Numerical static analysis with Soot

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(joint work with Francesca Scozzari and Simone Di Nardo Di Maio)

Jandom

JVM-based Analyzer for Numerical DOMains

- forward intra-procedural analyses
- numerical properties
- different target languages
  - a simple *C*-style imperative language
  - linear transition systems
  - *Baf*, *Jimple* (sort of. . .)
- written in Scala (JVM-based comes from here)

NEW features

- inter-procedural summary-based analysis
- pair sharing analyses

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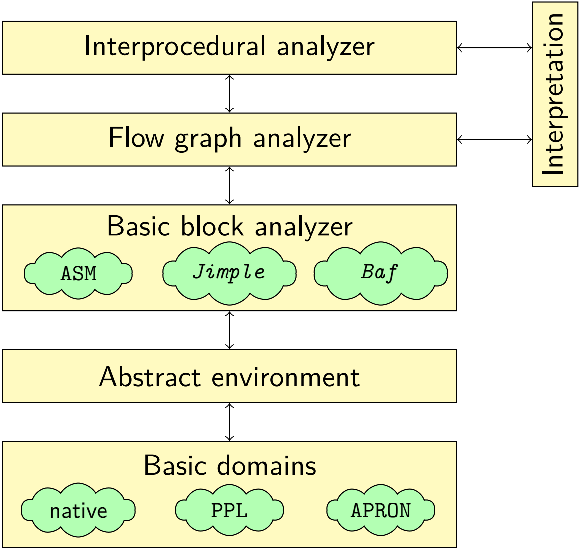
HELP! looking for new acronym

Jandom architecture



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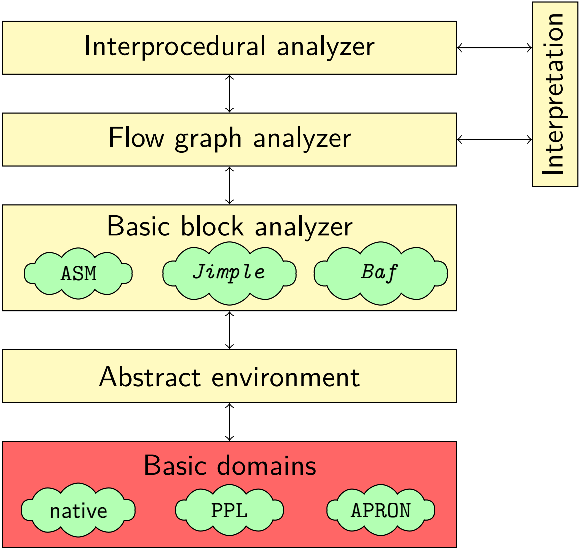

Basic domains

Basic domains describe general properties of program executions and are not tied to a specific target language.

- several families of basic domains
  - numerical domains
  - sharing domains
- each family has its own API
- all basic domains support:
  - lattice operations
  - widening (upper bound which guarantees termination)
- similar to a `FlowSet` in *Soot* but
  - immutable
  - type safe
  - no collection-style methods such as add, `iterator`, etc...

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Numerical domains

Represent the values of numerical variables.

