Université Libre de Bruxelles
Computer Science Department

MEMO-F524 Masters thesis

An Efficient and Parallel Abstract Interpreter in Scala

— First Algorithm —

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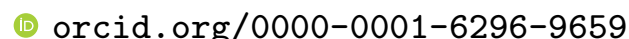
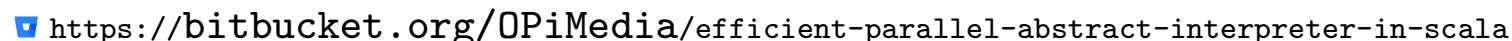

orcid.org/0000-0001-6296-9659

November 12, 2018


https://bitbucket.org/OPiMedia/efficient-parallel-abstract-interpreter-in-scala

Vrije Universiteit Brussel

Promotors: Coen De Roover, Wolfgang De Meuter
Advisor: Quentin Stievenart

The context: Abstract Interpretation for Static Analysis
The problematic: Too heavy for real programs
First parallel algorithm
Implementation
First results
Done and todo
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We need **tools** to help us to **build correct programs**.

Testing is not enough.

Figure: First "flight" of Ariane 5 in 1996.

Static Analysis:
study the **behaviour of programs without executing** them.

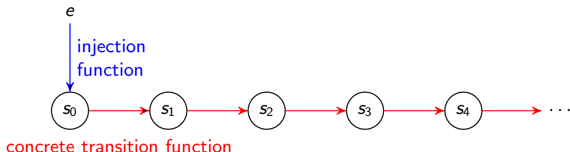
Not trivial questions about the behaviour of a program
are **undecidable** (RICE's theorem).

Abstract Interpretation:
approximation technique to perform static analysis.

Trade-off:
approximation must be **enough precise** to have an useful analysis,
and enough imprecise to make the problem **decidable**.

From Concrete Interpretation...

Trace: concrete interpretation with **small-step semantics**, for **one** instance.



Program is **executed** by interpreter,
described by an **Abstract Machine** (AM).

- One execution is for one instance on this program.
- e is for one expression, i.e. a program.
- s_i are the successive states during this execution.

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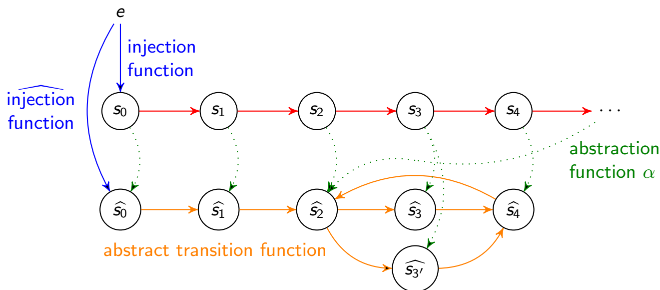
Trace: concrete interpretation with **small-step semantics**, for **one** instance.



Abstracting Abstract Machine (**A**AM).
2 over-approximations:

- on addresses: by modulo; give a finite state space
- on values: abstraction

Abstract transition function returns **all** directly reachable states.

State graph: abstract interpretation, for **all** instances.
"*The abstract simulates the concrete*" (Might).

Approximation of values: abstraction

Based on mathematical notion of **lattice** (**partially ordered sets** with additional properties).

Examples of abstraction for the set of integer values:

- the type integer
- intervals
- sign: $\{\ldots, -3, -2, -1, 0, 1, 2, 3, \ldots\}$ abstracted by $\{\bot, -, 0, +, (- \text{ and } 0), (0 \text{ and } +), \top\}$

Figure: René MAGRITTE, **Le Calcul Mental**. 1940.

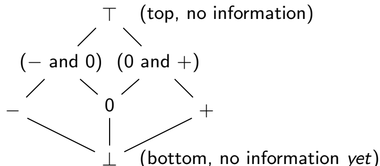


Figure: HASSE diagram of the complete lattice of signs.

Properties of a lattice are such that it contains the **join** of 2 elements and the succession of operation give a **fixed point**.

