MOPSA

Multilingual Static Analysis for Program Verification using Abstract Interpretation

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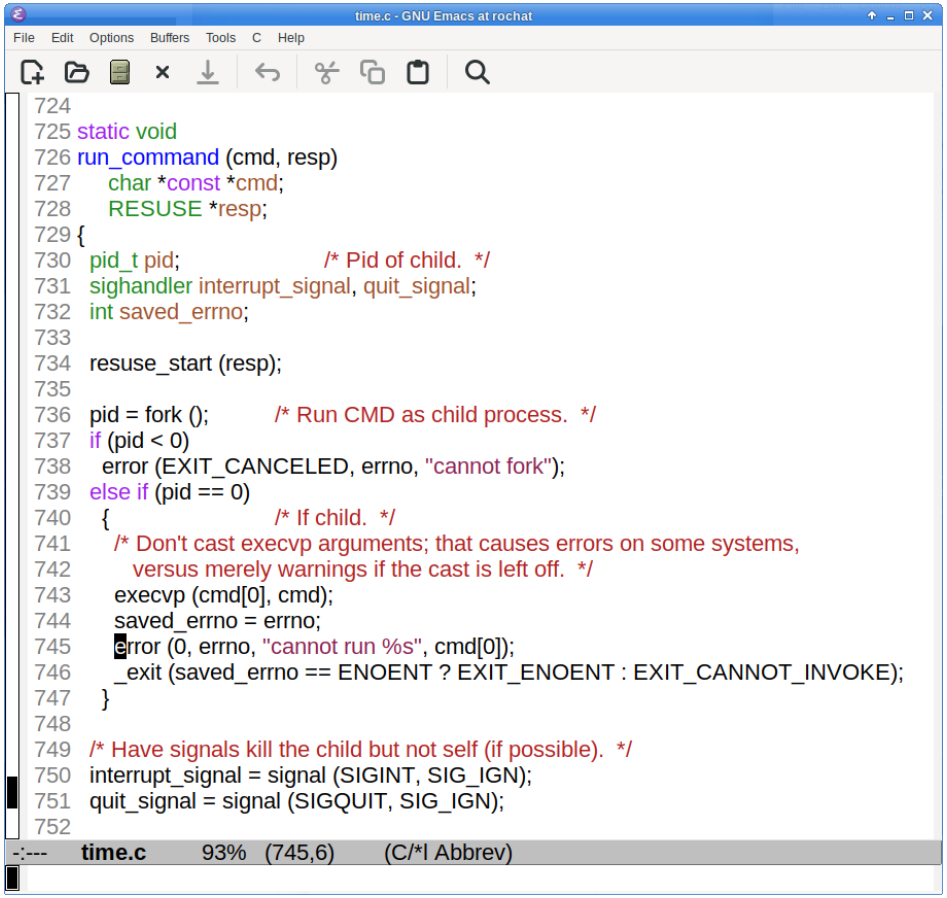
Program verification by static analysis



- analyze source code at compile time, without executing it
- fully automatic (no annotation, no interaction), moderately efficient
- report on non-functional correctness and assertion violations
  run-time errors, CWE, coding guidelines, etc.

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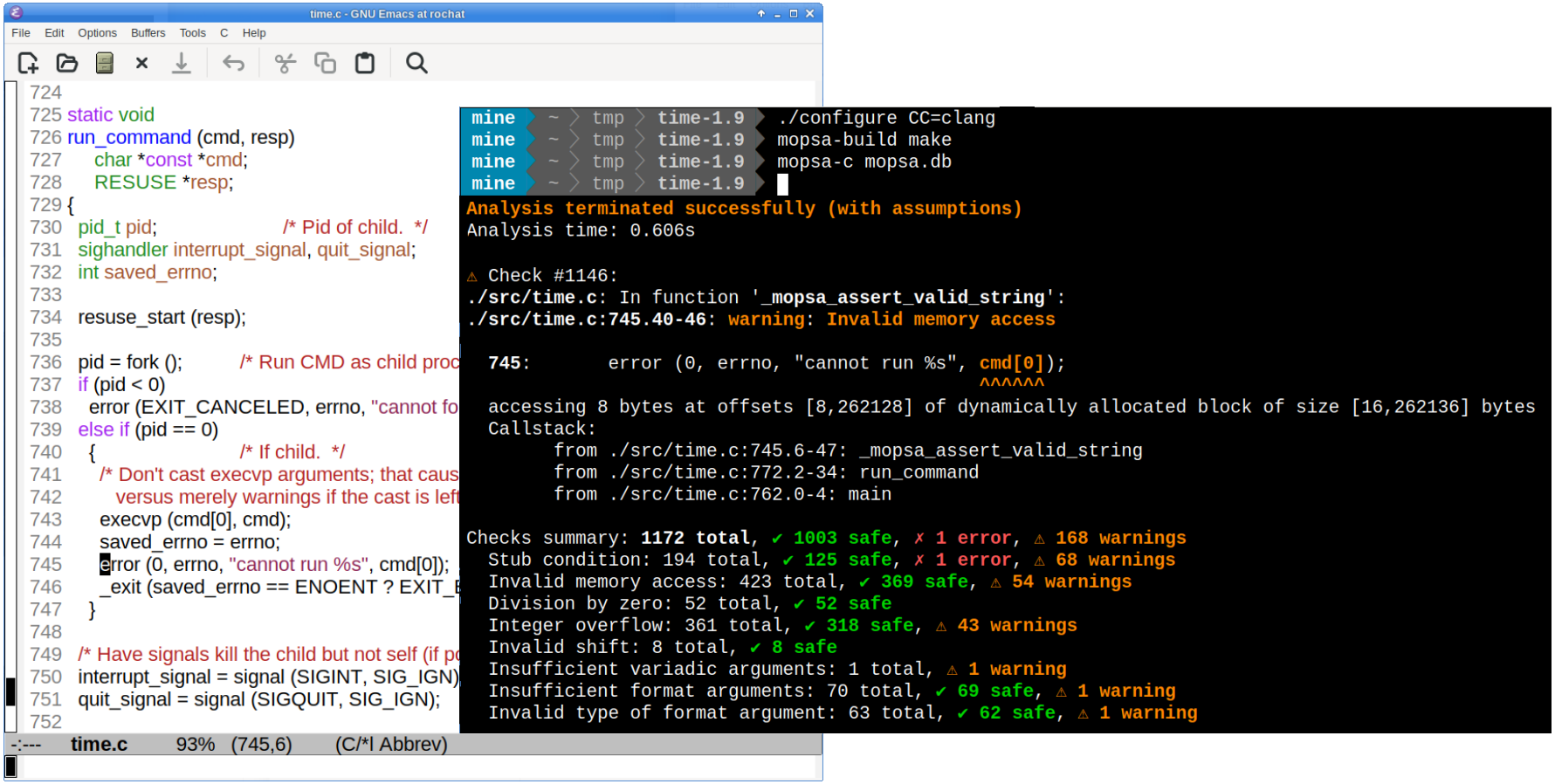

