APR Team

Mopsa – Static program verification by abstract interpretation

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Overview

- APR Team: themes and activities
- Static analysis by abstract interpretation
  - introduction
  - example analyses developed in APR
  - Mospa: designing a Modular Open Platform for Static Analysis

APR Team

APR: Algorithms, Programs, Resolution

Principles: complementary approaches to safe and efficient software

- Language: design, implementation, automated analysis
- Algorithmic: modeling, complexity analysis, random generation

From theory to practice:

- formal methods: semantics (language) and combinatoric (algorithmic)
- concrete objectives: software prototype, industrial applications

Connections:

- teaching, from introductory programmatic courses
  to research-oriented master-level teaching
- strong link with IRILL (Center for Research and Innovation on Free Software)
- academic and industrial project partners (Airbus, . . .)

APR: a few projects

- Analytic combinatorics for concurrency
  - simulate and analyze large combinatorial models
  - application to generate interleavings to test concurrent systems
  - Arbogen: fast uniform random generator for trees
- Multicore, concurrent, mobile programming
  - parallel algorithms: Graph-GPU
  - session types for web programming ($\pi-$calculus)
- Embedded system programming
  - functional programming on micro-controllers (Ocaml)
  - virtual machine approach and optimisation: OMicrob
  - mixing synchronous and functional programming: OCaLustre
- Static program analysis

  ⋮

Static analysis

Static analysis

Goal: program verification by static analysis

source

```
int search(int* t, int n) {
  int i;
  for (i=0; i<n; i++) {
    if (t[i]) break;
  }
  return t[i];
}
```

$\Longrightarrow$

analysis result

```
int search(int* t, int n) {
  int i;
  for (i=0; i<n; i++) {
    // 0 ≤ i < n
    if (t[i]) break;
  }
  // 0 ≤ i ≤ n ∨ n < 0
  return t[i];
}
```

✓

✗

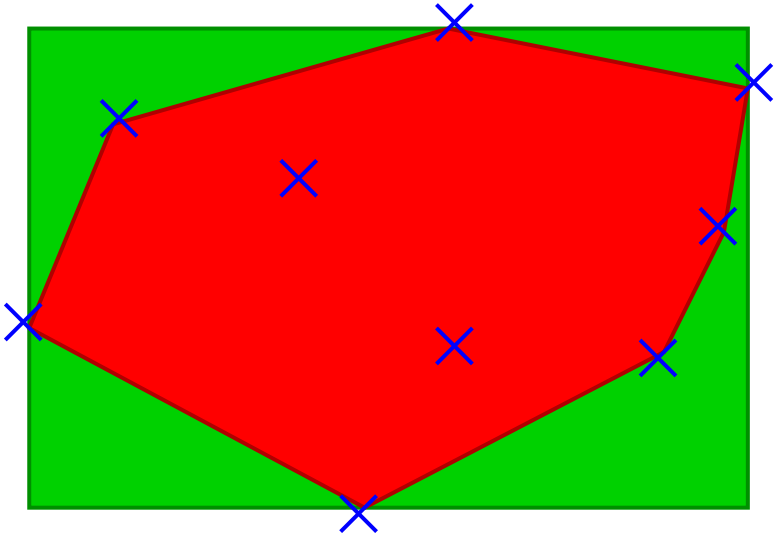
- work directly on the source code
- infer properties on program executions
- automatically (cost effective)
- by constructing dynamically a semantic abstraction of the program
- deduce program correctness or raise alarms
  implicit specification: absence of RTE; or user-defined properties: contracts
- with approximations (efficient, but possible false alarms)
- soundly (no false positive)

Based on the abstract interpretation framework.

Abstract interpretation

Abstract interpretation: theory of the approximation of (program) semantics

Principle: be tractable by reasoning at an abstract level



concrete executions :	$\{(0,3),(5.5,0),(12,7),\ldots\}$	(not computable)
box domain :	$X \in [0,12] \wedge Y \in [0,8]$	(linear cost)
polyhedra domain :	$6X + 11Y \geq 33 \wedge \cdots$	(exponential cost)

Abstract computations

Define an interpretation of atomic statements in the abstract domain.

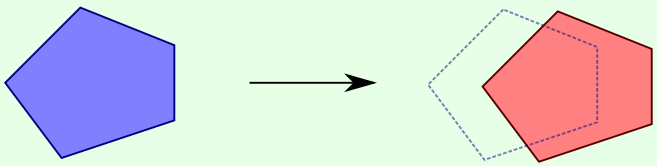
Compose the interpretation to analyze the program.

