From Python to the French Tax Code: Applying Formal Methods on Real Systems

Raphaël Monat

SyCoMoRES team

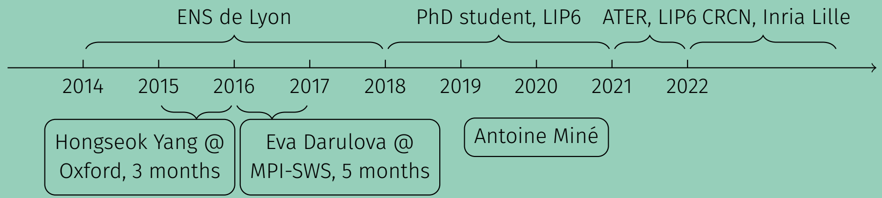
`rmonat.fr`

DI Seminar

22 March 2023

Introduction

Curriculum



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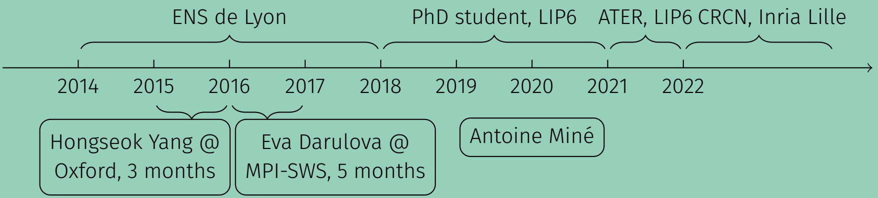

Research field: formal methods

$\Rightarrow$ Improve confidence in software.

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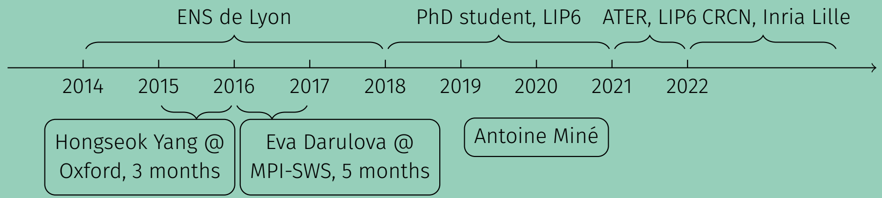

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Means

- Theory: formal definition and reasoning over systems
- Practice: software development

Personal methodology

Constant back and forth between theory and practice

1. Find interesting bugs, properties or systems to study (GitHub, ...)
2. Theoretical study and solution
3. Implementation and experimental validation (on 1)

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Studied systems

- Python programs using C libraries $\rightsquigarrow$ static analysis
  - Abdelraouf Ouadjaout (LIP6)
  - Antoine Miné (LIP6)

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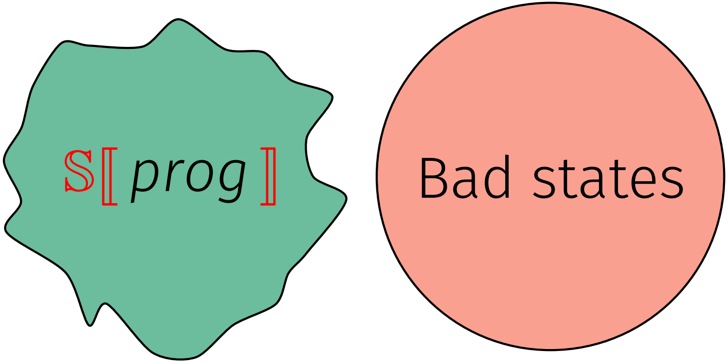
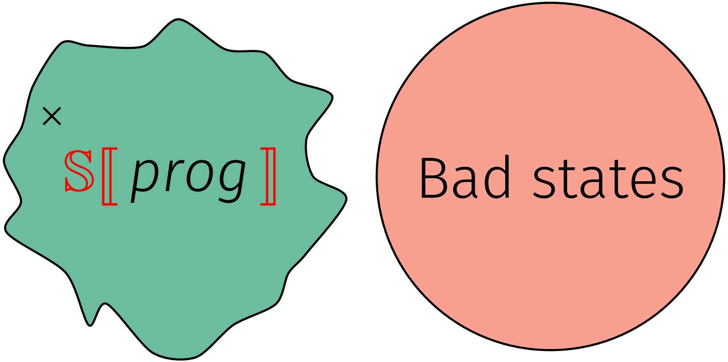
Studied systems

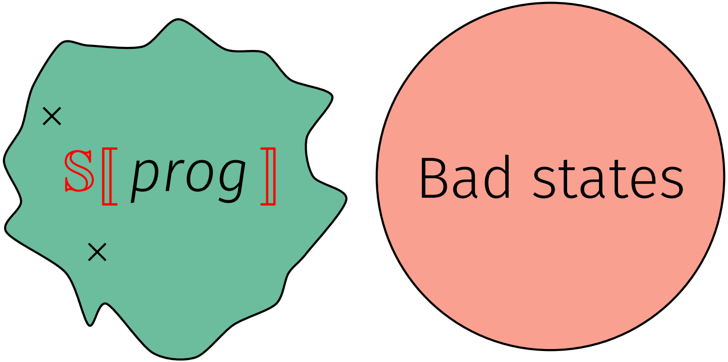
- Python programs using C libraries ⇝ static analysis
  - Abdelraouf Ouadjaout (LIP6)
  - Antoine Miné (LIP6)
- Implementation of the French tax code ⇝ compiler, modernization
  - Denis Merigoux (Inria Prosecco)
  - Jonathan Protzenko (MSR)


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


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



Cheap approach: test *prog*.