Example of a state graph on a very simple program

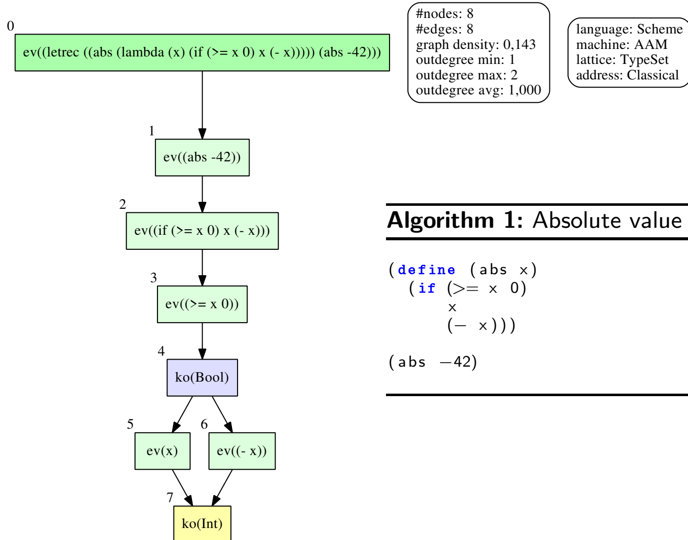


Figure: State graph of the abs program with lattice type.

Algorithm 1: Absolute value of −42

```
(define (abs x)
  (if (>= x 0)
      x
      (- x)))

(abs -42)
```

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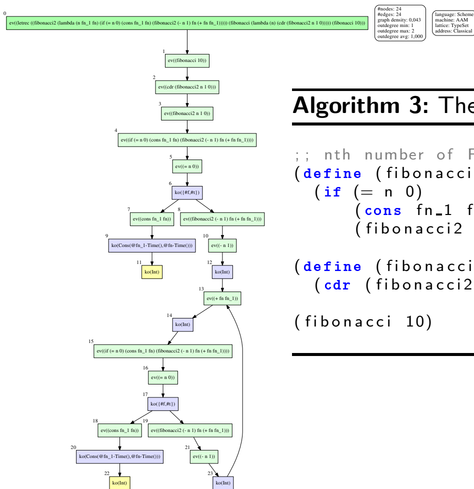
Algorithm 2: The 10th FIBONACCI number.

```
;; nth number of Fibonacci (by recursive process)
(define (fibonacci n)
  (if (<= n 1)
      n
      (+ (fibonacci (- n 1))
         (fibonacci (- n 2)))))

(fibonacci 10)
```

Figure: State graph of the FIBONACCI program with lattice type.

Example of a state graph on a other very simple program (bis)



Algorithm 3: The 10th FIBONACCI number.

```
;; nth number of Fibonacci (by iterative process)
(define (fibonacci2 n fn_1 fn)
  (if (= n 0)
      (cons fn_1 fn)
      (fibonacci2 (- n 1) fn (+ fn fn_1))))

(define (fibonacci n)
  (cdr (fibonacci2 n 1 0)))

(fibonacci 10)
```

Figure: State graph of the FIBONACCI program with lattice type.

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With an AAM the problem is became decidable.
But in general an AAM is **too slow** to analyse real programs.

One way to have a faster AAM is to
parallelize generation of the state graph.

Goal of this master thesis:
implement and compare several parallelizations of AAM in the framework Scala-AM.

Parallel model for the implementation: **actors** with **Akka**.

Language analysed: **Scheme**.

Figure: Agents Smith from the *Matrix* trilogy.

Actor model

Actor, like an object, isolated entity with its own encapsulated data and behaviour. With some fundamental differences.

- Entirely private.
- **No shared** mutable state (so no data race).
- Communication by immutable **asynchronous messages** (sent and received sequentially).
- Each actor has a mailbox (a queue).
- Capability to create other actors.

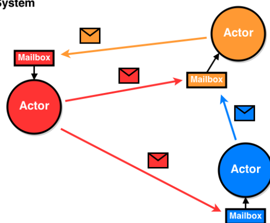

Figure: Richard Doyle. *Using Akka and Scala to Render a Mandelbrot Set*. 2014.
http://blog.scottlogic.com/2014/08/15/using-akka-and-scala-to-render-a-mandelbrot-set.html

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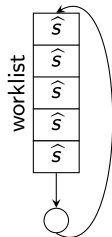
Factorized version from K. Dewey, V. Kashyap, B. Hardekopf. *A parallel abstract interpreter for JavaScript*. 2015.

