How static program analysis can help trusting Python programs

Raphaël Monat – SyCoMoRES team

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InCyber
3 March 2025

Introduction

whoami

Research Scientist at Inria since Sep. 2022.

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Automated verification of Catala programs

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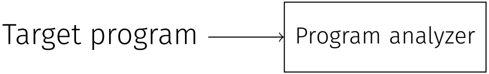
- Binary code analysis [Bal+19] (for worst-case execution time, security)
- Type systems for privacy

Automated Program Analysis

Target program

Automated Program Analysis



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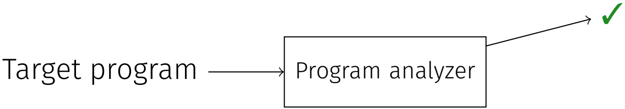

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Program analyzer

✓

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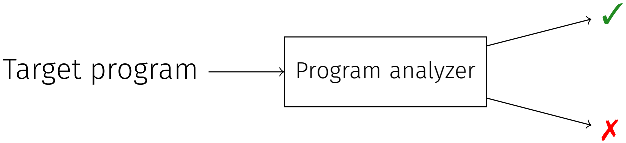

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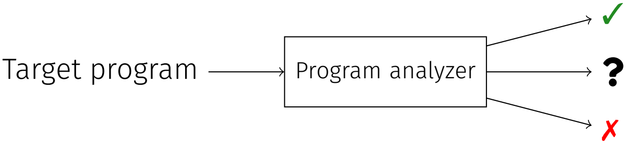

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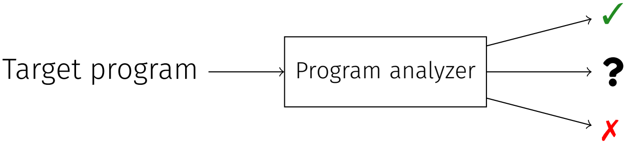

Motivation

Sheer quantity of programs and changes during their life:

Manual processes (e.g. testing, manual verification) will not scale!

Turing & Rice to the Rescue

Sound	All errors in program reported by analyzer

Turing & Rice to the Rescue

All errors reported by analyzer are replicable in program

Complete

Sound

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Guaranteed Termination

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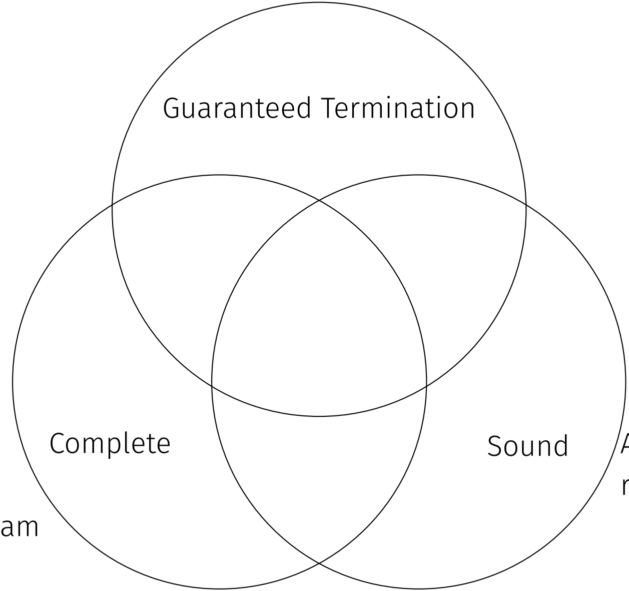

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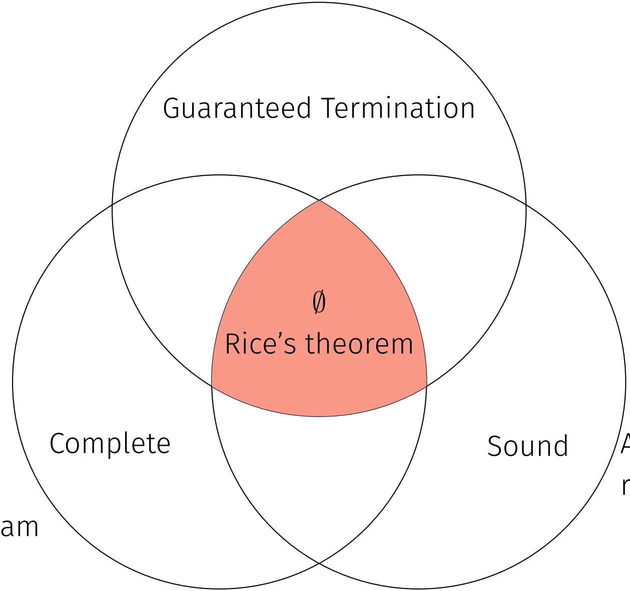

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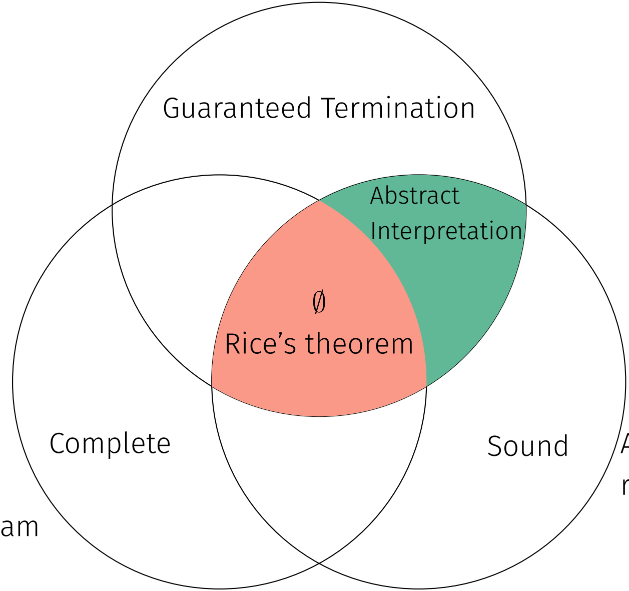