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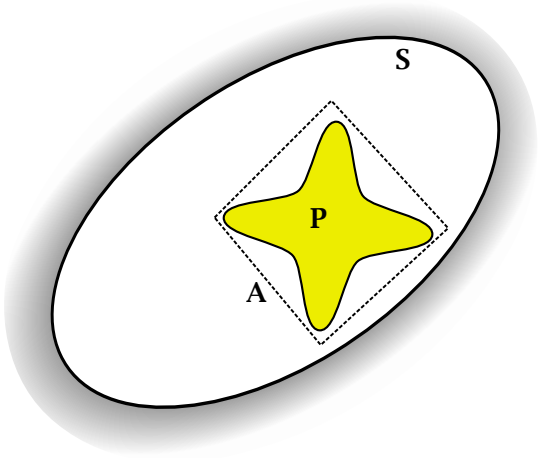
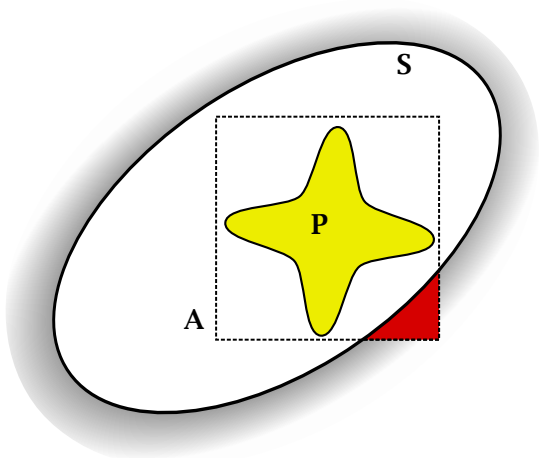
Sound semantic static analysis



sound and precise analysis



false alarm

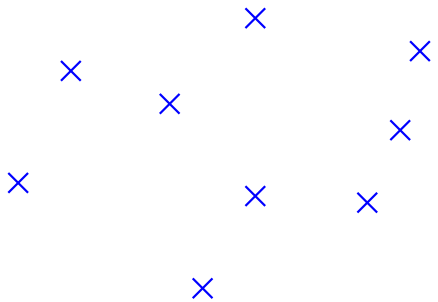
- compute an over-approximation A of reachable program states P and compare to a specification S
- $P \subseteq A$ by construction, guaranteed by abstract interpretation theory
- $A \subseteq S$: no bad state found $\Longrightarrow$ guarantee the absence of error!
- $A \not\subseteq S$: bad state found $\Longrightarrow$ inconclusive (true or false alarm)

A formal method sound and incomplete for the proof of absence of errors

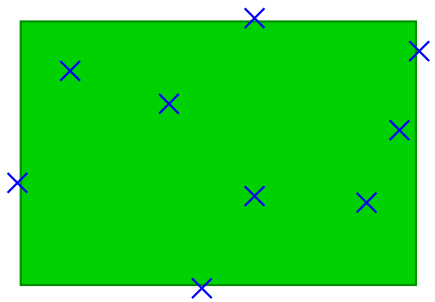
$\neq$ SAST, linters, but also $\neq$ model-checkers, deductive verification, theorem provers

Abstract domains:

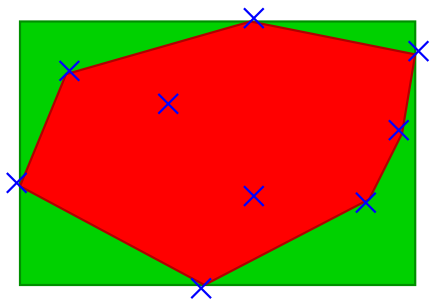
- computable, efficient symbolic representations of reachable states
  $\Longrightarrow$ non-representable sets are over-approximated



concrete memory states



box abstraction



polyhedral abstraction
relational abstraction

Abstract Interpretation

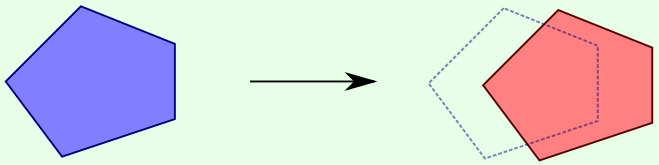
Efficiently computing over-approximations

Abstract domains:

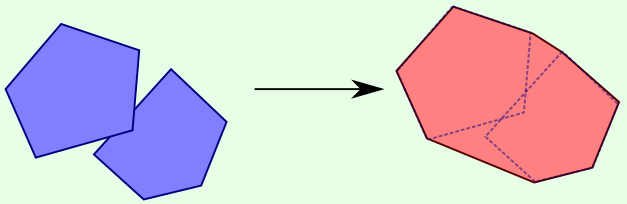
- computable, efficient semantic operators in the abstract world
  with soundness proof
- iterators traverse the program (CFG or AST)

Example: Polyhedra operations

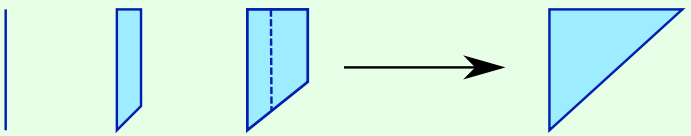
Assignments
• `X ← X + 1` •
translation



Branches: join
if ··· **then** ··· • **else** ··· • **fi** •
convex hull



Loops: inductive invariants
while • ··· **do** ··· **done**
iteration with widening ▽



MOPSA

MOPSA

Modular Open Platform for Static Analysis

Goal: open-source static analysis platform

- for research and education in abstract interpretation
- easy to extend for new languages and new properties
- develop, test, reuse abstractions
- open-source (LGPL)

Contributors

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https://gitlab.com/mopsa/mopsa-analyzer

MOPSA characteristics

Some classic aspects:

- whole-program forward abstract interpretation
- by induction on the AST
- in a collection of communicating abstract domains, sound by design
- analyze run-time errors in C programs

More original aspects:

- new languages: Python, OCaml
- multi-language: programs mixing C and Python
- new properties: non-regression for patches, endianess portability, exploitability, inferring counter examples
- experiments in new analysis engineering and architecture...
- academic implementation! not industrial-scale! various levels of maturity!

Feature: Extensible syntax tree for multiple languages

Classic design: common intermediate representation (JVM, LLVM, Clight,...)

- ✔ low-level: few and simple language constructs
- ✗ loss of high-level information and structure
- ✔ maximum sharing of abstract domains, easily retargetable (?)
- ✗ ...maybe not, if the language is too widely different! (Python?)

MOPSA design: extensible AST

- ✔ preserve the original AST of each source language
- ✔ and relevant fragments supported by well-known domains
  e.g., scalar fragment, pointer-free fragment, integer arithmetic
- ✔ translation is dynamic, more power (exploit abstract information)
- ✗ less efficient
- ✗ hard to keep track of sub-languages, possible match failures at run-rime

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Feature: Distributed iterators and delegation

```
type stmt_kind += S_while of expr * stmt
type stmt_kind += S_c_for of expr * expr * expr * stmt
type stmt_kind += S_py_for of expr * expr * stmt * stmt
```