Algorithm 4: The sequential worklist algorithm

```
procedure MAIN_PROCESS(worklist, memo, ς̂old, ς̂new, ς̂)
    if memo does not contain partition(ς̂) then
        memo[partition(ς̂)] := ς̂
        put ς̂ on worklist
    else
        ς̂old := memo[partition(ς̂)]
        ς̂new := ς̂old ⊔ ς̂
        if ς̂new ≠ ς̂old then
            memo[partition(ς̂)] := ς̂new
            put ς̂new on worklist
        end_if
    end_if
end_procedure

procedure SEQUENTIAL
    put the initial abstract state ς̂0 on the worklist
    initialize map memo : Partition → Σ♯ to empty
    repeat
        remove an abstract state ς̂ from the worklist
        for_all abstract states ς̂′ in next_states(ς̂) do
            MAIN_PROCESS(worklist, memo, ς̂old, ς̂new, ς̂′)
        end_for
    until worklist is empty
end_procedure
```



Worklist parallel strategy

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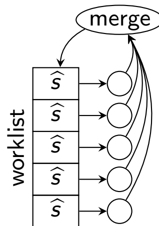
Factorized version from K. Dewey, V. Kashyap, B. Hardekopf. *A parallel abstract interpreter for JavaScript*. 2015.

Algorithm 5: The worklist parallel algorithm

```
put the initial abstract state ς̂0 on the worklist
initialize templist to empty
initialize map memo : Partition → Σ♯ to empty
repeat
    for_all abstract states ς̂ in the worklist do_in_parallel
        for_all abstract states ς̂′ in next_states(ς̂) do
            begin_thread_safe
                MAIN_PROCESS(templist, memo, ς̂old, ς̂new, ς̂′)
            end_thread_safe
        end_for
    end_parallel_for
    swap worklist and templist
until worklist is empty
```



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Redundant computations.

Synchronization at the merge step.

Article test on few real JavaScript programs.
Results show that this adaptation of the sequential algorithm is not optimal.

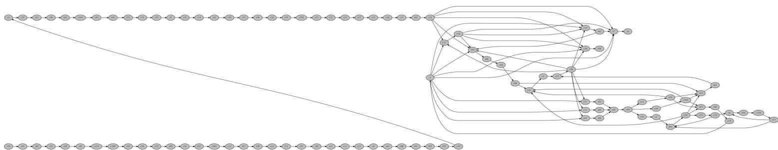

Figure: L. Andersen, M. Might. *Multi-core Parallelization of Abstracted*. 2013.

Improvements with producer/consumer model.

Better, per-context parallel strategy

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Authors of *A parallel abstract interpreter for JavaScript* introduce a per-context parallel strategy.
The main idea is to separate these two parts:

- state exploration
- control of state space by some merging operations.

The intuitive idea is to parallelize “functions” instead basic “blocks”.

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Actor logic

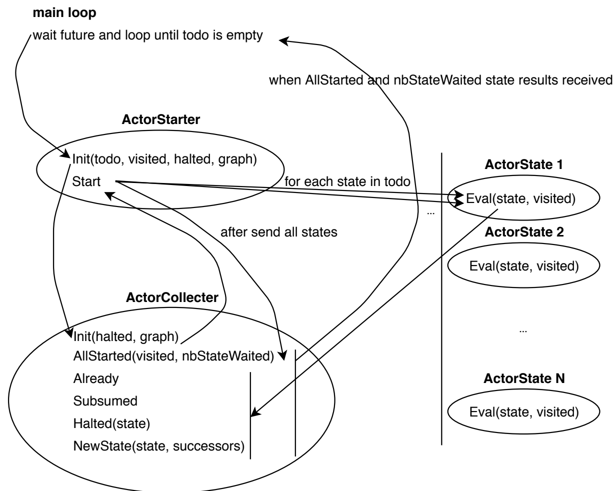

Figure: Actors logic used to implemented the worklist parallel strategy.