Example (Nested loop)

```
for (x = 0; x < 10; x++)
  for (y = x; y < 10; y++)
    // do something here
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Example (Invariant inside the nested loop)

$$\begin{cases} 0 \leq x \leq 9 \\ y \geq 9 \\ y - x \leq 0 \end{cases}$$

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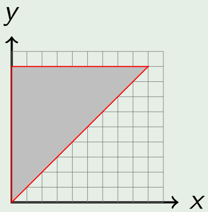

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Numerical domains API

The API for numerical domains is well understood:

- linear assignment
  - `x = 3*x + 2*y`
- non-deterministic assignment
  - `x = ?`
- intersection with half-planes
  - `if (x <= y - z) then`
- projection over a lower dimensional space
  - `istore 3`
- embedding onto a higher dimension space
  - `iload 3`
- and other. . .

Implementations of numerical domains

Three different sources for numerical domains:

1. `Jandom` native implementations
   - interval and parallelotope domains
   - JVM not well suited to the purpose, see
     W. Kahan and Joseph D. Darcy
     How Java's Floating-Point Hurts Everyone Everywhere
2. Parma Polyehdra Library (PPL) based domains
   - many domains: polyehdra, octagons, congruences, etc. . .
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3. in the future. . . add support for the APRON library

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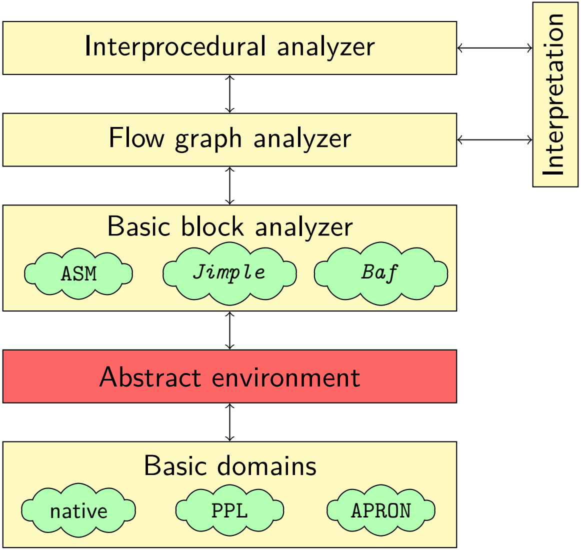
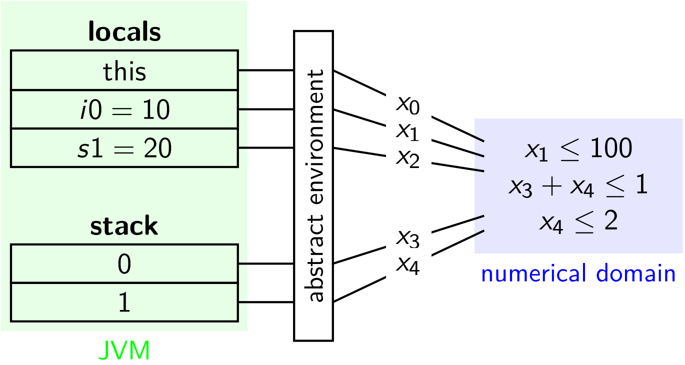


Abstract environments

An abstract environment

- is the glue between the basic domains and the language we want to analyze
- maps operations in the language into operations on the domains



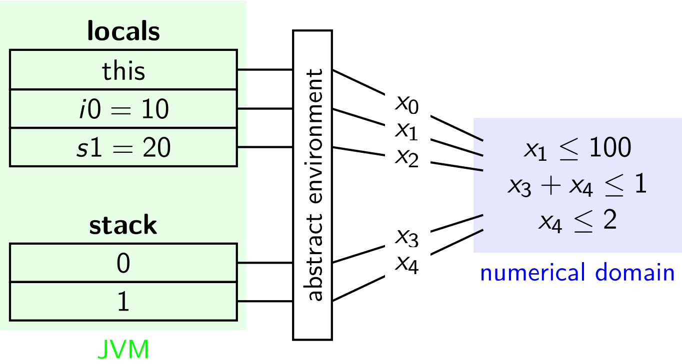
Abstract environments

Bytecode:

- iadd

Translation:

- $x_3 = x_3 + x_4$
- remove variable x_4



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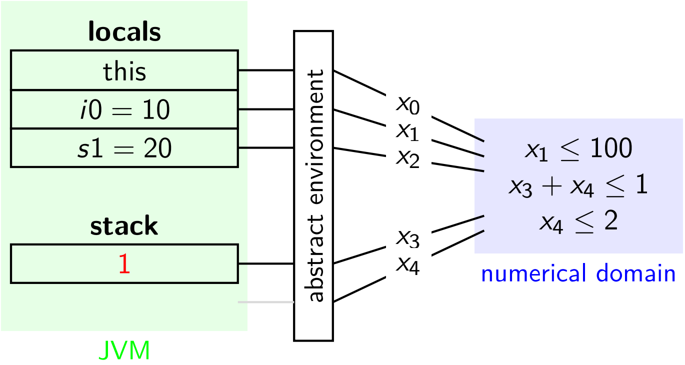