simple loops: `Universal.iterators.loops`

- matches `S_while`
- computes a fixpoint with acceleration ∇

C loops: `C.iterators.loops`

- matches `S_c_for (init, cond, incr, body)`
- rewrite into `S_while`
- and call interpreter recursively

```
init;
while (cond) {
  body;
  incr;
}
del init;
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Python loops: `Python.desugar.loops`

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- optimize simpler cases based on dynamic types (e.g., ranges)
- and call interpreter recursively

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it = iter(iterable);
while (1) {
  try:  target = next(it);
  except:  StopIteration:  break;
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In MOPSA, iterators are just abstract domains... without internal abstract state

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Feature: Dynamic expression rewriting with case analysis

Flexible, modular way for domains to communicate:

- rewrite (part of) expressions, introduce new variables (embed abstractions)
- delegate to other domains (unaware of other abstractions, decoupling)
- possible perform case analysis with disjunctions (split the abstract state)

Example: string length domain

Abstracts character array a as $P_a : a[v_a] = 0 \wedge (\forall k \in [0, v_a[: a[k] \neq 0)$

- maintain internally a map $a \mapsto P_a$
- introduce an integer variable v_a for each P_a
- rewrite a sub-expression $a[i] == 0$ in abstract element $X^\sharp$ into a disjunction:
  - $(0, \mathbb{S}[\![i < v_a]\!] X^\sharp)$
  - $(1, \mathbb{S}[\![i = v_a]\!] X^\sharp)$
  - $([0, 1], \mathbb{S}[\![i > v_a]\!] X^\sharp)$

  keep some relationality between i, $a[i]$, and v_a
- $\mathbb{S}[\![i < v_a]\!]$, etc. are handled by (relational) numeric abstract domains

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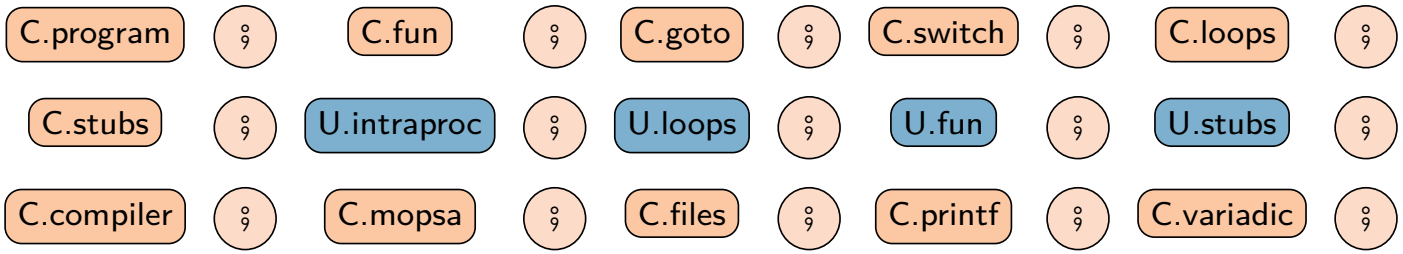
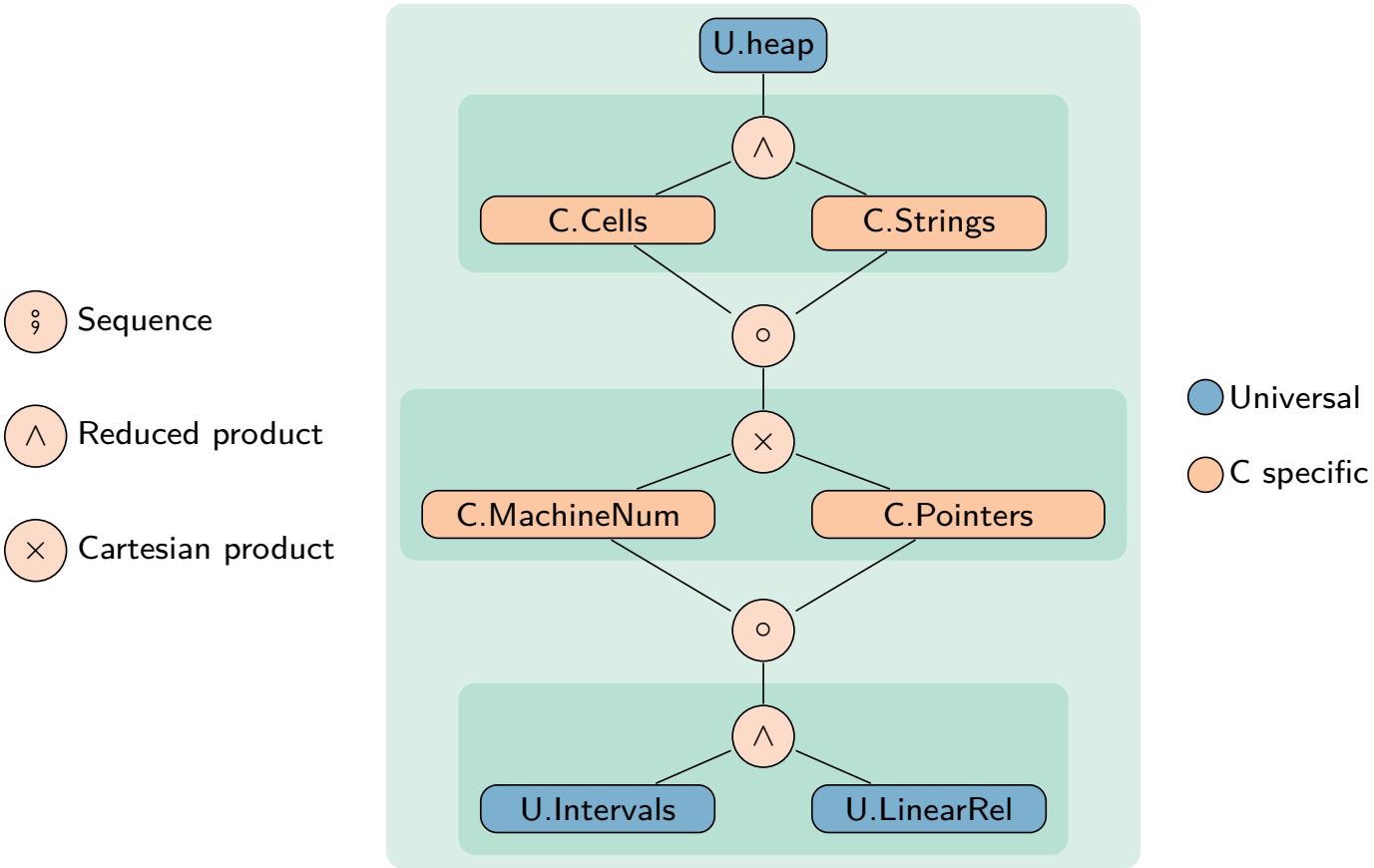
Example: Domains for a C analysis





Modeling C libraries

Requirement

For soundness, we need the C source or a model of every function called

stub for 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;
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int open (const char *__file, int __oflag, ...);
```

- logic-based contract language, but with C expressions (sweet spot)
- stubs are executed at each call (not a specification to verify)
- for MOPSA: just another language (delegation, rewriting, etc.)
  - add abstract semantic operators for $\forall$, $\exists$, etc.
  - general notion of resources (generalizes dynamic memory allocation)

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C benchmarks: Juliet

Experiments

CWE	Lines	Time (h:m:s)	✅	⚠
Stack-based Buffer Overflow	234k	00:59:12	89%	11%
Heap-based Buffer Overflow	174k	00:37:12	86%	14%
Buffer Underwrite	93k	00:18:28	86%	14%
Buffer Over-read	75k	00:14:45	85%	15%
Buffer Under-read	89k	00:18:26	87%	13%
Integer Overflow	440k	01:24:47	52%	48%
Integer Underflow	340k	01:02:27	55%	45%
Divide By Zero	109k	00:13:17	55%	45%
Double Free	17k	00:04:21	100%	0%
Use After Free	14k	00:02:40	100%	0%
Illegal Pointer Subtraction	1k	00:00:24	100%	0%
NULL Pointer Dereference	21k	00:04:53	100%	0%