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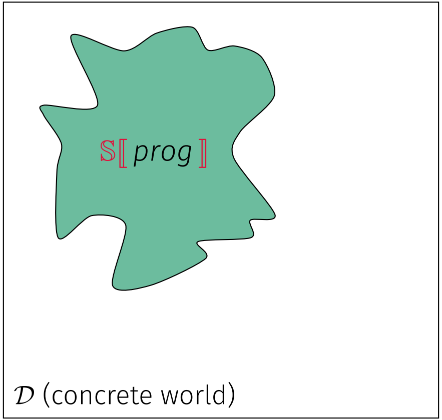
Abstract Interpretation for Software Safety


$\mathbb{S}[\![\, prog \,]\!]$
$\mathcal{D}$ (concrete world)

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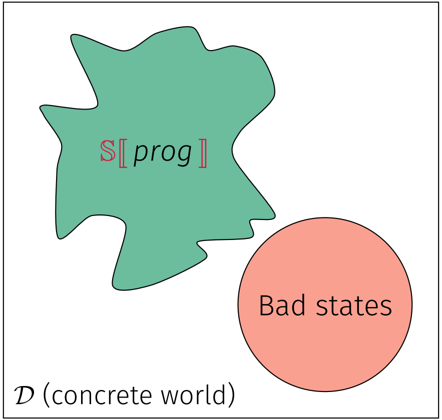
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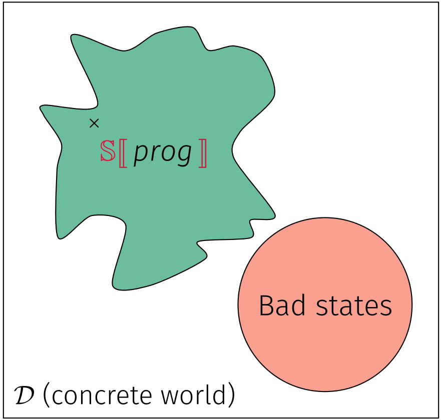

Tests

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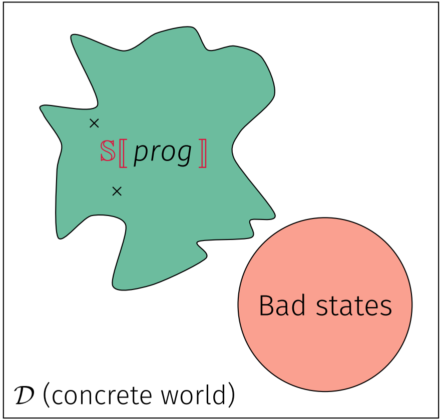
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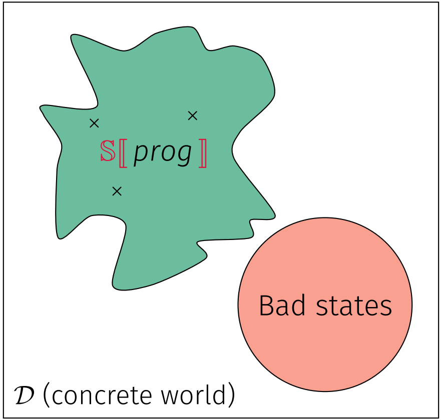
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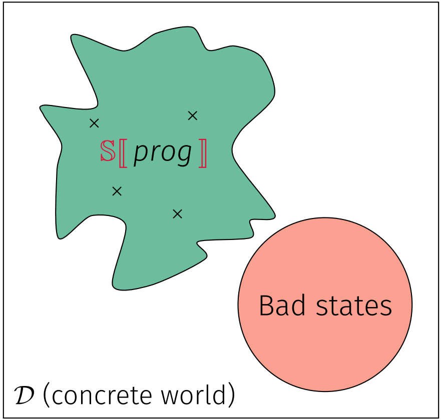
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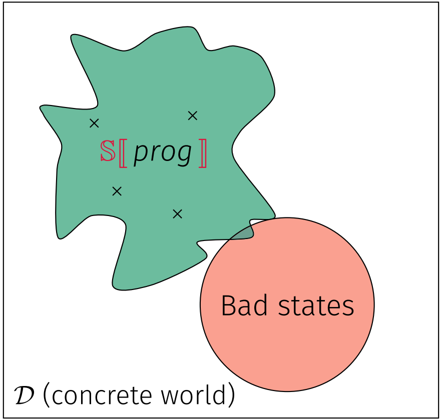
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Tests are not sound

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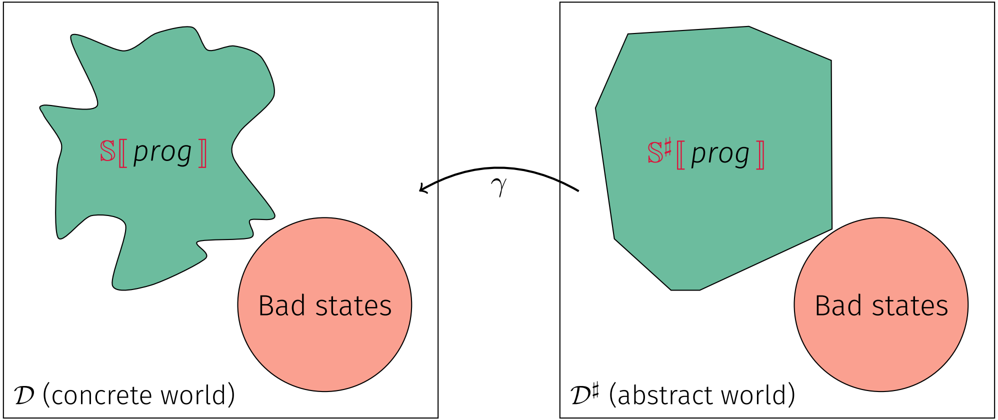


