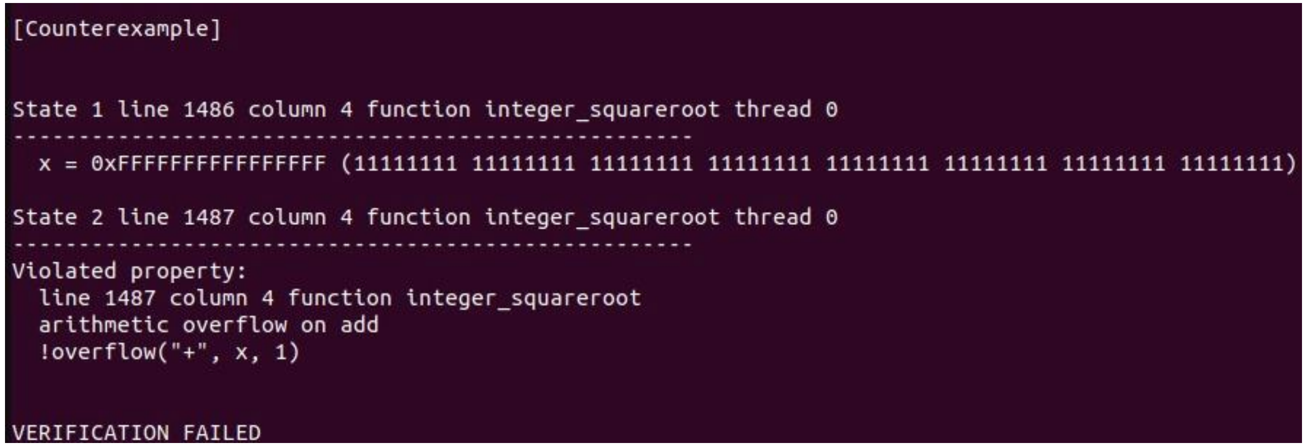
Consensus Specification https://github.com/ethereum/consensus-specs

- A set of runnable specifications in Python.
- Each function invoked individually with non-deterministic values.
- Arithmetic overflow and division-by-zero when calling *integer_square_root* below with INT_MAX as a parameter.



```python
def integer_squareroot(n: uint64) -> uint64:
    """
    Return the largest integer ``x`` such that ``x**2 <= n``.
    """
    x = n
    y = (x + 1) // 2
    while y < x:
        x = y
        y = (x + n // x) // 2
    return x
```

Consensus library code



```
[Counterexample]


State 1 line 1486 column 4 function integer_squareroot thread 0
----------------------------------------------------
  x = 0xFFFFFFFFFFFFFFFF (11111111 11111111 11111111 11111111 11111111 11111111 11111111 11111111)

State 2 line 1487 column 4 function integer_squareroot thread 0
----------------------------------------------------
Violated property:
  line 1487 column 4 function integer_squareroot
  arithmetic overflow on add
  !overflow("+", x, 1)


VERIFICATION FAILED
```

ESBMC-Python output

Experimental Results

Category	Test Cases	Memory Usage	Execution Time
Arith operations	2	26.4 MB	33.5 ms
Assignments	5	18.5 MB	38 ms
Assume	4	16.5 MB	28.2 ms
Binary operations	2	20.5 MB	29.5 ms
Binary types	4	20.4 MB	28.5 ms
Built-in functions	7	19.9 MB	28.1 ms
Classes	9	19 MB	27.1 ms
Conditionals	4	17.8 MB	25.5 ms
Functions	11	21.8 MB	30 ms
Imports	8	15.3 MB	49.1 ms
Logical operations	6	20.4 MB	24.5 ms
Loops	10	20.7 MB	35.4 ms
Non-determinism	4	21.4 MB	29.2 ms
Numeric types	6	20.9 MB	29.1 ms
Type annotation	3	14.5 MB	27.3 ms

- Benchmark suite consisting of 85 programs, categorized into 15 groups.

- Tests with both failling and passing assertions to evaluate reasoning on different Python features.

- The verification time (24.5 to 49.1 ms) is satisfactory compared to other BMC tools.

- Memory consumption (14.5 to 26.4 MB) is also usual and considered low for modern computers.

Conclusion

- ESBMC-Python demonstrates the feasibility of using BMC for the formal verification of Python programs.
- The verification process is fully automated and does not require user annotations.
- Our tool identified a significant real-world issue.

Next steps:

- Add support for additional features: Concurrency, unhandled exceptions, and unbounded integer handling.
- Enhance type annotation and integrate a type checker.
- Enable verification for AI libraries.

ESBMC-Python: A Bounded Model Checker for Python programs

Thank you

github.com/esbmc/esbmc

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