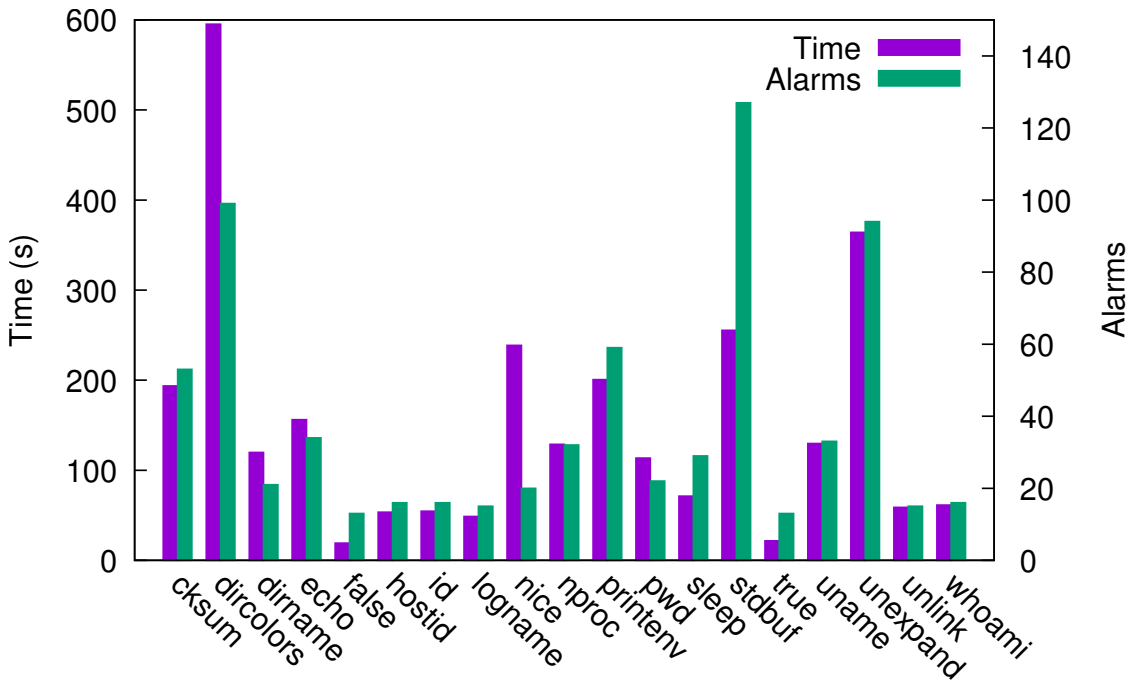
Analyzed 12 CWEs (13,261 tests) from NIST Juliet v1.3
each test comes with a good and a bad version

- ✅ good case safe **and** 1 error in bad case.
- ⚠ good case unsafe **or** many errors in bad case.

for all tests, the bad case reports an error (sound)

[with A. Ouadjaout @ SAS'20]

C benchmarks: Coreutils



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- `main` is called with a symbolic string array `argv` of arbitrary size

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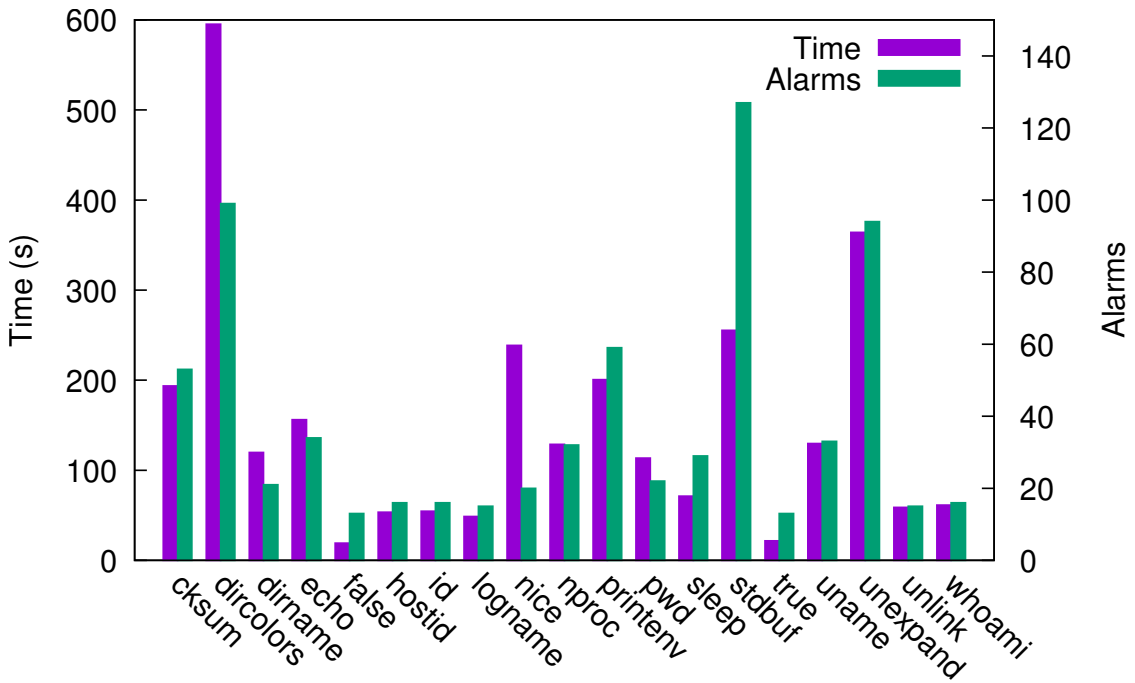

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SV-COMP 2024 competition

1st place for Software Systems category !

Challenges in Python analysis

```
def f(a, b):
  return a + b
```

$$
\begin{aligned}
&\mathbb{E}[\![\, e_1 + e_2 \,]\!](f, \epsilon, \Sigma) \overset{\text{def}}{=} \\
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- control-flow very dependent on the dynamic type

  $\Rightarrow$ a precise flow- and context-sensitive value analysis is necessary!