$\mathbb{S}[\![\, prog \,]\!]$

Bad states

$\mathcal{D}$ (concrete world)

γ

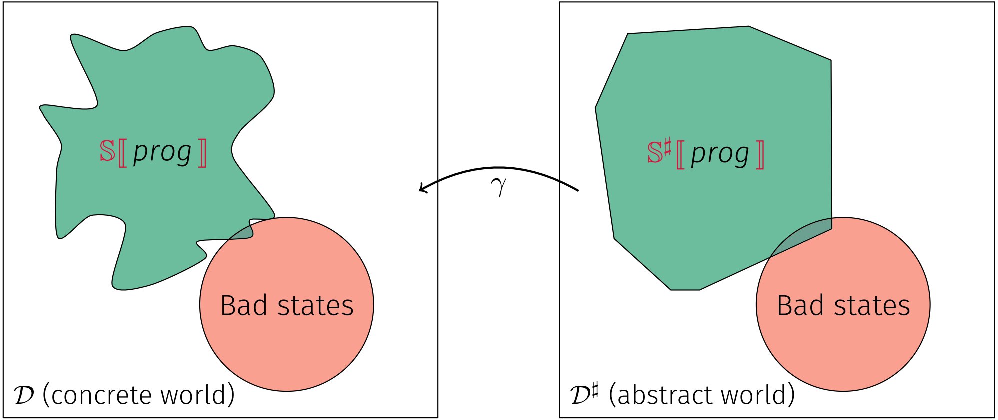
$\mathbb{S}^\sharp[\![\, prog \,]\!]$

Bad states

$\mathcal{D}^\sharp$ (abstract world)

Safe program

Abstract Interpretation for Software Safety



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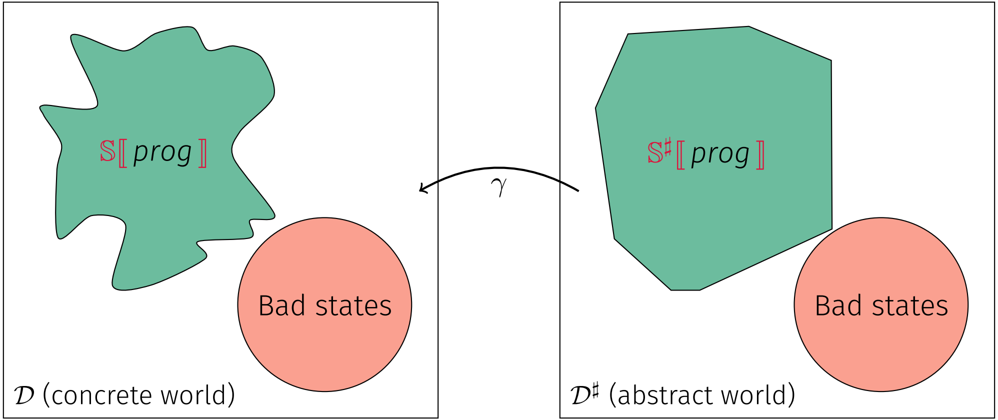
True alarm

Abstract Interpretation for Software Safety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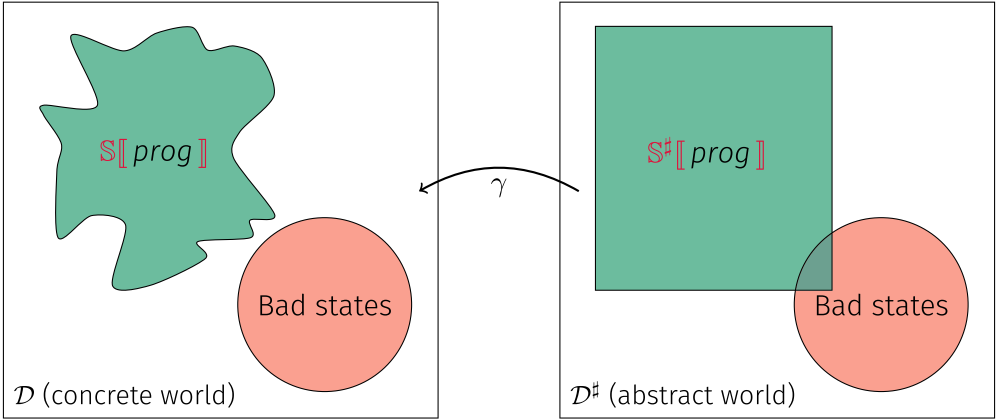
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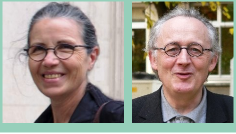
False alarm (due to imprecisions)

A Brief History of Abstract Interpretation

1977: foundational paper by Radhia and Patrick Cousot [CC77]



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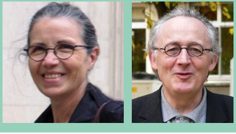

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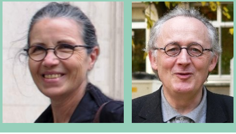

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Now: democratizing static analysis?