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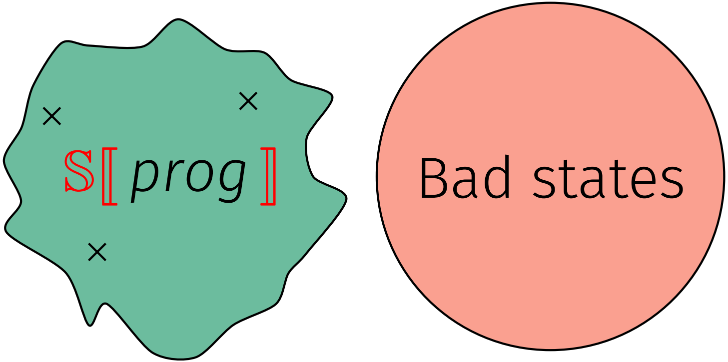

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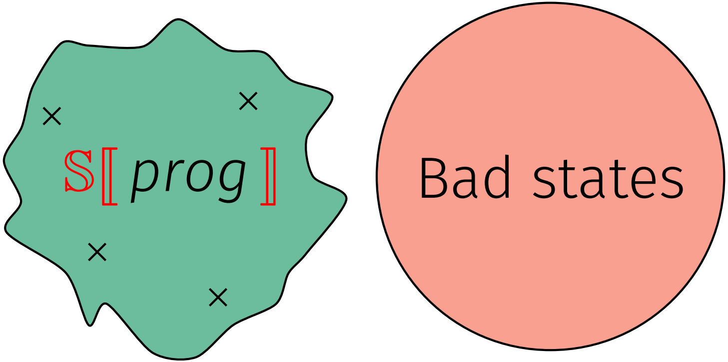

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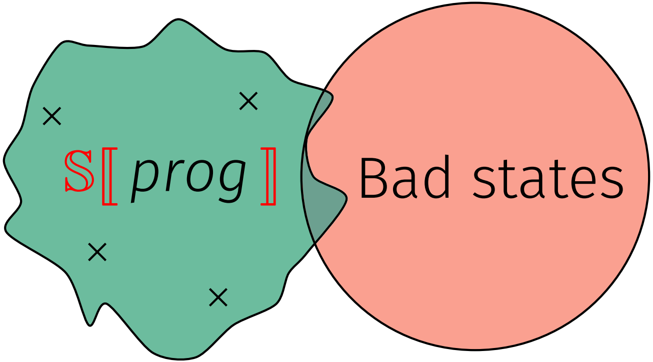

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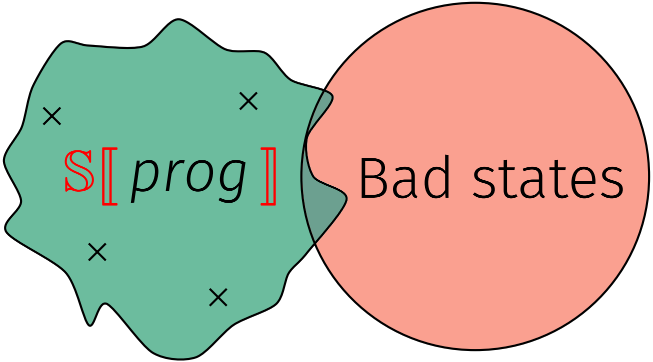

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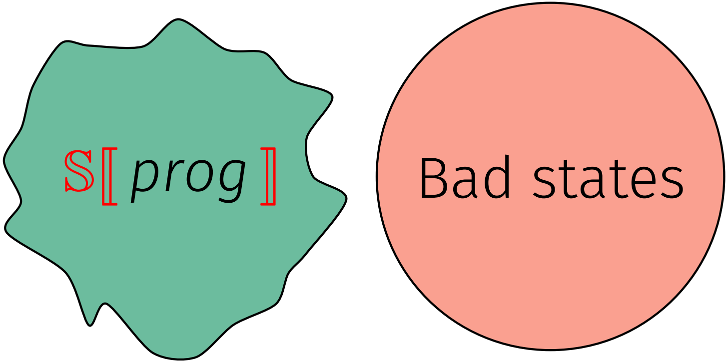

Cheap approach: test *prog*.

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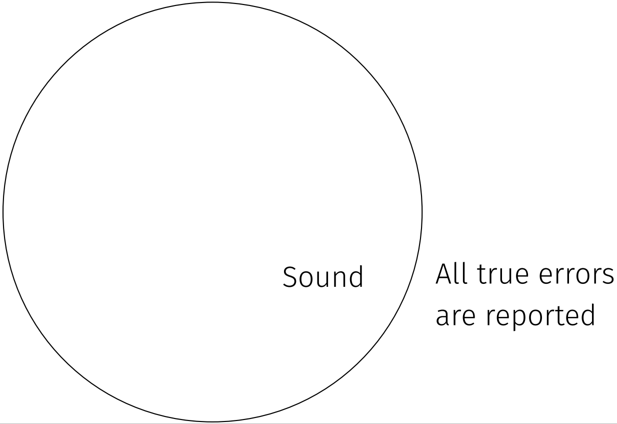
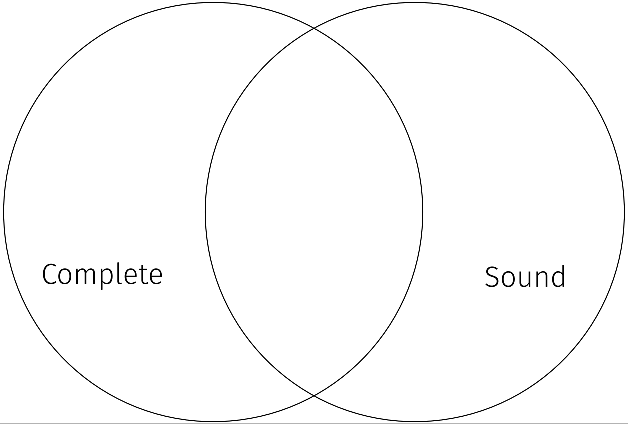
Would there be a way to automatically prove programs correct?

An impossibility theorem



An impossibility theorem

All reported errors are true errors



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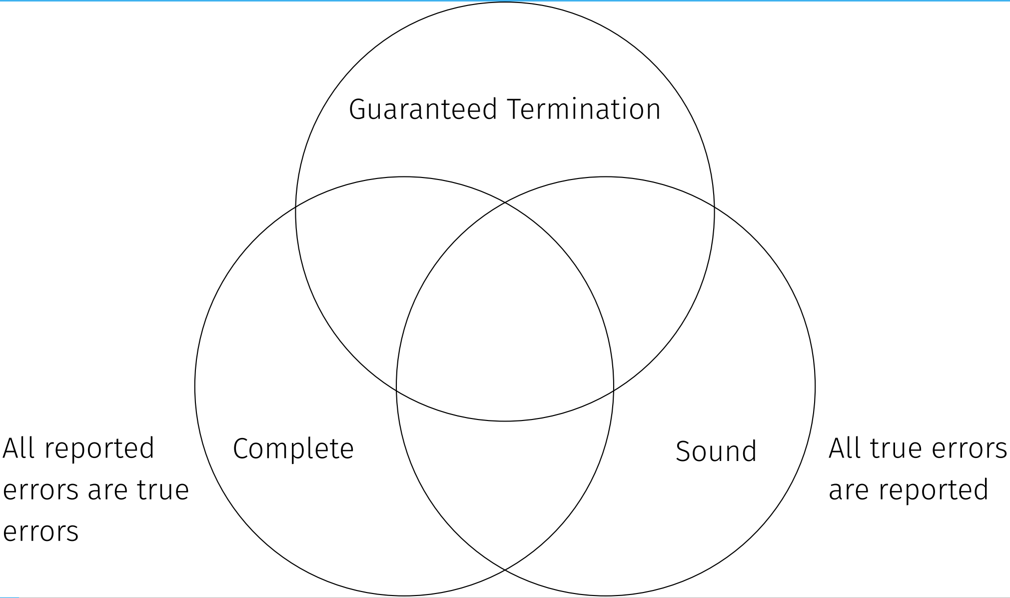