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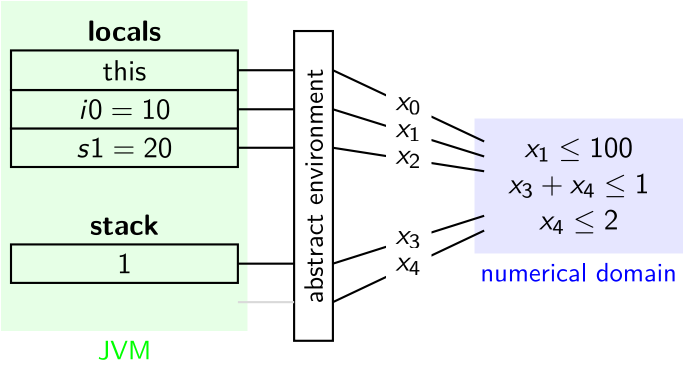

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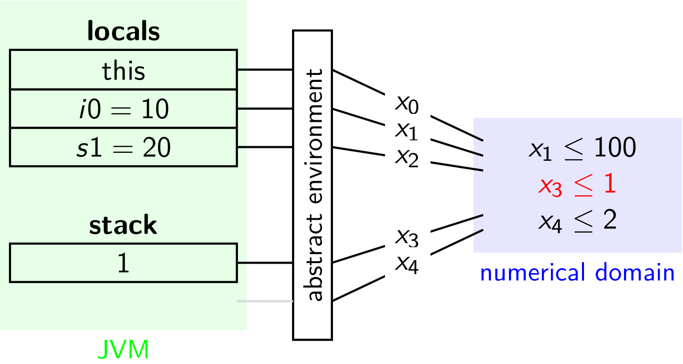

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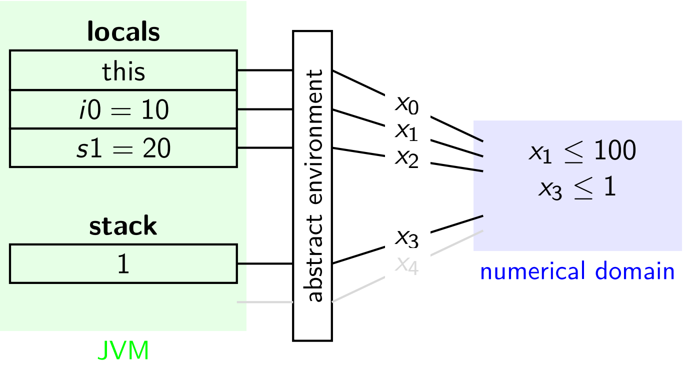

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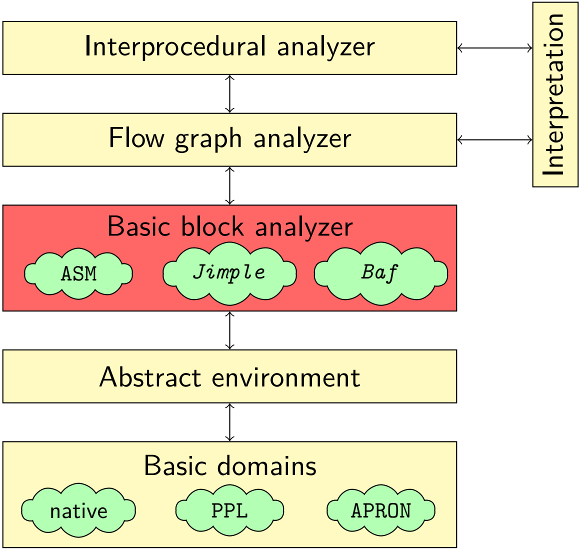

Basic blocks

A somewhat different definition of basic block:

Definition (Basic block)

A basic block is a sequence of instructions such that only the first one may be the target of a jump.

Consequences:

- encompass the standard definition of basic block
- fewer basic blocks are needed
- basic block may have many outgoing edges

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- we want a `return` statement to begin a basic block

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Basic blocks and *Soot*

We use the standard `Block` class and two new `BlockGraph` classes:

`BigBlockGraph` builds a `BlockGraph` according to our requirements

`UnitBlockGraph` build a `BlockGraph` where each block is composed of a single unit (useful for debugging).

These are written in Java and could be integrated into *Soot*.

Implementation notes

In the case of `BigBlockGraph`, overriding `computeLeader` was not enough, since `buildBlocks` method assumes that every jump instruction is the tail of a block.

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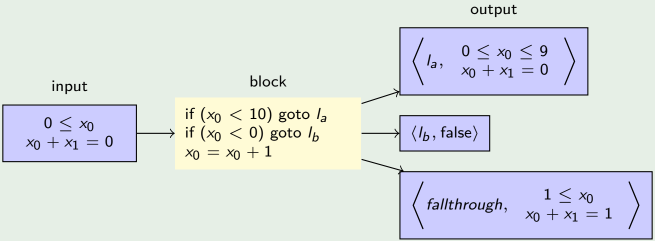
Basic block analyzer

A basic block analyzer:

- takes a block
- takes an input property
- returns a set of target blocks and the corresponding property

Example (Analysis of a basic block)



Baf vs *Jimple* vs *Grimple*

Generally *Jimple* is considered simpler to analyze than *Baf*. I am not entirely sure this holds in our case:

- *Jimple* has less instructions, but we need to interpret expressions