Scala implementation – main loop

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Algorithm 6: The main loop, until the worklist todo is empty

```
@scala.annotation.tailrec
def loop(todo: List[State], visited: VS[State], halted: Set[State], graph: Graph):
    ParAAMOutput = todo match {
  case Nil => {             // finished, the worklist todo is empty
    actorSystem.terminate
    ParAAMOutput(halted, VisitedSet[VS].size(visited), timeout.time, graph, false, stats)
  }

  case _ =>
    if (timeout.reached)  // exceeded the maximal time allowed, stop
      ParAAMOutput(halted, VisitedSet[VS].size(visited), timeout.time, graph, true, stats)
    else {                  // will send each state from worklist todo to ActorState
      val future = actorStarter ? ActorStarter.Init(todo, visited, halted, graph)

      val (newTodo, newVisited, newHalted, newGraph) =
        Await.result(future, Timeout("some" seconds).duration)
          .asInstanceOf[(List[State], VS[State], Set[State], Graph)]

      loop(newTodo, newVisited, newHalted, newGraph)
    }
}
```

Scala implementation – ActorStarter 1/2

Algorithm 7: Init other actors, send states to all ActorState

```
final class ActorStarter extends Actor {
  import ActorStarter._

  var todo: List[State] = null
  var newVisited: VS[State] = VisitedSet[VS].empty
  var actorI: Int = -1
  var nb: Int = -1

  override def receive = {
    case Init(todo: List[State], visited, halted: Set[State], graph: Graph) =>
      this.todo = todo
      newVisited = visited
      actorI = 0
      nb = 0
      actorCollecter ! ActorCollecter.Init(halted, graph, sender)

    case Start =>
      for (state <- todo) {
        if (actors(actorI) == null)  // create new actor
          actors(actorI) = actorSystem.actorOf(Props(new ActorState))

        actors(actorI) ! ActorState.Eval(state, newVisited, actorCollecter)
        newVisited = VisitedSet[VS].add(newVisited, state)

        actorI += 1
        if (actorI == maxActorStates) actorI = 0
        nb += 1
      }

      actorCollecter ! ActorCollecter.AllStarted(newVisited, nb)
  }
}
...
```

Scala implementation – ActorStarter 2/2

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Algorithm 8: Init other actors, send states to all ActorState

```
...
object ActorStarter {
  val Start = 1
  case class Init(todo: List[State], visited: VS[State], halted: Set[State], graph: Graph)
}

val actorStarter: ActorRef = actorSystem.actorOf(Props(new ActorStarter))
```

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Algorithm 9: Starts ActorStarter, collect results from all ActorState

```
final class ActorCollecter extends Actor {
  import ActorCollecter._

  var mainSender: ActorRef = null
  var newTodo: List[State] = null
  var newHalted: Set[State] = null
  var newGraph: Graph = null
  var nb: Int = -1  // count AllStarted received + the number of state results receive
  var nbStateWaited: Int = -1
  var newVisited: VS[State] = VisitedSet[VS].empty

  def increment() = {
    nb += 1
    if (nb > nbStateWaited)  // all started and finished all states, then send results
      mainSender ! (newTodo, newVisited, newHalted, newGraph)  // to actorStarter
  }

  override def receive = {
    case NewState(state: State, successors: Set[State]) =>
      newGraph = newGraph.map(_.addEdges(state, successors))
      newTodo ++= successors
      increment
    case Already => increment
    case Subsumed => increment
    case Halted(state: State) =>
      newHalted += state
      increment
...
```

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Algorithm 10: Starts ActorStarter, collect results from all ActorState

```
...
    case Init(halted: Set[State], graph: Graph, mainSender: ActorRef) =>
      this.mainSender = mainSender
      newTodo = Nil
      newHalted = halted
      newGraph = graph
      nb = 0
      nbStateWaited = Int.MaxValue  // biggest value to avoid end before init par AllStarted
      newVisited = VisitedSet[VS].empty
      sender ! ActorStarter.Start  // to actorStarter
    case AllStarted(visited, nbStateWaited: Int) =>
      this.nbStateWaited = nbStateWaited
      newVisited = visited
      increment
  }
}
object ActorCollecter {
  val Already = 2
  val Subsumed = 3
  case class NewState(state: State, successors: Set[State])
  case class Halted(state: State)
  case class Init(halted: Set[State], graph: Graph, mainSender: ActorRef)
  case class AllStarted(visited: VS[State], nbStateWaited: Int)
}

val actorCollecter: ActorRef = actorSystem.actorOf(Props(new ActorCollecter))
```