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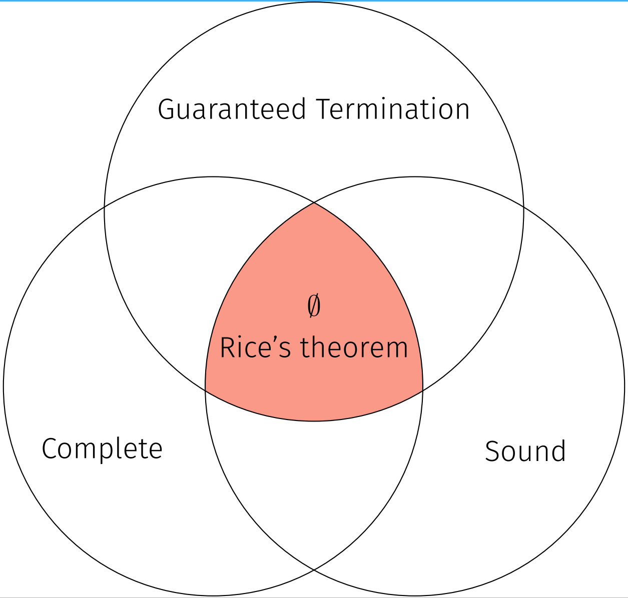

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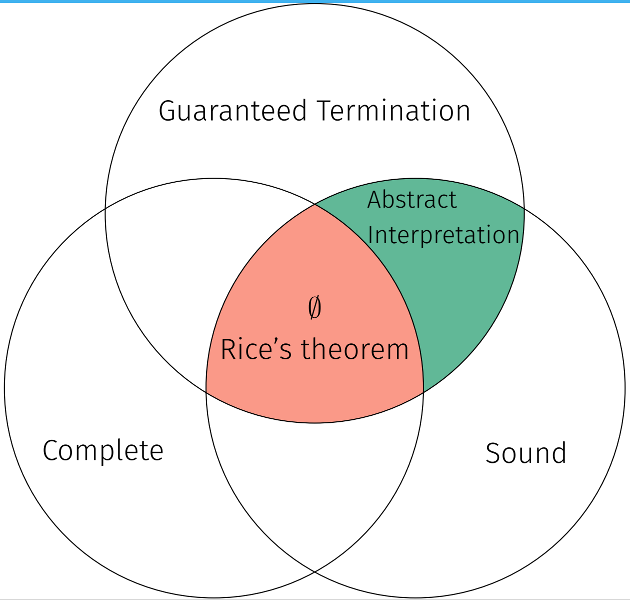

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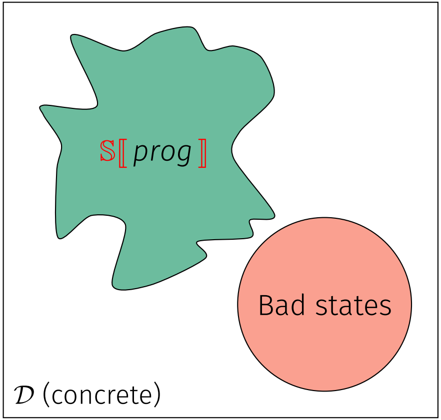
Abstract interpretation – the big picture



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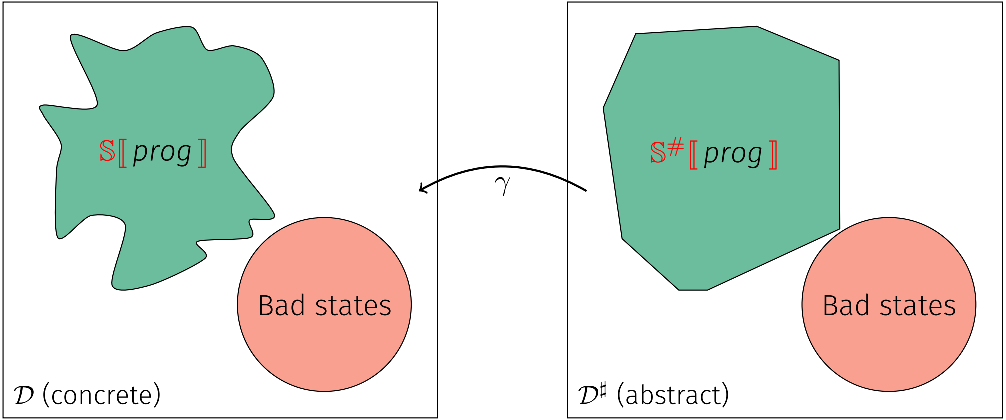

Program proved safe

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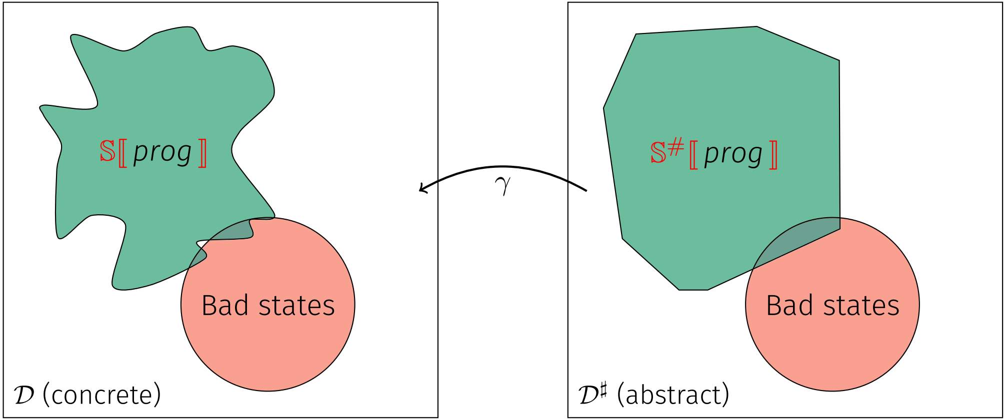