- *Jimple* has no stack, but the easiest way to analyze expressions is to evaluate them recursively, hence re-introducing a stack
- if analyzing an entire assignment in one step, analysis may be faster and more precise

Them, why do not move to *Grimple*?

- numerical domains have API to analyze a result of complex linear assignments and comparison
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Example of possible benefits of *Grimple*

Consider

- the octagon domain, which represents all conditions of the kind $\pm x_1 \pm x_2 \leq c$
- the assignment $z = z + x + y$
- the precondition $z = w \wedge x + y = 0$
- after the assignment, $z = w \wedge x + y = 0$ still holds
- if we break the assignment in $z = z + x$ and $z = z + y$ we loose the property after the first assignment.

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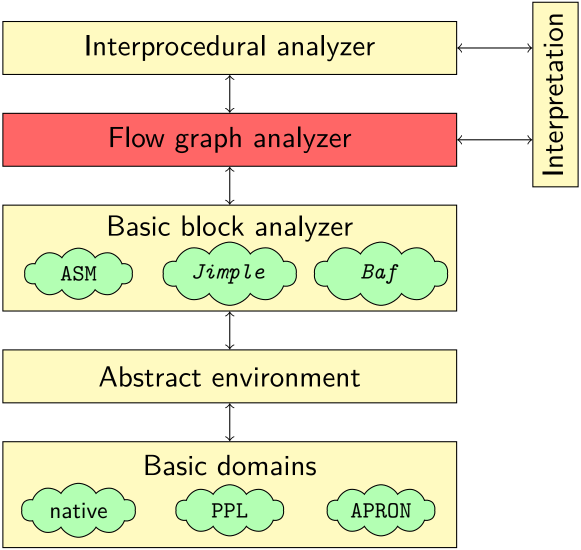

Flow graph analyzer

Similar to `BranchedFlowAnalysis` but

- over `Blocks` instead of `Units`;
- directly supports use of widening to ensure convergence of analysis;
- directly support ascending and descending phases;
- it will support many iterations strategies.

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Widening

- Widening should replace union on loops for domains with infinite ascending chains.
- Possible in `BranchedFlowAnalysis` but not as much as flexible.

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Ascending and descenging phases

- Widening causes loss of precision. It is possible to partially recover precision with descending chains.
- Again, something is possible with `BranchedFlowAnalysis` but not as much as flexible

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Iteration strategies

Worklist algorithms are not always the best choice:

- recursive vs iterative strategies;
- guided abstract interpretation.

An example of intraprocedural analysis