Example in the polyhedra domain

Assignment:

• `X = X + 1` •

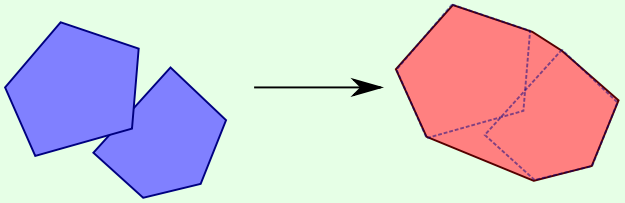
translation



Join after branches:

if ··· **then** ··· • **else** ··· • **fi** •

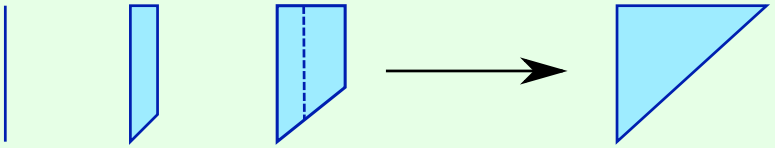
convex hull



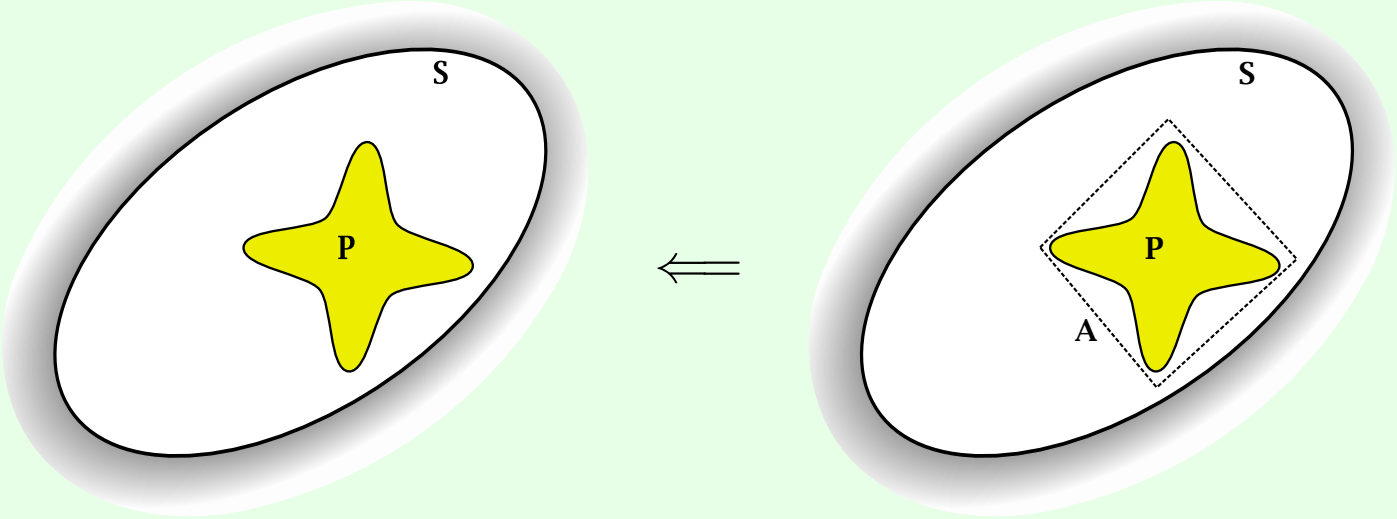
Loop invariants:

while • ··· **do** ··· **done**

iteration with widening



Soundness and precision

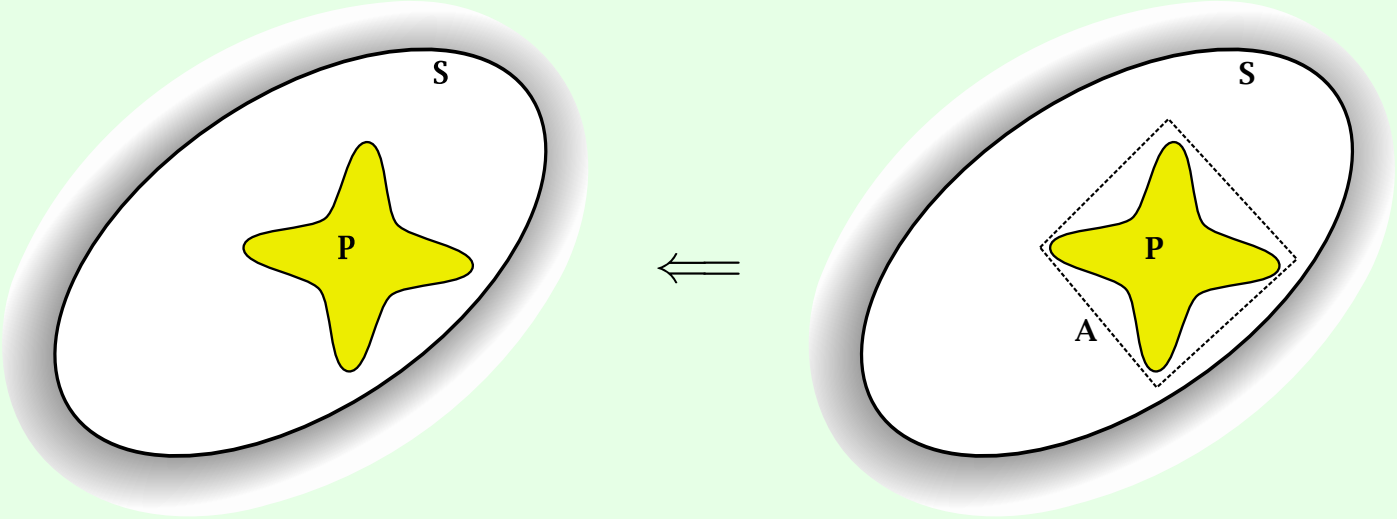


$P \subseteq S$ $\qquad$ $A \subseteq S$

Goal : prove that a program P satisfies its specification S

$\Longrightarrow$ we consider only its abstraction A and check that $A \subseteq S$

Soundness and precision



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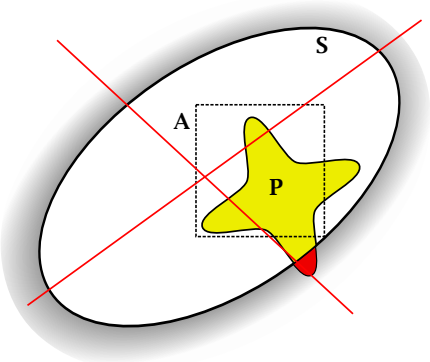
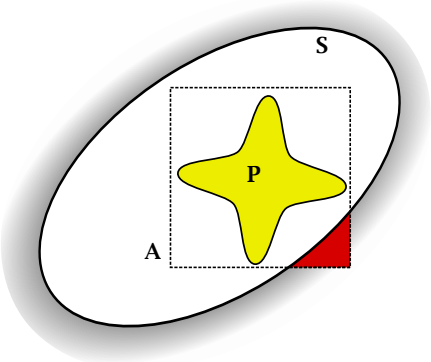


impossible
unsound analysis
where $A \subseteq S$
but $P \not\subseteq A$



undesirable
imprecise analysis
where $A \not\subseteq S$
but $P \subseteq A$

Example projects

APR research in static analysis

Goal : analyze more complex properties, for more general programs, beyond safety analysis of embedded C programs

- analysis of Python programs (A. Fromherz, R. Monat)
- probabilistic analysis of communication protocols (A. Ouadjaout)
- analysis of program patches (D. Delmas)
- analysis of string manipulations in C (M. Journault)
- analysis of TinyOS device drivers (A. Ouadjaout)
- static analyses under weakly memory models (T. Suzanne)
- novel algorithms for numeric domains (A. Marechal)
- combining abstract interpretation and constraint programming (G. Ziat)

Analysis of Python programs

Highly dynamic language, lack of static information in the source
$\Longrightarrow$ advanced semantic static analyses can help !