True alarm

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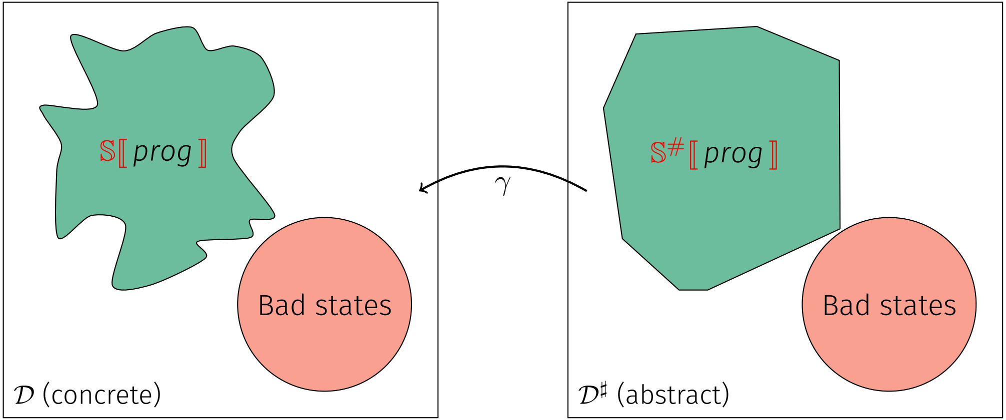

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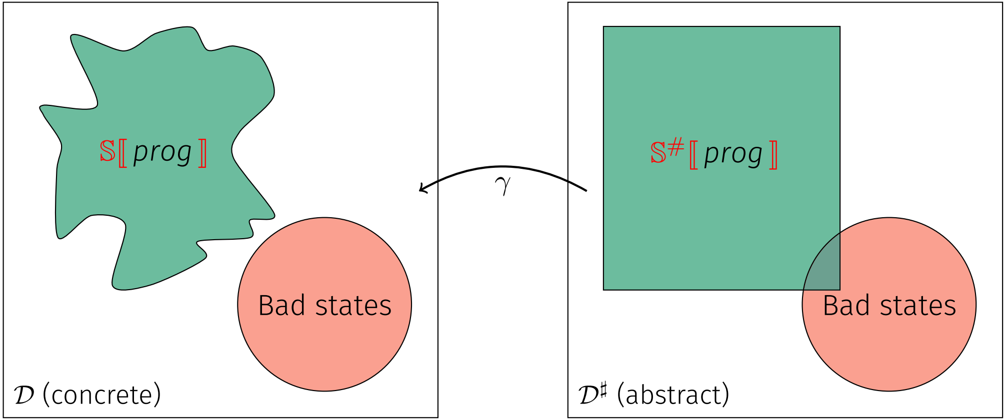

False alarm (Abstraction too coarse)

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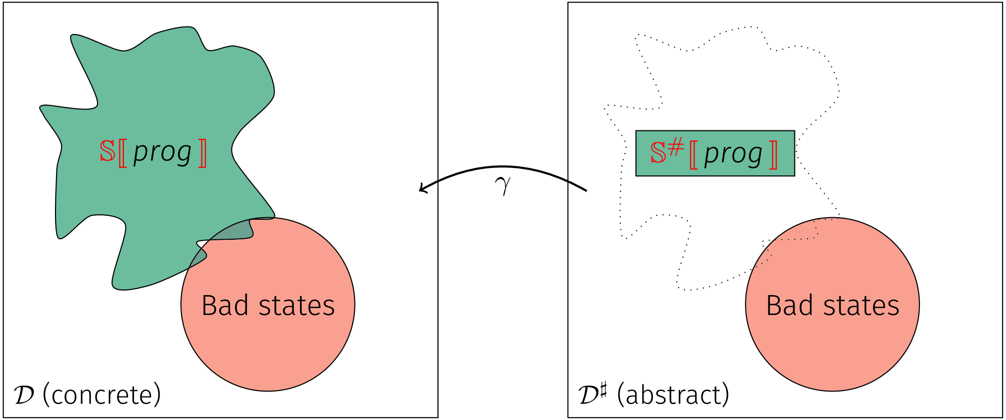

Unsound analysis
(shouldn't happen)

P. Cousot and R. Cousot. "Abstract Interpretation: A Unified Lattice Model for Static Analysis of Programs by Construction or Approximation of Fixpoints". POPL 1977

Critical software certification through static analysis

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Critical software certification through static analysis

Embedded C

- Generated code
- ~~Dynamic allocation~~

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Democratizing static analysis?

- General C software (dynamic allocation, ...)
- Other languages
- Framework to implement analyses

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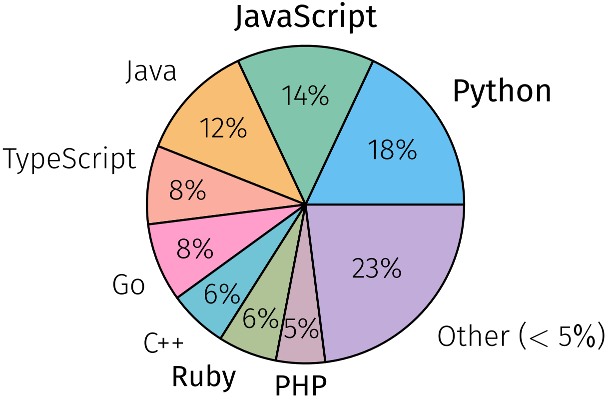
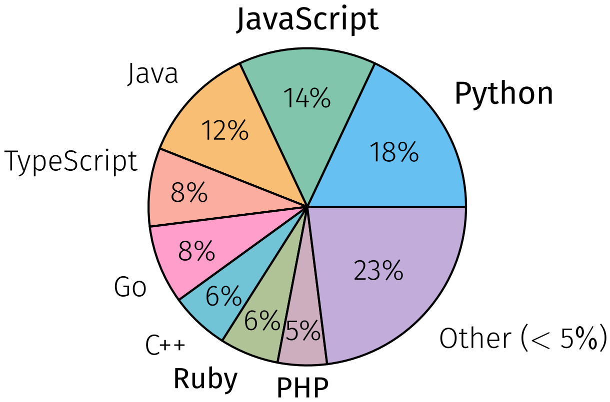
Dynamic programming languages



Most popular languages on GitHub

Dynamic programming languages



Most popular languages on GitHub

New features

- Dynamic typing
- Dynamic object structure

Outline

A Taste of Python

Python's specificities

No standard

- CPython is the reference

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

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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)