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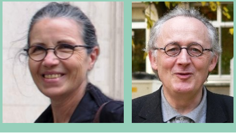

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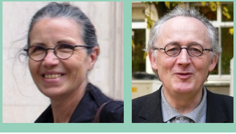

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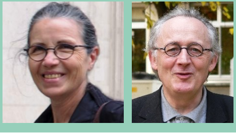

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- From full programs to libraries

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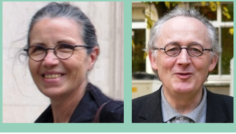

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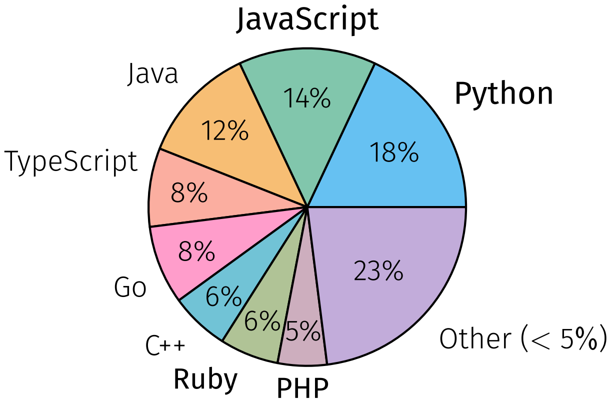
Now: democratizing static analysis?

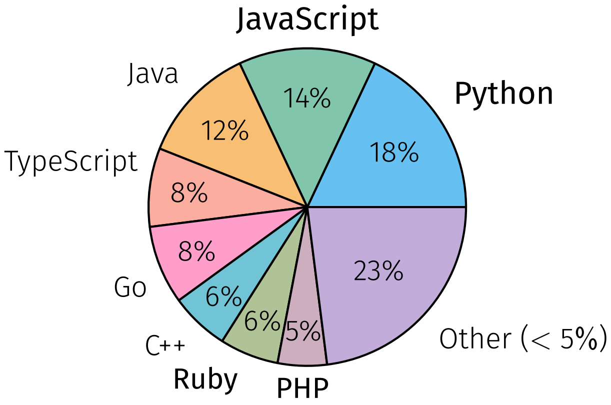
- From embedded C software to
  - General C software (dynamic allocation, ...)
  - Other languages
- From full programs to libraries
- Framework to implement analyses

Dynamic programming languages



Most popular languages on GitHub

Dynamic programming languages



Most popular languages on GitHub

New features

- Dynamic typing
- Dynamic object structure

Outline

1 A Taste of Python

2 Analyzing Python Programs

3 Analyzing Python Programs with C Libraries

4 A Modern Program Analyzer: Mopsa

A Taste of Python

Python's specificities

No standard

CPython is the reference

$\Longrightarrow$ manual inspection of the source code and handcrafted tests

Python’s specificities

No standard

CPython is the reference

⟹ manual inspection of the source code and handcrafted tests

Operator redefinition

- Calls, additions, attribute accesses
- Operators eventually call overloaded `__methods__`

Protected attributes

```python
class Protected:
  def __init__(self, priv):
    self._priv = priv
  def __getattribute__(self, attr):
    if attr[0] == "_": raise AttributeError("...")
    return object.__getattribute__(self, attr)

a = Protected(42)
a._priv # AttributeError raised
```

Python’s specificities (II)

Dual type system

- Nominal (classes, MRO [Bar+96])

Fspath (from standard library)

```python
class Path:
  def __fspath__(self): return 42

def fspath(p):
  if isinstance(p, (str, bytes)):
    return p
  elif hasattr(p, "__fspath__"):
    r = p.__fspath__()
    if isinstance(r, (str, bytes)):
      return r
  raise TypeError

fspath("/dev" if random() else Path())
```

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Python’s specificities (II)

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Exceptions

Exceptions rather than specific values

- ▶ `1 + "a"` ⇝ `TypeError`
- ▶ `l[len(l) + 1]` ⇝ `IndexError`

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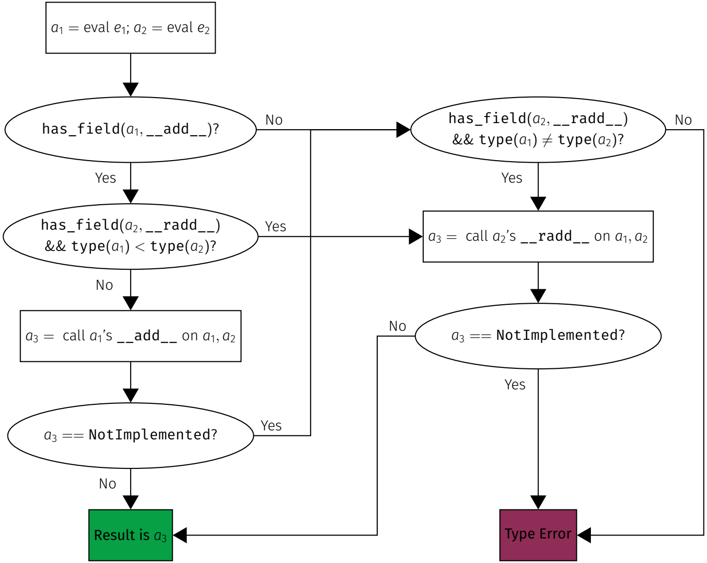
Example Semantics – binary operators



$a_1 =$ eval e_1; $a_2 =$ eval e_2

`has_field`(a_1, `__add__`)?

Yes

`has_field`(a_2, `__radd__`) && `type`(a_1) $<$ `type`(a_2)?

No

$a_3 =$ call a_1's `__add__` on a_1, a_2

$a_3 ==$ `NotImplemented`?