$$
\begin{array}{l}
\mathbb{E}[\![\, e_1 + e_2 \,]\!](f, \epsilon, \Sigma) \stackrel{\text{def}}{=} \\
\quad \text{let } (f_1, \epsilon_1, \Sigma_1, v_1) = \mathbb{E}[\![\, e_1 \,]\!]\,(f, \epsilon, \Sigma) \text{ in} \\
\quad \text{let } (f_2, \epsilon_2, \Sigma_2, v_2) = \mathbb{E}[\![\, e_2 \,]\!]\,(f_1, \epsilon_1, \Sigma_1) \text{ in} \\
\quad \text{if } \mathit{hasattr}(v_1, \texttt{\_\_add\_\_}, \Sigma_2) \text{ then} \\
\quad\quad \text{let } (f_3, \epsilon_3, \Sigma_3, v_3) = \mathbb{E}[\![\, v_1.\texttt{\_\_add\_\_}(v_2) \,]\!]\,(f_2, \epsilon_2, \Sigma_2) \text{ in} \\
\quad\quad \text{if } v_3 = \texttt{NotImpl} \wedge \mathit{typeof}(v_1) \neq \mathit{typeof}(v_2) \text{ then} \\
\quad\quad\quad \text{if } \mathit{hasattr}(v_2, \texttt{\_\_radd\_\_}, \Sigma_3) \text{ then} \\
\quad\quad\quad\quad \text{let } (f_4, \epsilon_4, \Sigma_4, v_4) = \mathbb{E}[\![\, v_2.\texttt{\_\_radd\_\_}(v_1) \,]\!]\,(f_3, \epsilon_3, \Sigma_3) \text{ in} \\
\quad\quad\quad\quad \text{if } v_4 = \texttt{NotImpl} \text{ then } \texttt{TypeError}(f_4, \epsilon_4, \Sigma_4) \text{ else } (f_4, \epsilon_4, \Sigma_4, v_4) \\
\quad\quad\quad \text{else } \texttt{TypeError}(f_3, \epsilon_3, \Sigma_3) \\
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\quad\quad \text{let } (f_3, \epsilon_3, \Sigma_3, v_3) = \mathbb{E}[\![\, v_2.\texttt{\_\_radd\_\_}(v_1) \,]\!]\,(f_2, \epsilon_2, \Sigma_2) \text{ in} \\
\quad\quad \text{if } v_3 = \texttt{NotImpl} \text{ then } \texttt{TypeError}(f_3, \epsilon_3, \Sigma_3) \text{ else } (f_3, \epsilon_3, \Sigma_3, v_3) \\
\quad \text{else } \texttt{TypeError}(f_2, \epsilon_2, \Sigma_2)
\end{array}
$$

```
def gen():
  i =0
  while i < 10:
    i += 1
    yield i

def f():
  b = gen()
  j =0
  while j < 5:
    j += 1
    a = b.__next__()
```

- complex semantics of operators
- type-based case analysis

- complex control (generators)
- continuation-based semantics

Python analyses :

- formal semantic of Python 3
- value-analysis, uncaught exceptions (A. Fromherz)
- type-based modular analysis (R. Monat)

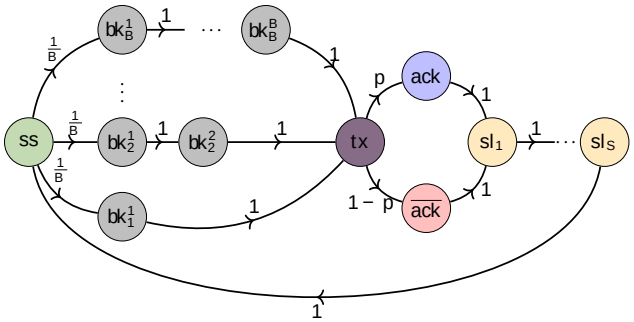
Remaining challenges:

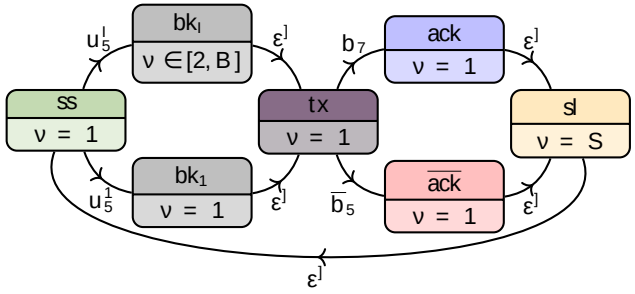
- large library and built-ins
- meta-programming introspection, dynamic classes
- eval

Analysis of probabilistic properties

Communication protocols in a stochastic environment (A. Ouadjaout)

```
int n = 0, a = 0;
while (1) {
    data = sense();
    sleep(uniform(1, B)); // Uniform backoff
    if (unicast(data)) a++; // Transmission with ack
    n++;
    sleep(S) // Save energy
}
```





- concrete Markov chain model for one parameter value
- inferred abstract Markov chain with symbolic parameters B, S