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())
```

Barrett, Cassels, Haahr, Moon, Playford, and Withington. "A Monotonic Superclass Linearization for Dylan". OOPSLA 1996

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Exceptions

Exceptions rather than specific values

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

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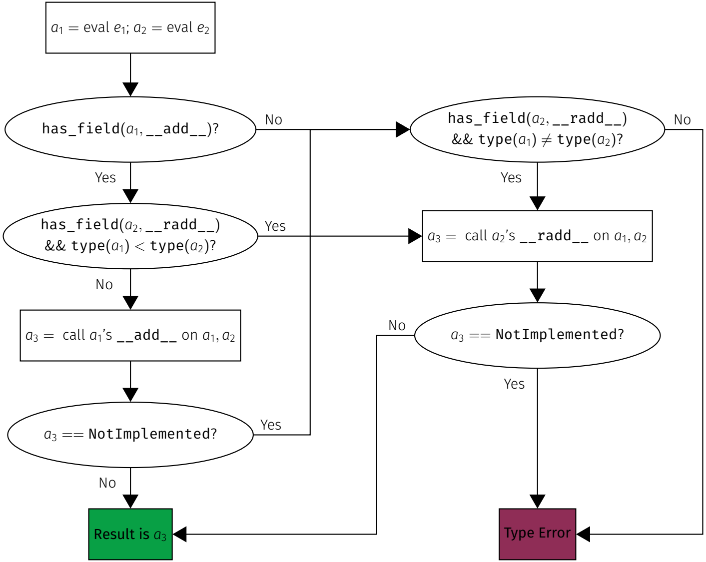
Example Semantics – binary operators



Crazy Python

Custom infix operators

```
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

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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Supported constructs

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Unsupported constructs

- Recursive functions
- `eval`
- Finalizers

Analysis | Domains required

Averaging numbers

```python
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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8  l = [randint(0, 20)
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Proved safe?

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

Searching for a loop invariant (l. 4)

Environment abstraction

$m \mapsto @^\sharp_{\texttt{int}^\sharp} \quad i \mapsto @^\sharp_{\texttt{int}^\sharp}$

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Stateless domains: **list content**,

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Numeric abstraction (intervals)

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

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

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

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Numeric abstraction (polyhedra)

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

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

Averaging tasks

```
1  class Task:
2    def __init__(self, weight):
3      if weight < 0: raise ValueError
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6  def average(l):
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Searching for a loop invariant (l. 4)

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$m \mapsto @^\sharp_{\mathtt{int}^\sharp}$ $\quad i \mapsto @^\sharp_{\mathtt{int}^\sharp}$ $\quad \underline{\mathrm{els}}(l) \mapsto @^\sharp_{\mathtt{Task}}$

$\underline{@^\sharp_{\mathtt{Task}} \cdot \mathtt{weight}} \mapsto @^\sharp_{\mathtt{int}^\sharp}$

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Attributes abstraction

$@^\sharp_{\mathtt{Task}} \mapsto (\{\mathtt{weight}\}, \emptyset)$

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Stateless domains: list content, list length

Environment abstraction

$m \mapsto @^\sharp$ … $@^\sharp_{\texttt{Task}}$

Conclusion

- Different domains depending on the precision
- Use of auxiliary variables (<u>underlined</u>)

$0 \leq i < \underline{\mathrm{len}(l)}$ $\quad 5 \leq \underline{\mathrm{len}(l)} \leq 10$

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Modular Open Platform for Static Analysis[1]

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Modular Open Platform for Static Analysis[1]

- One AST to analyze them all
  - Multilanguage support
  - Expressiveness
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  - Composition
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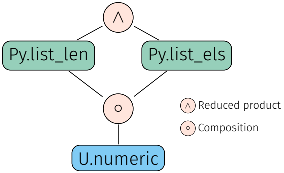

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Mopsa | Dynamic, semantic iterators with delegation

Universal.Iterators.Loops
Matches `while(...){...}` Computes fixpoint using widening

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for(init; cond; incr) body
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↓

C.iterators.loops

Rewrite and analyze recursively

Universal.Iterators.Loops

Matches `while(...){...}`

Computes fixpoint using widening

Mopsa | Dynamic, semantic iterators with delegation

```
for(init; cond; incr) body
```

C.iterators.loops

Rewrite and analyze recursively

```
init;
while(cond) {
  body;
  incr;
}
```

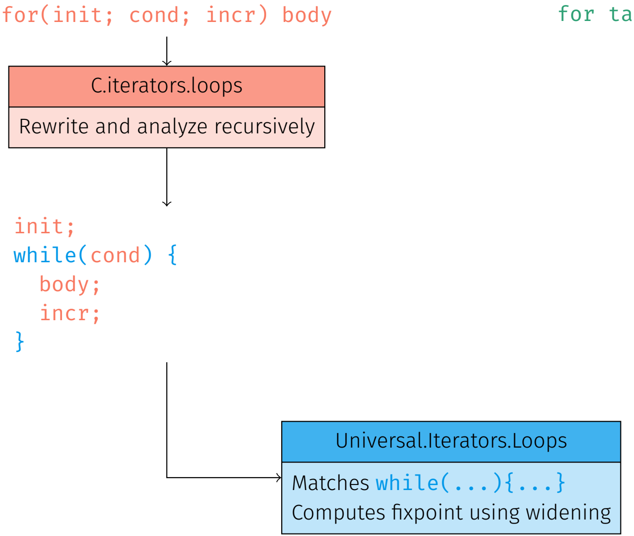
Universal.Iterators.Loops

Matches `while(...){...}`

Computes fixpoint using widening

Mopsa | Dynamic, semantic iterators with delegation

```
for target in iterable: body
```



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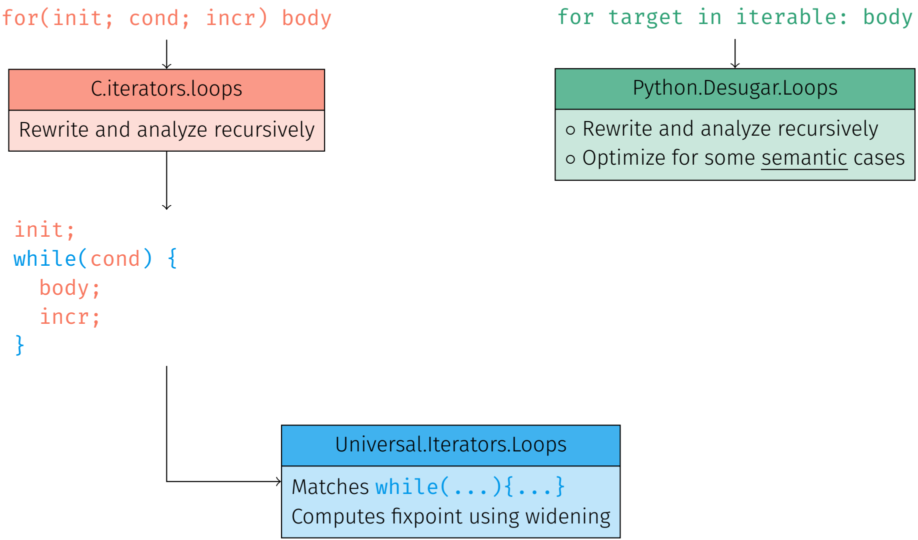