No

Result is a_3

Yes

No

Yes

`has_field`(a_2, `__radd__`) && `type`(a_1) $\neq$ `type`(a_2)?

Yes

$a_3 =$ call a_2's `__radd__` on a_1, a_2

$a_3 ==$ `NotImplemented`?

No

Yes

Type Error

No

Crazy Python

Custom infix operators

```python
class Infix(object):
    def __init__(self, func): self.func = func
    def __or__(self, other): return self.func(other)
    def __ror__(self, other): return Infix(lambda x: self.func(other, x))

instanceof = Infix(isinstance)
b = 5 |instanceof| int

@Infix
def padd(x, y):
  print(f"{x} + {y} = {x + y}")
  return x + y
c = 2 |padd| 3
```

Credits `tomerfiliba.com/blog/Infix-Operators/`

Analyzing Python Programs

Analysis Overview

Goal

Detect runtime errors: uncaught raised exceptions

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Detect runtime errors: uncaught raised exceptions

Supported constructs

Our analysis supports:

- Objects
- Exceptions
- Dynamic typing
- Introspection
- Permissive semantics
- Dynamic attributes
- Generators
- `super`
- Metaclasses

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Detect runtime errors: uncaught raised exceptions

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Unsupported constructs

- Recursive functions
- `eval`
- Finalizers

Analysis Domains Required

Averaging numbers

```
def average(l):
  m = 0
  for i in range(len(l)):
    m = m + l[i]
  m = m // (i + 1)
  return m

l = [randint(0, 20)
  for i in range(randint(5, 10))]
m = average(l)
```

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 1  def average(l):
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```

Proved safe?

- `m // (i+1)`
- `m + l[i]`

Searching for a loop invariant (l. 4)

“Nominal type” abstraction

m : `int` i : `int`

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Stateless domains: **list content**,

“Nominal type” abstraction

m : `int` i : `int` **<u>els</u>(l) : `int`**

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Stateless domains: list content,

“Nominal type” abstraction

m : `int` i : `int` $\underline{\text{els}}(l)$: `int`

Numeric abstraction (intervals)

$m \in [0, +\infty)$ $\underline{\text{els}}(l) \in [0, 20]$

$i \in [0, +\infty)$

Analysis Domains Required

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Searching for a loop invariant (l. 4)

Stateless domains: list content, **list length**

“Nominal type” abstraction

$m : \texttt{int} \quad i : \texttt{int} \quad \underline{\text{els}}(l) : \texttt{int}$

Numeric abstraction (intervals)

$m \in [0, +\infty) \qquad \underline{\text{els}}(l) \in [0, 20]$

$\boldsymbol{i \in [0, 10]} \qquad \boldsymbol{\underline{\text{len}}(l) \in [5, 10]}$

Analysis Domains Required

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Stateless domains: list content, list length

"Nominal type" abstraction

$m : \texttt{int} \quad i : \texttt{int} \quad \underline{\text{els}}(l) : \texttt{int}$

Numeric abstraction (polyhedra)

$m \in [0, +\infty) \qquad \underline{\text{els}}(l) \in [0, 20]$

$\mathbf{0 \leq i < \underline{len}(l) \qquad 5 \leq \underline{len}(l) \leq 10}$

Analysis Domains Required

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Searching for a loop invariant (l. 4)

Stateless domains: list content, list length

“Nominal type” abstraction

$0 \leq i < \underline{\text{len}}(l) \qquad 5 \leq \underline{\text{len}}(l) \leq 10$

Conclusion

- Different domains depending on the precision
- Use of auxiliary variables (underlined)

Proved safe?

- `m // (i+1)`
- `m + l[i]`

Comparison of the type and value analyses [MOM20b]

Averaging numbers

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Type analysis

- `IndexError` (l. 4)

Comparison of the type and value analyses [MOM20b]

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 4      m = m + l[i]
 5    m = m // (i + 1)
 6    return m
 7
 8  l = [randint(0, 20)
 9    for i in range(randint(5, 10))]
10  m = average(l)
```

Type analysis

- `IndexError` (l. 4)
- `ZeroDivisionError` (l. 5)

Comparison of the type and value analyses [MOM20b]

Averaging numbers

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Non-relational value analysis

`IndexError` (l. 5)

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Non-relational value analysis

`IndexError` (l. 5)

Relational value analysis

No alarm!

Benchmarks

Name	LOC	Type Analysis					Non-relational Value Analysis				
		Time	Mem.	Exceptions detected			Time	Mem.	Exceptions detected		
				Type	Index	Key			Type	Index	Key
nbody.py	157	1.5s	3MB	0	22	1	5.7s	9MB	0	**1**	1
scimark.py	416	1.4s	12MB	1	1	0	3.4s	27MB	1	**0**	0
richards.py	426	13s	112MB	1	4	0	17s	149MB	1	**2**	0
unpack_seq.py	458	8.3s	7MB	0	0	0	9.4s	6MB	0	0	0
go.py	461	27s	345MB	33	20	0	2.0m	1.4GB	33	20	0
hexiom.py	674	1.1m	525MB	0	46	3	4.7m	3.2GB	0	**21**	3
regex_v8.py	1792	23s	18MB	0	2053	0	1.3m	56MB	0	**145**	0
processInput.py	1417	10s	64MB	7	7	1	12s	85MB	7	**4**	1
choose.py	2562	1.1m	1.6GB	12	22	7	2.9m	3.7GB	12	**13**	7
Total	9294	4.0m	2.8GB	59	2214	12	13m	9.1GB	59	228	12

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Conclusion

The non-relational value analysis

- does not remove false type alarms
- significantly reduces index errors
- is $\simeq 3\times$ costlier

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- ▶ does not remove false type alarms
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- ▶ is $\simeq 3\times$ costlier

Heuristic packing and relational analyses

- ▶ Static packing, using function's scope
- ▶ Rules out all 145 alarms of `regex_v8.py` (1792 LOC) at 2.5× cost

Trusting Python programs

Our analysis can summarize

- Module imports
- Object creation
- Function calls
- Resource accesses (files, network, …)

Analyzing Python Programs with C Libraries

Combining C and Python – motivation

One in five of the top 200 Python libraries contains C code

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Pitfalls

- Different values (arbitrary-precision integers in Python, bounded in C)
- Different runtime-errors (exceptions in Python)
- Garbage collection
- Less approaches to detect multi-language attacks [MBO22]

Combining C and Python – example

counter.c