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Algorithm 11: evaluate states

```
final class ActorState extends Actor {
  import ActorState.Eval

  override def receive = {
    case Eval(state: State, visited, actorCollecter: ActorRef) =>
      if (VisitedSet[VS].contains(visited, state))  // already
        actorCollecter ! ActorCollecter.Already
      else if (subsumption &&                        // subsumed
        VisitedSet[VS].exists(visited, state, (s2: State) => s2.subsumes(state)))
        actorCollecter ! ActorCollecter.Subsumed
      else if (state.halted)                         // halted stated
        actorCollecter ! ActorCollecter.Halted(state)
      else                                           // new state
        actorCollecter ! ActorCollecter.NewState(state, state.step(sem))
  }
}
object ActorState {
  case class Eval(state: State, visited: VS[State], actorCollecter: ActorRef)
}
```

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First (very rough) results

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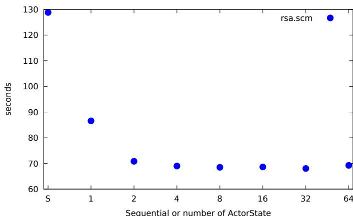

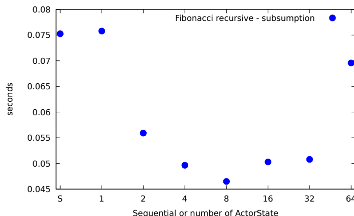

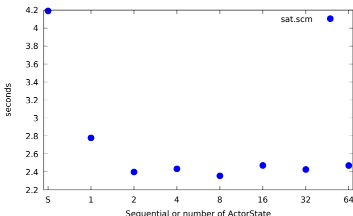

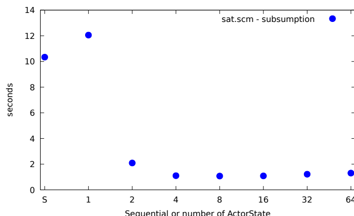

Quick average on 5 repetitions after 3 repetitions skipped (3 and 1 for rsa.scm) with Scala 2.12.7 and Akka 2.5.18 (Java 1.8.0 – GraalVM 1.0.0) on Intel Xeon Gold 6148 2.40GHz, 16 “cores” available (Hydra).

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Work done

- Reading of theoretical background on lattices, AAM and parallelism.
- Redaction of an introduction to the subject (preparatory work, previous year).
- Learning actors, Akka.
- Learning use of some tools: sbt, Scala environments. . .
- Learning functioning of Scala-AM.
- Removed some parts of Scala-AM (other machines or languages), implementation of little features.
- Implemented the worklist parallel algorithm.
- Reimplemented the `Graph` data structure.
- Some thoughts about a kind of metric to characterize "ideal" parallelization of given Scheme programs.

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Work to be done

- Maybe revise the implementation of the worklist parallel algorithm.
- Think about how and to what to benchmark.
- Implement better parallel algorithm(s).
- Try impact of metrics considered.
- Evaluate all of them,
  identify advantages and disadvantages for each of them.
- Reading of other articles on parallelization.
- Final redaction.

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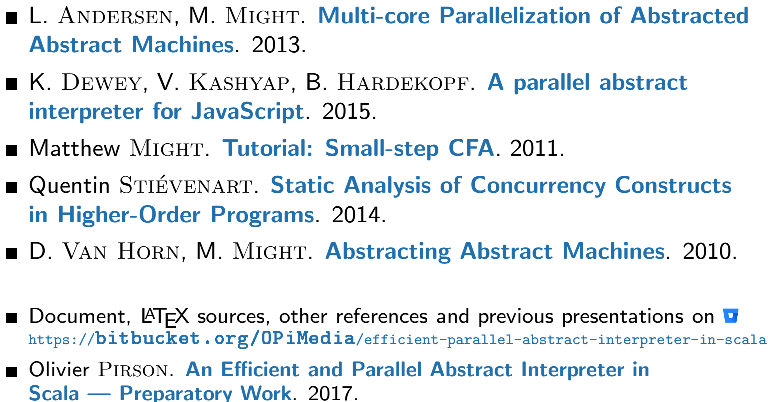
Thank you! Questions time...



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- Matthew Might. **Tutorial: Small-step CFA**. 2011.
- Quentin Stiévenart. **Static Analysis of Concurrency Constructs in Higher-Order Programs**. 2014.
- D. Van Horn, M. Might. **Abstracting Abstract Machines**. 2010.

- Document, LaTeX sources, other references and previous presentations on https://bitbucket.org/OPiMedia/efficient-parallel-abstract-interpreter-in-scala
- Olivier Pirson. **An Efficient and Parallel Abstract Interpreter in Scala — Preparatory Work**. 2017.