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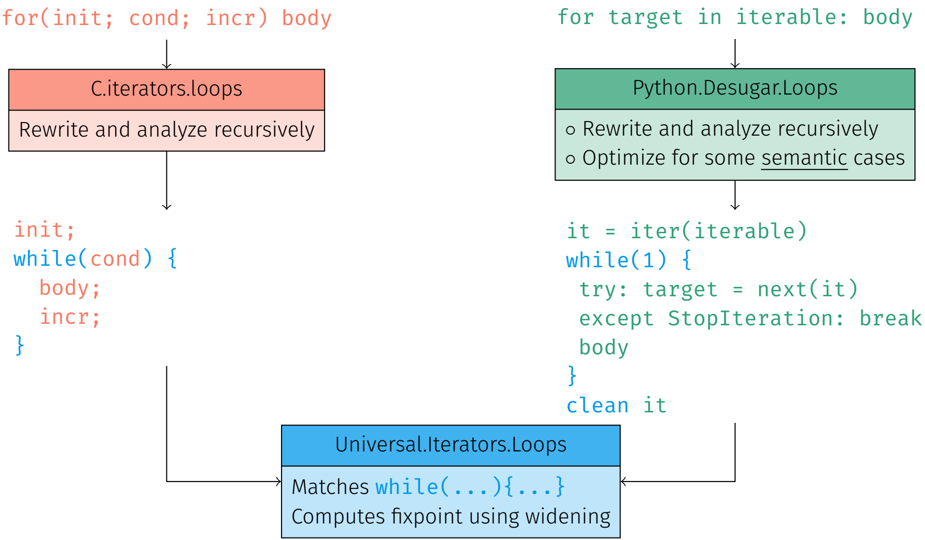
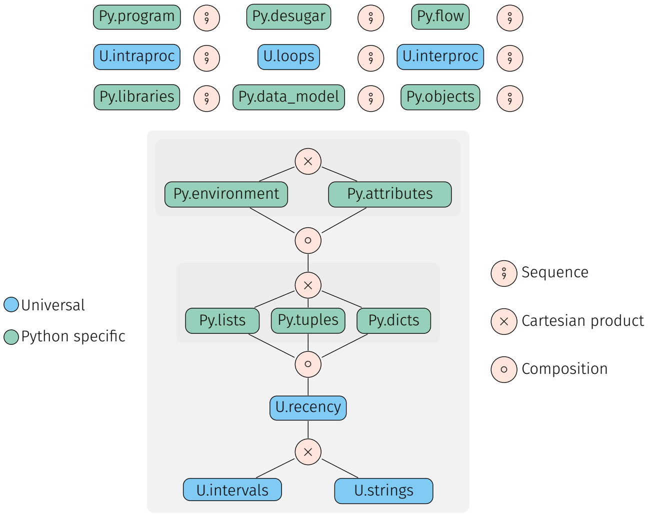


Definition of the Value Analysis



Comparison of the type and value analyses

Averaging tasks

```
1  class Task:
2    def __init__(self, weight):
3      if weight < 0: raise ValueError
4      self.weight = weight
5
6  def average(l):
7    m = 0
8    for i in range(len(l)):
9      m = m + l[i].weight
10   m = m // (i + 1)
11   return m
12
13 l = []
14 for i in range(randint(5, 10)):
15   l.append(Task(randint(0, 20)))
16 m = average(l)
```

Type analysis

- `ValueError` (l. 3)

R. Monat, A. Ouadjaout, and A. Miné. “Value and allocation sensitivity in static Python analyses”. SOAP@PLDI 2020

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Non-relational value analysis

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Relational value analysis

No alarm!

R. Monat, A. Ouadjaout, and A. Miné. "Value and allocation sensitivity in static Python analyses". SOAP@PLDI 2020

Comparison of the type and value analyses (II)

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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richards.py	426	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	**2**	0
unpack_seq.py	458	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0	0
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Heuristic packing and relational analyses

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

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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- Different values (arbitrary-precision integers in Python, bounded in C)
- Different runtime-errors (exceptions in Python)
- Garbage collection

Combining C and Python – example

counter.c

```c
typedef struct {
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} Counter;

static PyObject*
CounterIncr(Counter *self, PyObject *args)
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    self->count += i;
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count.py

```python
from counter import Counter
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How to analyze multilanguage programs?

Type annotations

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class Counter:
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How to analyze multilanguage programs?

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Rewrite into Python code

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```

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

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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

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```python
1  from counter import Counter
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```

```
⚠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
```

High-level idea

Difficulty: shared memory

- Each language may change the memory state, and has a different view of it
- Synchronization? We could perform a full state translation, but
  - the cost would be high in the analysis
  - some abstractions can be shared between Python and C

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State separation ⇝ reduced synchronization

- Observation: structures are directly dereferenceable by one language only
- Switch to other language otherwise (`c.incr()` ⇝ `self->count += 1`)
  Additional hypothesis: C accesses to Python objects through the API
- Synchronization: only when objects change language for the first time
- Mopsa supports shared abstractions

Multilanguage semantics

Concrete definition

- Builds upon the Python and C semantics

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- Builds upon the Python and C semantics
- Defines the API: calls between languages, value conversions
- Boundary functions handling the reduced synchronization