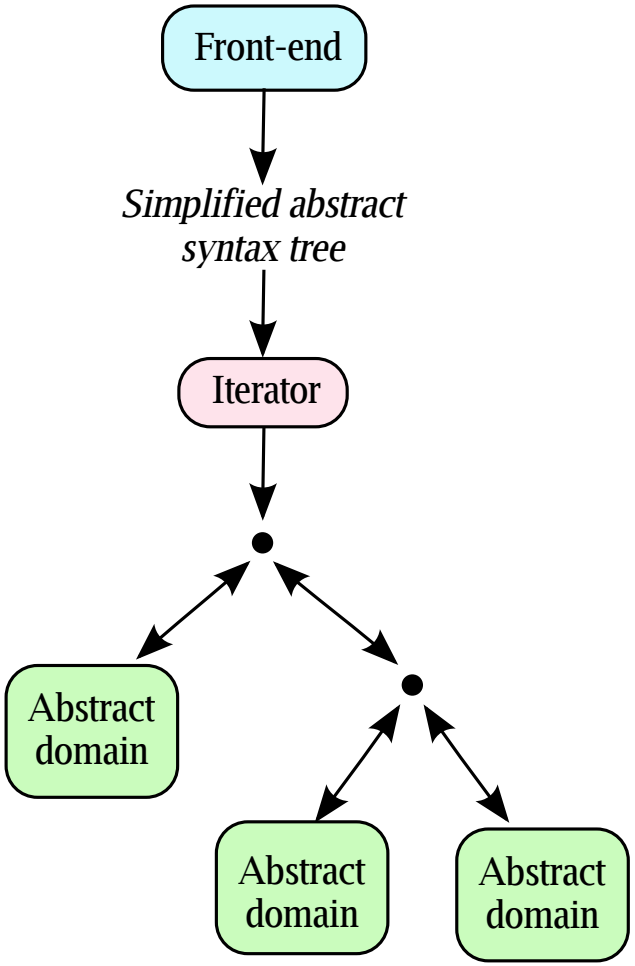
- infer automatically an abstract Markov chain from the program source
- compute quantitative properties: *goodput*
  safe symbolic bounds, as a function of B and S

Modular Platform for Static Analysis

Beyond classic analyzer design

A classic analyzer (Astrée, Frama-C) has:

- a front-end
- a simplified target analysis language
- an iterator
- a tree-structure combination of abstractions with layered abstraction signatures



Limitations:

- static simplifications in the front-end criple precision before the analysis
- restrictions to domain composition and domain reuse

Mopsa characteristics

A novel static analysis platform in construction:

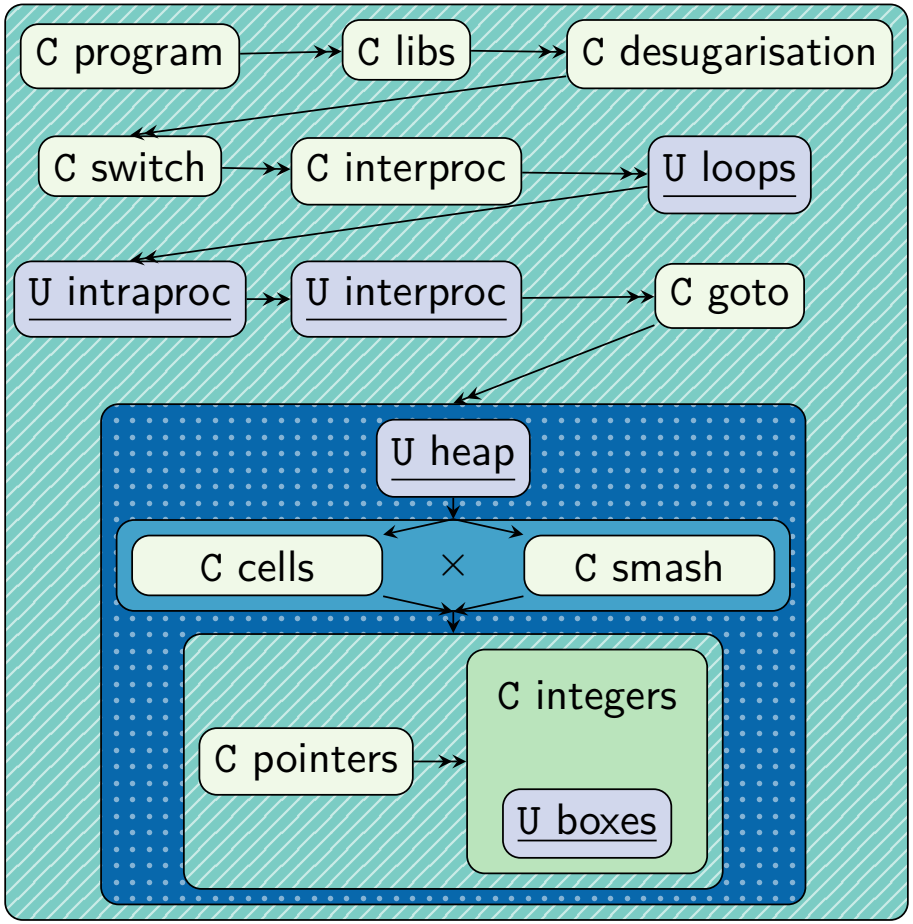
- a single extensible common AST to represent
  - each source language faithfully (C, Python)
  - simplified intermediate languages (numeric fragment, structure-free, etc.)
- generalized view of abstract domains
  - obey a common signature
  - represent partial functions (gather environments over different variables)
  - iterators over AST fragments are abstract domains
  - domains can dynamically rewrite expressions (delegation to other domains)
  - abstract state can be shared by several parent domain (DAG-organisation instead of tree)
- domain composition with inter-domain communication (reduced product, disjoint union)