- complex language to formalize!

  using a functional big-step semantics, close to the abstract interpreter implementation

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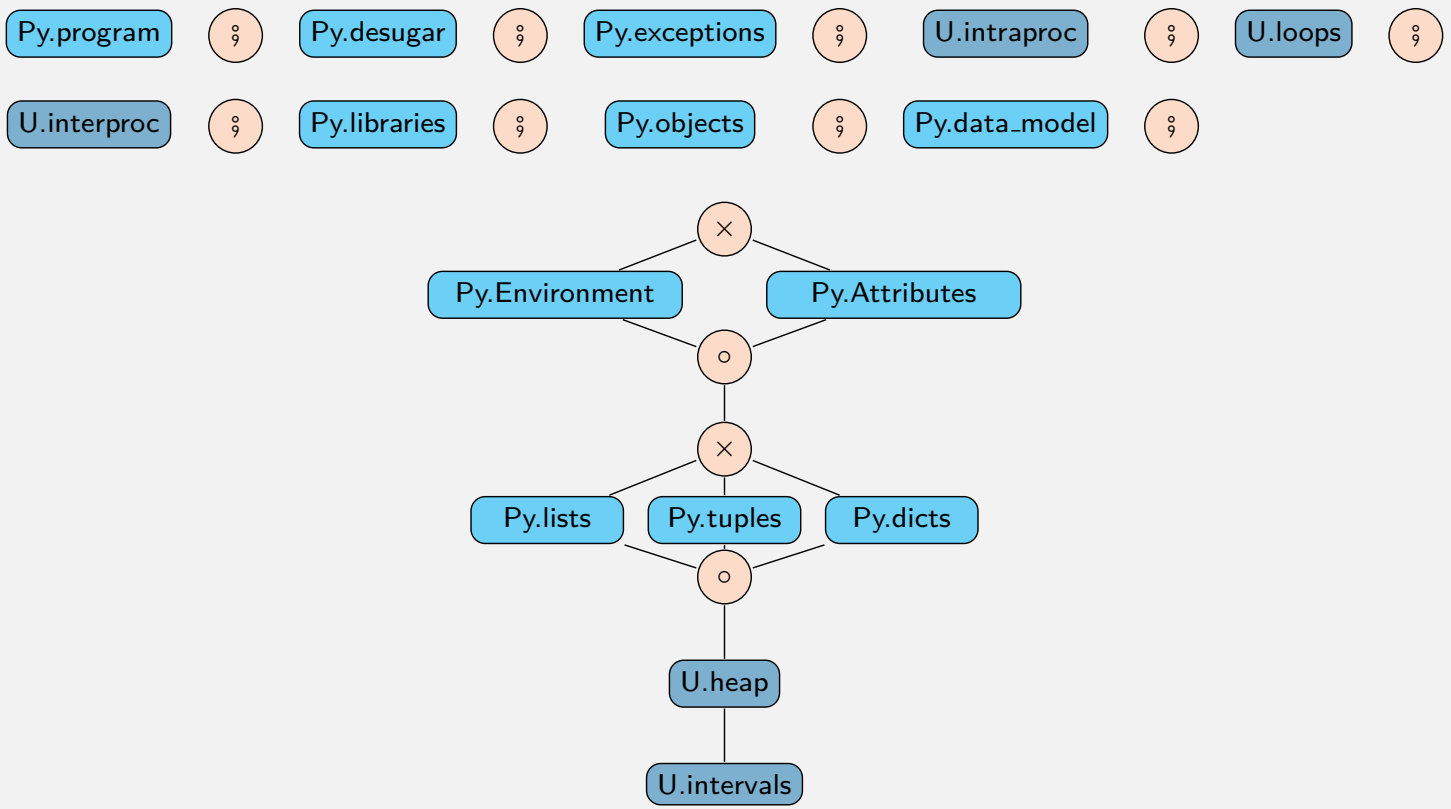
Domains for Python value analysis