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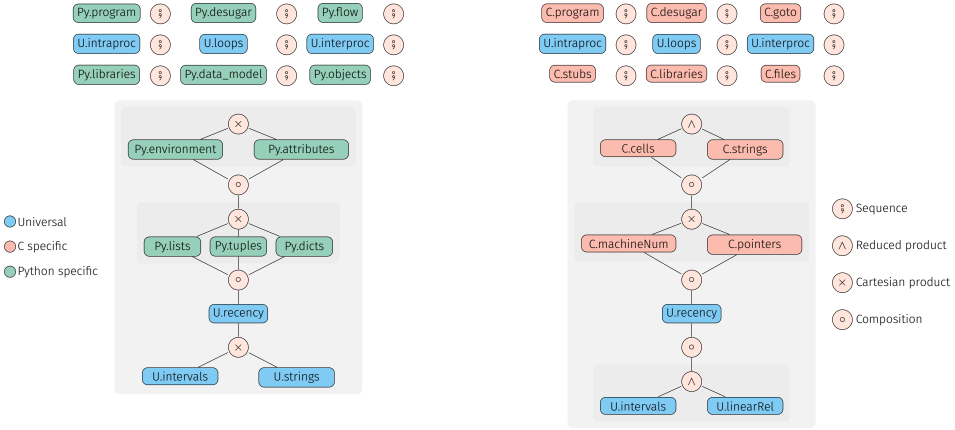
- Garbage collection not handled
- C access to Python objects only through the API (verified by Mopsa)
- Manual modelization from CPython's source code

From distinct Python and C analyses...



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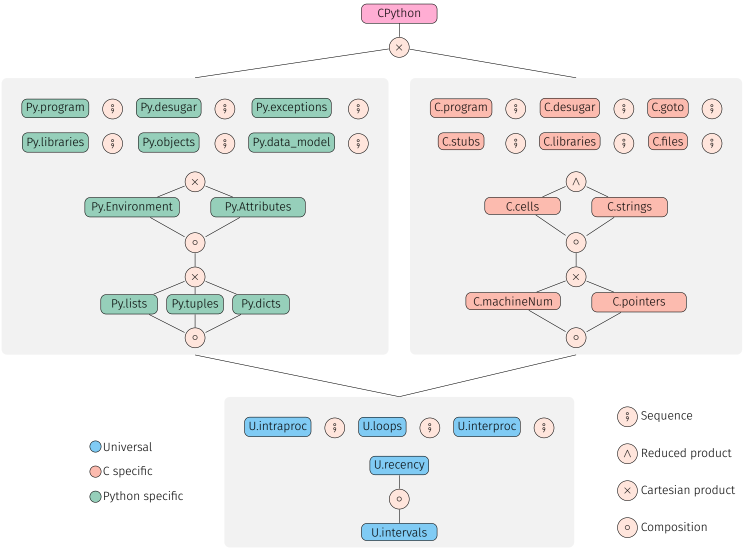

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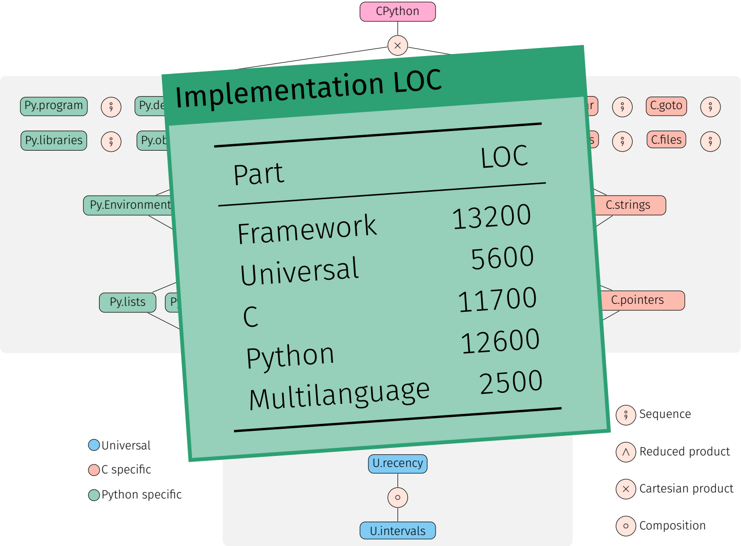

Implementation LOC

Part	LOC
Framework	13200
Universal	5600
C	11700
Python	12600
Multilanguage	2500

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)

Contributions around the static analysis of Python programs

Python's semantics $\leadsto [\![\cdot]\!]_{py}$

- Reverse-engineering CPython (160kLoc C)
- Backlinks to source code (auditability)
- On-paper formalization ($\simeq$ 44 pages)

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- First real multilanguage analysis
- Reuses off-the-shelf Python and C analyses
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Implementation into Mopsa

- Open-source analyzer for C and Python
- Factors abstractions between languages
- Sharing between abstractions

A Modern Compiler for the French Tax Code

Back to the introduction

Research field: formal methods

$\Rightarrow$ Improve confidence in software.

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Personal methodology

Constant back and forth between theory and practice

1. Find interesting bugs, properties or systems to study (GitHub, ...)
2. Theoretical study and solution
3. Implementation and experimental validation (on 1)

Legal implementations

French income tax

- 38M households, 75Md€ of income
- Made public in April 2016 : $\simeq$ 92kLoc M, custom language
- ⚠ Computation not reproducible in 2019

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Trusting the computation?

- Reproducibility of the computation?
- Accurate simulation of tax reforms?
- Compliance with the law, acting as specification?

Example M code

Variable declaration

```
IRNETBIS : calculee primrest = 0 : "IRNET avant bidouille du 8ZI" ;
8ZI : "Impot net apres depart a l'etranger (non residents)" ;
```

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```

Computation rule

```
rule 221220:
application : iliad  ;
IRNETBIS = max(0, IRNETTER -
                  PIR * positif(SEUIL_12 - IRNETTER + PIR)
                      * positif(SEUIL_12 - PIR)
                      * positif_ou_nul(IRNETTER - SEUIL_12));
```

M, briefly

The core of M: **arithmetic expressions** assigned to variables.

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- `undef` value

A formal semantics for M

We reverse-engineered the semantics:

- At first, using the online simulator[2]
- Later, using the private tests DGFiP sent us (August 7, 2019)

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The `undef` value

- Used for: default inputs, runtime errors & missing cases in inline conditionals
- Fun facts: $f + \texttt{undef} = f$, $f \div 0 = 0$, $x[|x| + 1] = \texttt{undef}$, $x[-1] = 0$...

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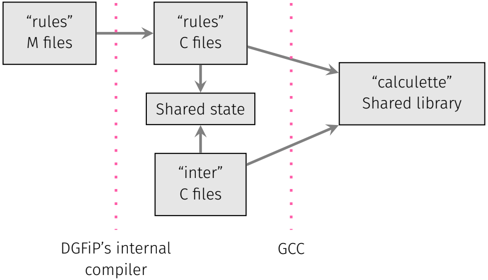
DGFiP’s legacy architecture

After 9 months of negotiations, we’re in!