```c
typedef struct {
    PyObject_HEAD;
    int count;
} Counter;

static PyObject*
CounterIncr(Counter *self, PyObject *args)
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    int i = 1;
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count.py

```python
from counter import Counter
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c = Counter()
power = randrange(128)
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- $\texttt{power} \leq 30 \Rightarrow \texttt{r} = 2^{\texttt{power}}$

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- $\texttt{power} \leq 30 \Rightarrow \texttt{r} = 2^{\texttt{power}}$
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- $\texttt{power} = 31 \Rightarrow \texttt{r} = -2^{31}$
- $32 \leq \texttt{power} \leq 64$: OverflowError: signed integer is greater than maximum
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How to analyze multilanguage programs?

Type annotations

```python
class Counter:
  def __init__(self): ...
  def incr(self, i: int = 1): ...
  def get(self) -> int: ...
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- Only types
- Typeshed: type annotations for the standard library, used in the single-language analysis before

How to analyze multilanguage programs?

Type annotations

Rewrite into Python code

```
class Counter:
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  def get(self):
    return self.count
  def incr(self, i=1):
    self.count += i
```

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- No integer wrap-around in Python

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    self.count += i
```

- No integer wrap-around in Python
- Some effects can’t be written in pure Python (e.g., read-only attributes)

How to analyze multilanguage programs?

Type annotations

Rewrite into Python code

Drawbacks of the current approaches

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Type annotations

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- Not the real code

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Our approach

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Our approach

- Analyze both the C and Python sources

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Our approach

- Analyze both the C and Python sources
- Switch from one language to the other just as the program does
- Reuse previous analyses of C and Python
- Detect runtime errors in Python, in C, and at the boundary

Analysis result

counter.c

```c
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} Counter;

static PyObject*
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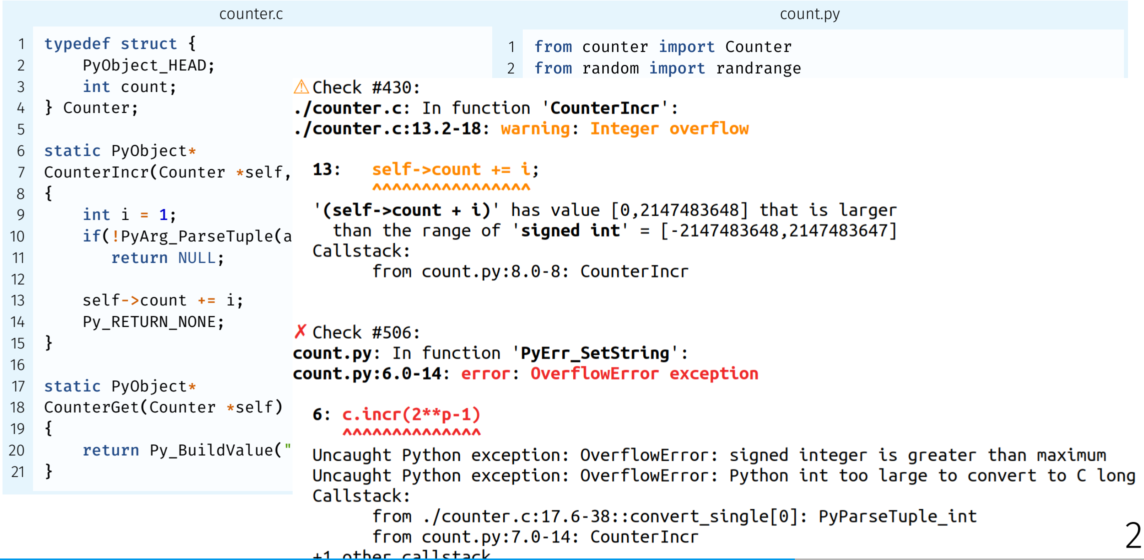
Analysis result



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8  {
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11        return NULL;
12
13     self->count += i;
14     Py_RETURN_NONE;
15 }
16
17 static PyObject*
18 CounterGet(Counter *self)
19 {
20     return Py_BuildValue("
21 }
```

count.py

```
1  from counter import Counter
2  from random import randrange
```

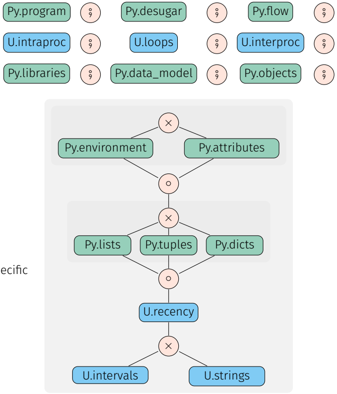
```
⚠Check #430:
./counter.c: In function 'CounterIncr':
./counter.c:13.2-18: warning: Integer overflow