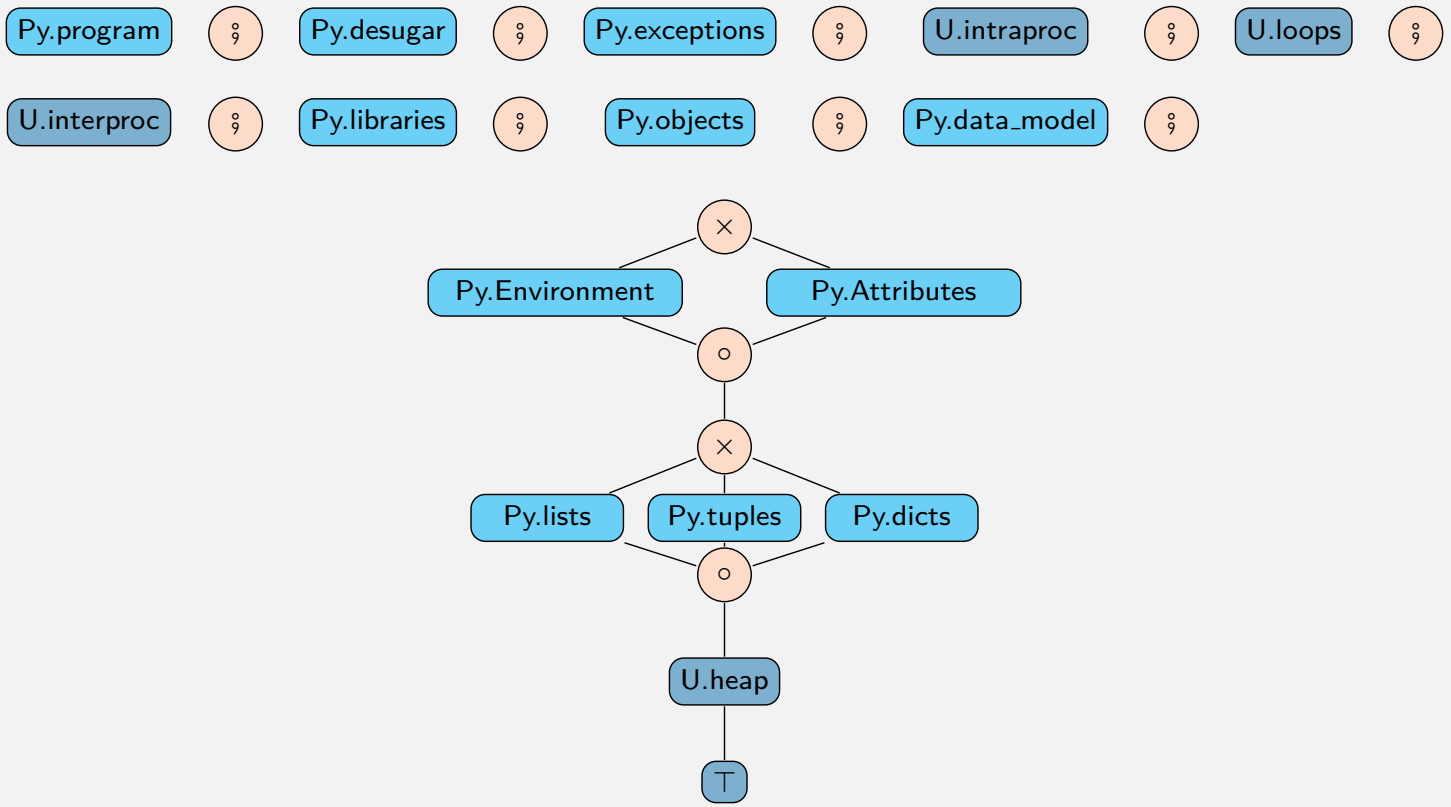
Example Python domain: Lists

- smash each list contents into a single "summary" variable
- keep the list length in a numeric variable

Application : analyze small programs (a few 100s of lines, few dependencies)

[with A. Fromherz & R. Monat @ SOAP'20, ECOOP'20]

Domains for Python type analysis



a type analysis is also easy to construct!

[with R. Monat @ SOAP'20, ECOOP'20]

Programs mixing C and Python

Python counter class in C

```
typedef struct {
  PyObject_HEAD;
  int counter;
} Counter;

static PyObject*
CounterIncr(Counter *self, PyObject *args) {
  int i = 1;
  if (!PyArg_ParseTuple(args, "|i", &i))
    return NULL;
  self->counter += i;
  Py_RETURN_NONE;
}

static PyObject* CounterGet(Counter *self) {
  return Py_BuildValue("i", self->counter);
}
```

Python client

```
from counter import Counter
from random import randrange

c = Counter()
power = randrange(128)
c.incr(2**power-1)
c.incr()
r = c.get()
```

what can go wrong?

- power ≤ 30: r $= 2^{\text{power}}$
- power $= 31$: r $= 2^{-31}$: C overflow (silent wrap-around)
- power $\in [32, 62]$: Python `OverflowError` (overflow on int)
- power ≥ 63: Python `OverflowError` (overflow on long)

Programs mixing C and Python

Python counter class in C

```
typedef struct {
  PyObject_HEAD;
  int counter;
} Counter;

static PyObject*
CounterIncr(Counter *self, PyObject *args) {
  int i = 1;
  if (!PyArg_ParseTuple(args, "|i", &i))
    return NULL;
  self->counter += i;
  Py_RETURN_NONE;
}

static PyObject* CounterGet(Counter *self) {
  return Py_BuildValue("i", self->counter);
}
```