```
static void nested() {
  int z = 0;
```
// $z = 0$
```
  for (int i = 0; i < 10; i++)
```
// $0 \le z \wedge 0 \le i \le 10 \wedge i \le z + 1$
```
    for (int j = 0; j < i; j++)
```
// $i \le 10 \wedge 0 \le j \wedge j \le i \wedge j \le z \wedge i - z - 2j - 1 \le 0$
```
      z = z + 1;
}
```

Actually, the result of the analyzer is much less nicer, since properties are reported on the intermediate representation, not the Java code.

Using *Soot* vs extending *Soot*

At the moment, `Jandom` uses *Soot* to implement a completely different framework.

Another choice would be to extend *Soot* to support the kind of analysis we are interested in.

Integration would obviously be beneficial, but there are some stopovers:

- implementation language: `Scala` vs `Java`
- `Jandom` supports different target languages

Thinking about this. . .

What we like in *Soot*

Multiple intermediate representations

Facilities for intra-procedural analyses such as

- automatic generation of control flow graphs

Facilities for inter-procedural analyses such as:

- ability to browse the classes and methods in a Scene
- automatic computation of call-graphs

What we do not like in *Soot*

Documentation

- not well organized
- not always complete

Not enough type safety at the IR level

- for example, an *AndExpr* may have numeric operands
- makes it difficult to check whether I have considered all possible cases when analyzing instructions
- but I am biased... I use Scala, after all.

Some annoying missing minor functionalities

- how do I get the maximum stack size in a *Baf* body?

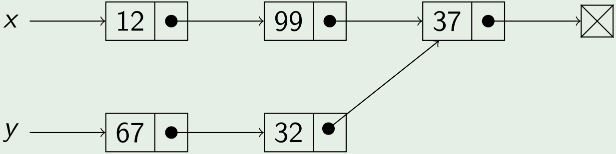
Future work

- Make `Jandom` definitively work instead of barely work
- Polishing interfaces
- Polishing user interface
- Speed optimization
  - Evaluate trade-off between mutable and immutable domains
  - Evaluate trade-off between functional and imperative style
- Using *Dava* to analyze directly over the AST ?

Sharing analysis

Two variables x and y share if it is possible to reach from them a common object.

Example (Variables x and y share)



`Jandom` implements an inter-procedural analysis for possible pair sharing, as defined by *Spoto and Secci* (SAS '05).

Possible pair sharing analysis

Given variables x, y and z the set $\{(x, x), (y, y), (x, y)\}$ means:

- x may share with itself (i.e., it is possibly not null);
- y may share with itself (i.e., it is possibly not null);
- x and y may share;
- z is definitively null.

Other variants:

- *set sharing + class analysis*
  M. Mendéz-Lojo and M. Hermenegildo (VMCAI '08)
- *pair sharing + linearity + aliasing*
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An API for sharing analysis?

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- language independent;
- suitable for other memory based analysis such as class or aliasing analysis.

At the moment, modeled over standard *Baf*/ *Jimple* operations:

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- test for nullness
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An example of interprocedural analysis

```
static int recursb(int x) {
  return recursa(x + 1);
}

static int recursa(int x) {
  if (x < 0)
    return recursb(x);
  else
    return x;
}
```

Inteprocedural analysis proves

on call to `recursa`:

$$ret \geq x \wedge ret \geq 0$$

on call to `recursb`:

$$ret \geq x + 1 \wedge ret \geq 0$$