 13:    self->count += i;
        ^^^^^^^^^^^^^^^^
 '(self->count + i)' has value [0,2147483648] that is larger
   than the range of 'signed int' = [-2147483648,2147483647]
 Callstack:
        from count.py:8.0-8: CounterIncr


✗ Check #506:
count.py: In function 'PyErr_SetString':
count.py:6.0-14: error: OverflowError exception

 6: c.incr(2**p-1)
    ^^^^^^^^^^^^^^
 Uncaught Python exception: OverflowError: signed integer is greater than maximum
 Uncaught Python exception: OverflowError: Python int too large to convert to C long
 Callstack:
        from ./counter.c:17.6-38::convert_single[0]: PyParseTuple_int
        from count.py:7.0-14: CounterIncr
 +1 other callstack
```

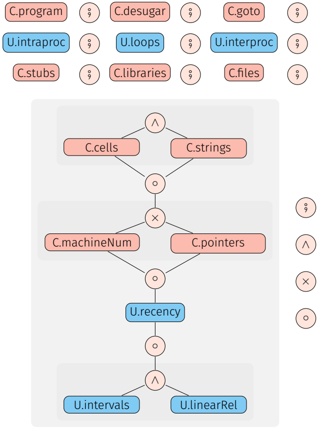
From distinct Python and C analyses...

🔵 Universal

🔴 C specific

🟢 Python specific


Py.program ⨾ Py.desugar ⨾ Py.flow ⨾
U.intraproc ⨾ U.loops ⨾ U.interproc ⨾
Py.libraries ⨾ Py.data_model ⨾ Py.objects ⨾
×
Py.environment
Py.attributes
∘
×
Py.lists
Py.tuples
Py.dicts
∘
U.recency
×
U.intervals
U.strings


C.program ⨾ C.desugar ⨾ C.goto ⨾
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∧
C.cells
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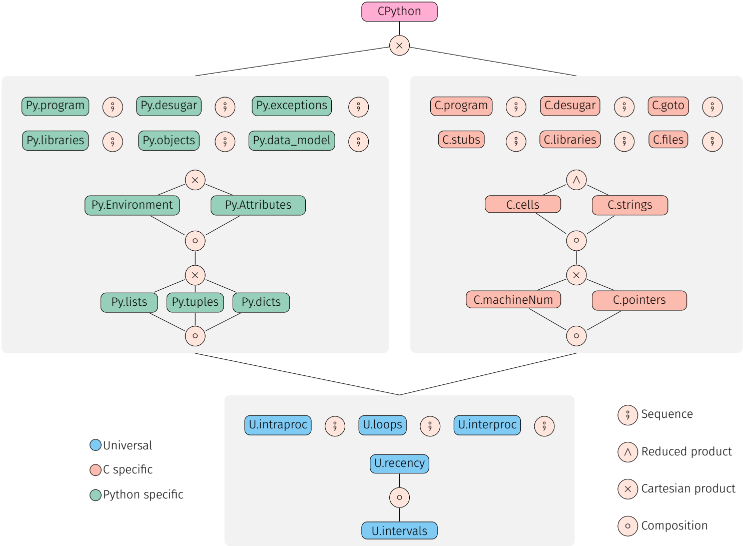
⨾ Sequence

∧ Reduced product

× Cartesian product

∘ Composition

From distinct Python and C analyses... to a multilanguage analysis!



CPython

×

Py.program ⨾ Py.desugar ⨾ Py.exceptions ⨾
Py.libraries ⨾ Py.objects ⨾ Py.data_model ⨾

×
Py.Environment Py.Attributes
∘
×
Py.lists Py.tuples Py.dicts
∘

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🔵 Universal
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∘ Composition

Benchmarks

Corpus selection

- Popular, real-world libraries available on GitHub, averaging 412 stars.
- Whole-program analysis: we use the tests provided by the libraries.

Library	C + Py. Loc	Tests	🕒/test	$\frac{\text{\# proved checks}}{\text{\# checks}}$ %	# checks
noise	1397	15/15	1.2s	99.7%	(6690)
cdistance	2345	28/28	4.1s	98.0%	(13716)
llist	4515	167/194	1.5s	98.8%	(36255)
ahocorasick	4877	46/92	1.2s	96.7%	(6722)
levenshtein	5798	17/17	5.3s	84.6%	(4825)
bitarray	5841	159/216	1.6s	94.9%	(25566)

Trusting Python+C programs

Our analysis can summarize

- Function calls
- Resource accesses (files, network, ...)

Made by either Python or C.

A Modern Program Analyzer: Mopsa

Mopsa

Modular **O**pen **P**latform for **S**tatic **A**nalysis [Jou+19]

`gitlab.com/mopsa/mopsa-analyzer`

Started by ERC Consolidator Grant (2016-2021) of Antoine Miné (LIP6, SU)

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Goals

- Explore new designs

  Including multi-language support

Modular Open Platform for Static Analysis [Jou+19]

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- Ease development of relational static analyses
  - High expressivity

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  - Including multi-language support
- Ease development of relational static analyses
  - High expressivity