Python client

```
from counter import Counter
from random import randrange

c = Counter()
power = randrange(128)
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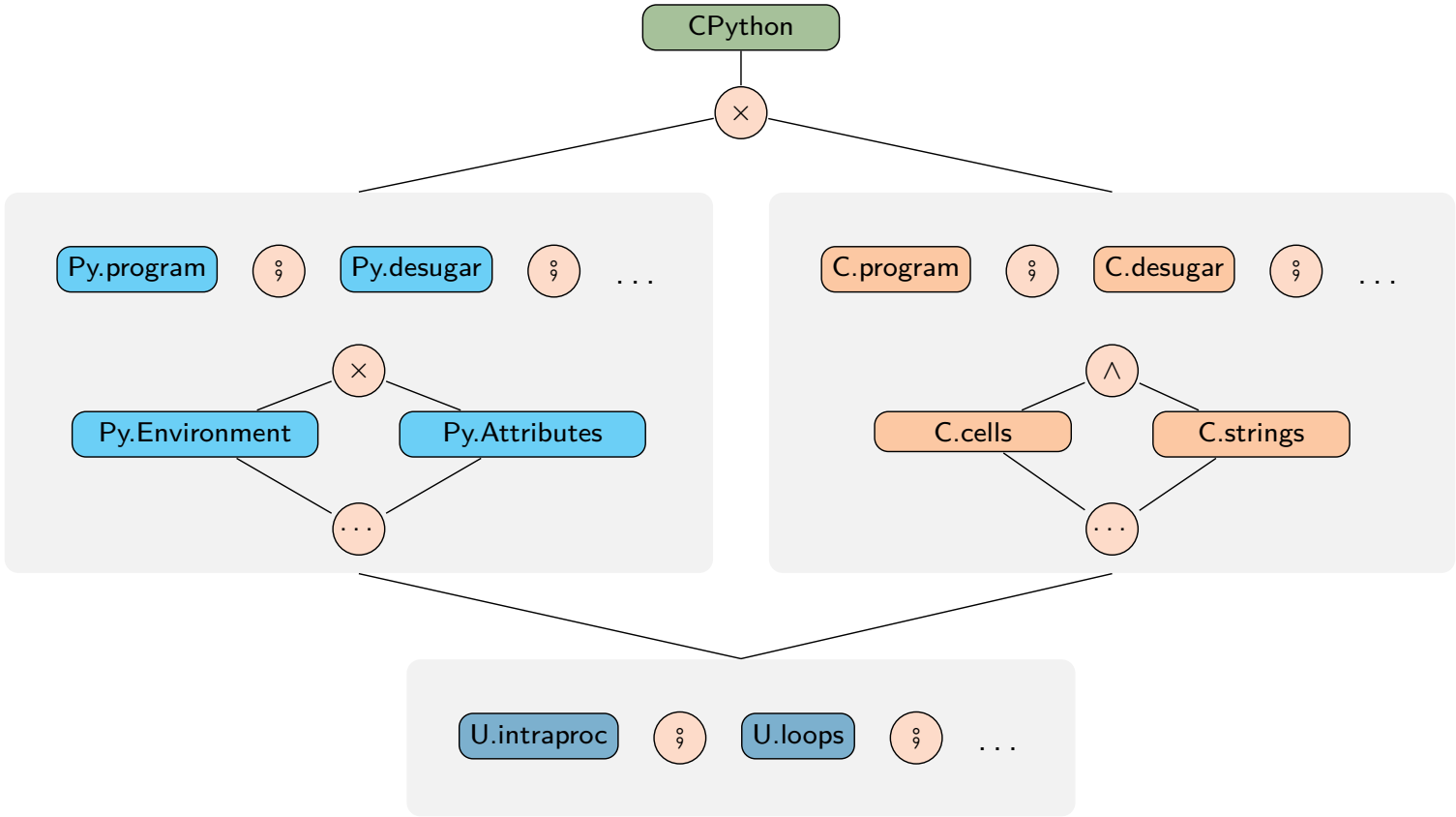
Domains for a C–Python value analysis



Analyze an AST containing both Python and C sources using

- Python domains: for Python code (some CPython API calls are translated to Python instructions)
- C domains: for C code (includes part of CPython implementation in C)
- CPython domain: translate objects between shared C and Python heaps with complementary views (boundary functions)

Application: small C libraries with Python bindings and unit tests ($\simeq$ a few K lines)

[with R. Monat @ SAS'21]

Patch analysis for C

```
172 172    /* Like fstatat, but cache the result.  If ST->st_size is -1, the
173 173       status has not been gotten yet.  If less than -1, fstatat failed
174     -     with errno == -1 - ST->st_size.  Otherwise, the status has already
    174 +     with errno == ST->st_ino.  Otherwise, the status has already
175 175       been gotten, so return 0.  */
176 176    static int
177 177    cache_fstatat (int fd, char const *file, struct stat *st, int flag)
178 178    {
179 179      if (st->st_size == -1 && fstatat (fd, file, st, flag) != 0)
180     -      st->st_size = -1 - errno;
    180 +      {
    181 +        st->st_size = -2;
    182 +        st->st_ino = errno;
    183 +      }
181 184      if (0 <= st->st_size)
182 185        return 0;
183     -    errno = -1 - st->st_size;
    186 +    errno = (int) st->st_ino;
184 187      return -1;
185 188    }
```

Diff from `remove.c` in Coreutils

- analyze a pair of programs
- whole-program iteration on both versions
- compute semantic differences: new program semantic and new domains
- goal: prove the absence of regressions

Application: 100-1500 line patches from Coreutils and Linux

[with D. Delmas @ SAS'19]

Exploitability analysis

Exploitable

```
void use(char * input) {
  char dest[10];
  strcpy(dest, input); // alarm!
}

void main() {
  char buf[100];
  fgets(buf, sizeof(buf), stdin);
  use(buf);
}
```

Non-exploitable

```
void use(char * input) {
  char dest[10];
  strcpy(dest, input); // alarm!
}

void main() {
  char buf[10]; // fixed!
  fgets(buf, sizeof (buf), stdin);
  use(rand() ? buf
             : "123456789012345");
}
```

- discover whether a runtime error depends on a user-controllable value
  $\Longrightarrow$ possibly exploitable bug
- reduce alarm number by reporting only exploitable ones
- combination of forward value analysis and taint analysis

[with F. Parolini @ VMCAI'24]

Backward under-approximations

Finding witnesses for a bug

```
char buf[3];
int i = 0;
int j = input(0, 10); // input value?
int arr[3];
while (i < 5) {
  j += random(0, 1);
  i++;
}
buf[j] = '\0'; // bug
```

- given an alarm, find a witness proving the presence of the bug
- requires inferring sufficient preconditions for a given postcondition
  - infer user-input values
  - despite possible non-determinism (choices out of control of the user)
  - despite abstractions (approximations)
- the analysis proceeds backwards from the bug
- sufficient preconditions must be under-approximated

[with M. Milanese @ VMCAI'24]

Future work

Aspects of MOPSA to improve:

- **modular analyses** (beyond whole-program analyses)
  - analyze a function once, reuse the result many times
  - reuse across different git projects (libraries, files)
  - incremental analyses (add use context gradually)
  - develop more symbolic abstractions of the memory (separation properties)
- consider additional properties
  - further portability & impact analyses
  - **lightweight analyses**
- support **additional languages**, boost **multilanguage support**
  - work on OCaml support, OCaml-C bindings


https://gitlab.com/mopsa/mopsa-analyzer


The End