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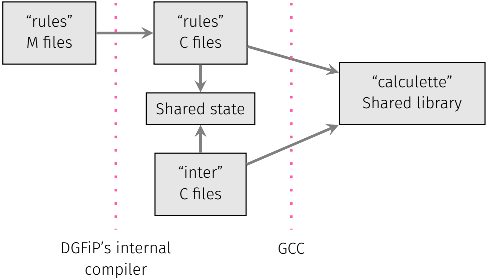

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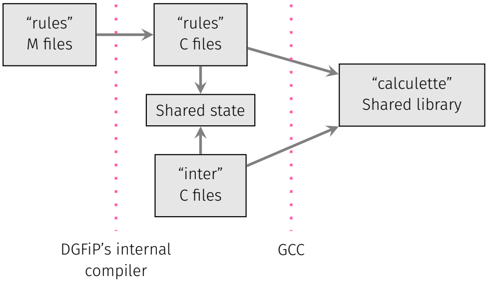

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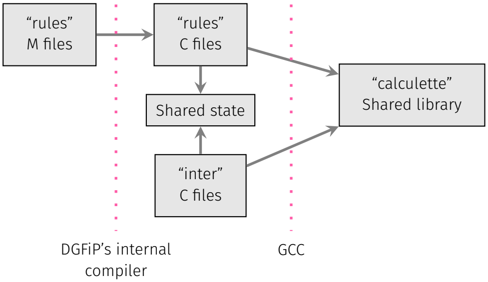

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How to extract the logic of the code?

DSLs to the rescue! Introducing M++

- High-level, no mutable state under the hood
- Tailored for the needs of the "inter" files and DGFiP devs
- 6,000 lines of "inter" C code ⇒ 100 lines of M++

MLANG's architecture

MLANG: written in OCaml, 10k lines of code

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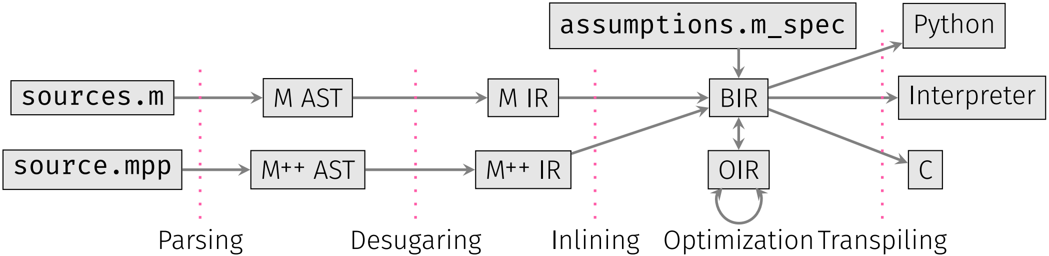

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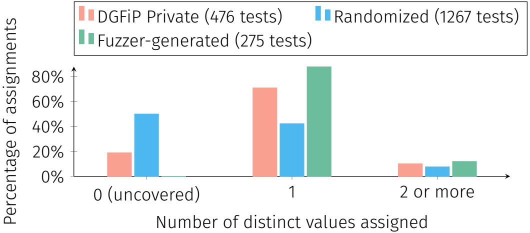

Code optimization

Compiler optimizations

- Global value numbering
- Dead code elimination
- Partial evaluation
- Dataflow defined-ness analysis

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Spec. name	# inputs	# outputs	# instructions	% reduction
All	2,459	10,411	129,683	80.2%
Selected outs	2,459	11	99,922	84.8%
Tests	1,635	646	111,839	83.0%
Simplified	228	11	4,172	99.4%
Basic	3	1	553	99.9%

# of instructions with optimizations disabled (2018 code): 656,020.

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"inter" code (C)	no	**DSL** M++ (6kLoc C $\rightsquigarrow$ 100 M++)
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$\Longrightarrow$ Now reproducible outside DGFiP!

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Interacting with DGFiP

- Long term work: 9 months to access the missing C code
- Pedagogy required: very legal environment

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Transfer to DGFiP!

Ongoing work to bring MLANG at DGFiP.

- 30-day mission between January and August 2022
- Supervision of 3 developers (2 OCamlPro, 1 DGFiP)

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Future DSLs

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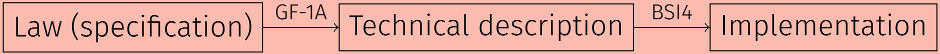

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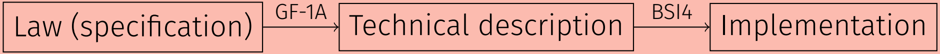

- No structural correspondance
- 2019$\rightsquigarrow$2020 : 30% of 90kLoc M changed

Does the implementation comply with the law?

Catala, another DSL to the rescue

Article D521-1 du code de la sécurité sociale

I - Pour l'application de l'article L. 521-1 , le montant des allocations familiales et de la majoration pour âge prévue à l'article L. 521-3 est défini selon le barème suivant :
1° Lorsque le ménage ou la personne a disposé d'un montant de ressources inférieur ou égal au plafond défini au I de l'article D. 521-3, les taux servant au calcul des allocations familiales sont fixés, en pourcentage de la base mensuelle prévue à l'article L. 551-1, à :
a) 32 % pour le deuxième enfant à charge ;

````
```catala
champ d'application AllocationsFamiliales :
  définition montant_initial_base_deuxième_enfant sous condition
    ressources_ménage ≤€ plafond_I_d521_3
  conséquence égal à
    si nombre de enfants_à_charge_droit_ouvert_prestation_familiale ≥ 2
    alors prestations_familiales.base_mensuelle ×€ 32 %
    sinon 0 €
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- Literal programming
- Default logic
- Participation to dev. team & interdisciplinary meetings
- Future: automated verification for Catala?

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Conclusion

Summary of the contributions

Static analysis of Python programs using C libraries

- Ouadjaout and Miné (LIP6, Sorbonne Université)
- SAS'21, ECOOP'20, VSTTE'19 (invited), *SOAP@PLDI'20* (award), JFLA'21 (fr, tool)
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Looking forward... an important question

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What kind of research for tomorrow's world?

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⚠ Avoiding rebound effect

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- ? Impact?

Looking forward... an important question

What kind of research for tomorrow's world?

- ⚠ Avoiding rebound effect
- ❓ Impact? Difficult to estimate a priori

From Python to the French Tax Code: Applying Formal Methods on Real Systems

Discussion

Interested in internships or PhDs?

Raphaël Monat

SyCoMoRES team

`rmonat.fr`

DI Seminar
22 March 2023

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