$\Longrightarrow$ engineering and formalization effort

OCaml implementation, released as open-source soon (framework + C)

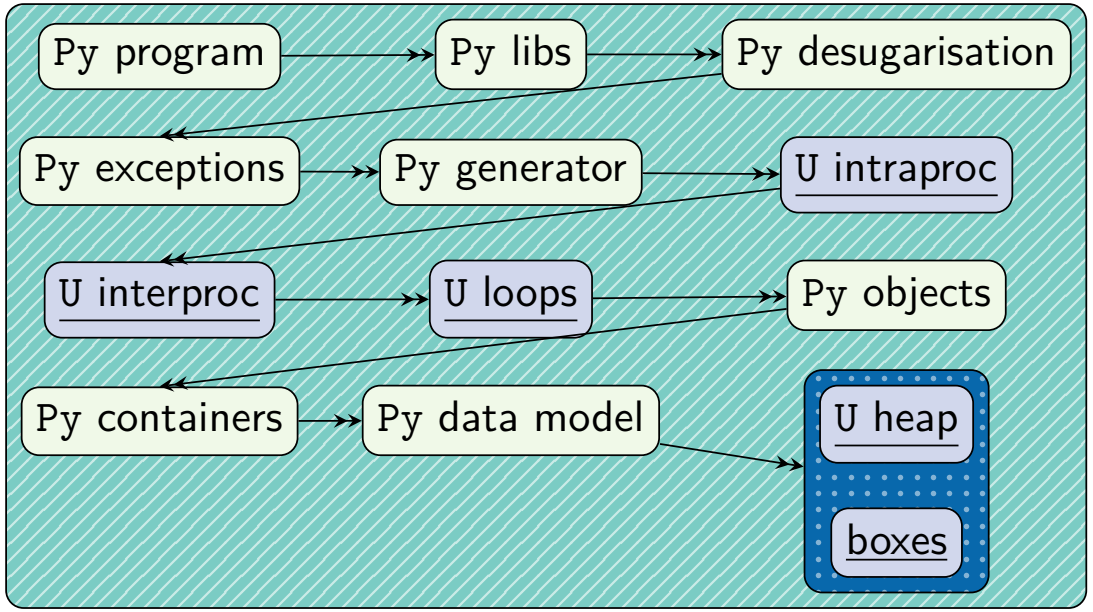
Goal: make analyzer design simpler and more effective.

Example: C value analyzer



Status: analysis of Juliet tests, analysis of coreutils in progress

Example: Python value analyzer



Status: analysis of a few regressions tests from Python distribution

Example: stub contract language

- inspired from ACSL
- target stub modeling (not functional verification)
- interpret formulas in abstract domains
  $\Longrightarrow$ domain dedicated to quantified formulas (strings, arrays)
- modeling of resources (memory, file descriptors, etc.)

open

```
/*$
 * requires: exists int i in [0, size(__file) - 1]: __file[i] == 0;
 *
 * case "success":
 *   local:   void* fd = new FileDescriptor;
 *   ensures: return == (int)fd;
 *
 * case "failure":
 *   assigns: _errno;
 *   ensures: return == -1;
 */
int open (const char *__file, int __oflag, ...);
```