- Open-source (LGPL)
- Can be used as an experimentation platform

Contributors (2018–2025, chronological arrival order)

- A. Miné
- A. Ouadjaout
- M. Journault
- A. Fromherz
- D. Delmas
- R. Monat
- G. Bau
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Maintainers in bold.

Works around Mopsa

Languages

C [JMO18; OM20], Python [MOM20a; MOM20b]

Works around Mopsa

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Multilanguage Python+C [MOM21]

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WIP: Michelson [Bau+22], OCaml [VMM23], Catala (date arithmetic [MFM24])...

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- Patch analysis [DM19]

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Properties

- **Absence of RTEs**
- Patch analysis [DM19]
- Endianness portability [DOM21]

Works around Mopsa

Languages

C [JMO18; OM20], Python [MOM20a; MOM20b]

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WIP: Michelson [Bau+22], OCaml [VMM23], Catala (date arithmetic [MFM24])...

Properties

- **Absence of RTEs**
- Patch analysis [DM19]
- Endianness portability [DOM21]
- Non-exploitability [PM24]

Works around Mopsa

Languages

C [JMO18; OM20], Python [MOM20a; MOM20b]

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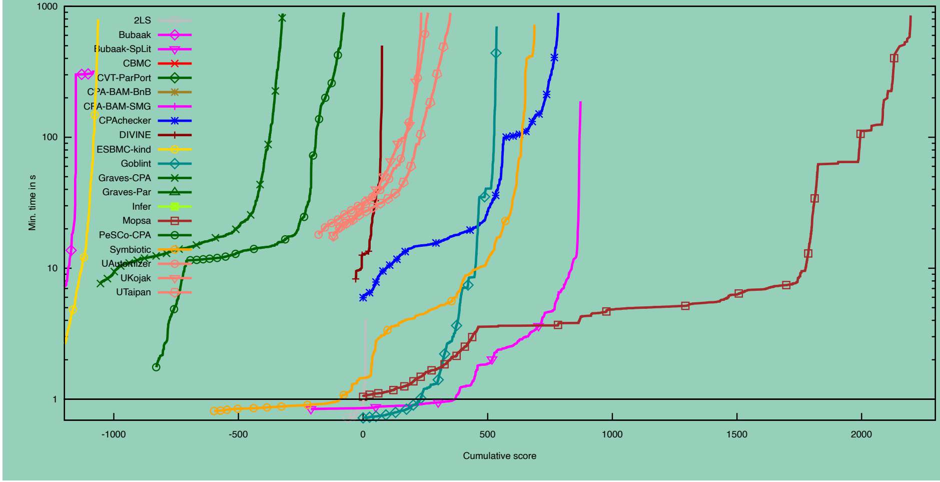
Properties

- **Absence of RTEs**
- Patch analysis [DM19]
- Endianness portability [DOM21]
- Non-exploitability [PM24]
- Sufficient precondition inference [MM24]

Works around Mopsa – II

Software Verification Competition

We won the “SoftwareSystems” track of SV-Comp 2024 [Mon+24]!



Conclusion

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Automated program analysis can help

understanding unknown programs

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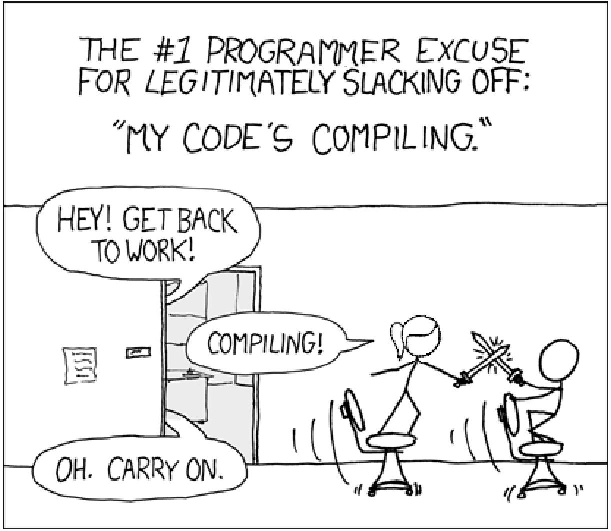

xkcd.com/303

Research Perspectives

Non-exploitability analysis from Parolini and Miné [PM24]

- Focus on alarms that users can trigger through program interaction

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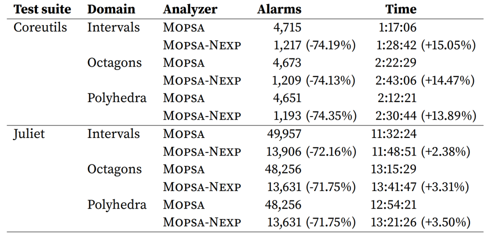

Test suite	Domain	Analyzer	Alarms	Time
Coreutils	Intervals	MOPSA	4,715	1:17:06
		MOPSA-NEXP	1,217 (-74.19%)	1:28:42 (+15.05%)
	Octagons	MOPSA	4,673	2:22:29
		MOPSA-NEXP	1,209 (-74.13%)	2:43:06 (+14.47%)
	Polyhedra	MOPSA	4,651	2:12:21
		MOPSA-NEXP	1,193 (-74.35%)	2:30:44 (+13.89%)
Juliet	Intervals	MOPSA	49,957	11:32:24
		MOPSA-NEXP	13,906 (-72.16%)	11:48:51 (+2.38%)
	Octagons	MOPSA	48,256	13:15:29
		MOPSA-NEXP	13,631 (-71.75%)	13:41:47 (+3.31%)
	Polyhedra	MOPSA	48,256	12:54:21
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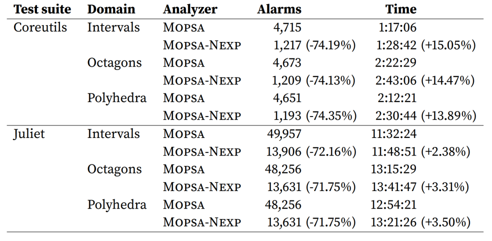

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Summarizing data accesses in Python-SQL programs

Ongoing work with Charles Paperman.

How static program analysis can help trusting Python programs

Raphaël Monat – SyCoMoRES team

`rmonat.fr`

InCyber
3 March 2025

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