Symbolic Execution with Interval Constraint Solving and Meta-Heuristic Search

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Software errors are expensive

Software is everywhere

Annual cost of software errors to the US economy is ~60B dollars [NIST2002]

Main approaches for finding errors

- Software Testing
  - Run code and observe effects
- Static Analysis
  - Analyze code without running it

Research Goal

Develop new techniques and improve existing techniques for Software Testing and Static Analysis

Symbolic Execution (SE)

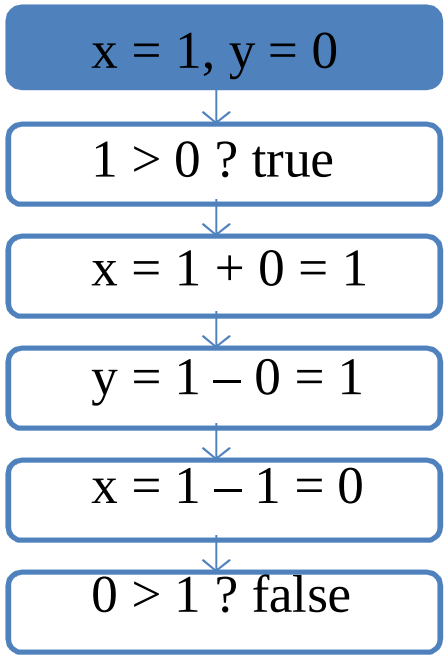
- Analysis of programs with unspecified inputs
  - Execute a program on symbolic inputs
  - Introduced in the 70s by L. Clarke, J. King
- Symbolic states represent sets of concrete states
- For each path, build a **path condition**
  - Condition on inputs for execution to follow that path
  - Check **satisfiability of path condition**
    - Explore only feasible paths
- Symbolic state
  - Symbolic values/expressions for variables, path condition, and program counter

Example: Standard Execution

Code that swaps 2 integers

```
int x, y;

if (x > y) {

  x = x + y;

  y = x – y;

  x = x – y;

  if (x > y)

    assert false;

}
```

Concrete Execution Path

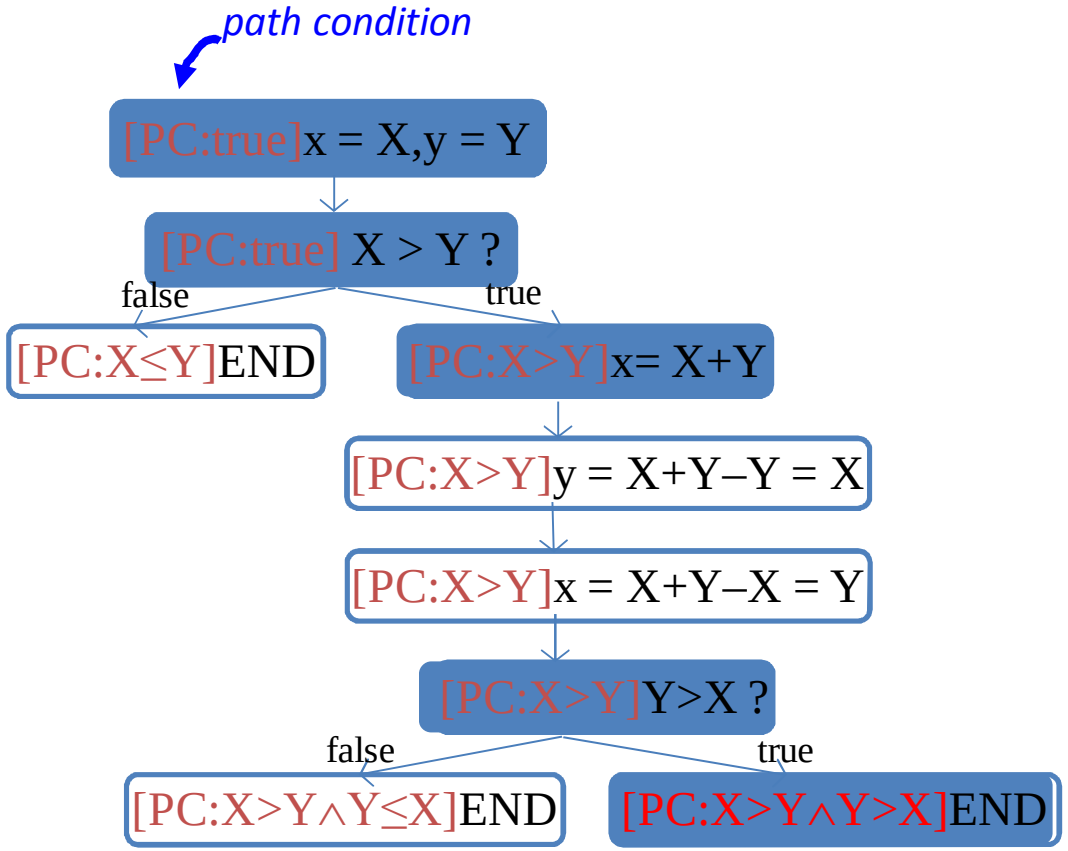


Example: Symbolic Execution

Code that swaps 2 integers:

```
int x, y;

if (x > y) {

  x = x + y;

  y = x – y;

  x = x – y;

  if (x > y)

    assert false;

}
```

Symbolic Execution Tree:



False!

Solve path conditions → test inputs

State-of-the-Art

- Explosion in number of tools and techniques
  - **Tools**: CUTE, CREST, DART, EGT, EXE, jCUTE, KLEE, PEX, PREFIX, SAGE, SMART, SPF, YOGI, etc.
  - **Industry**: Bell Labs, Fujitsu, IBM, Microsoft, etc.
  - **Government Labs**: NASA, etc.
  - **Universities**: Berkeley, EPFL, Illinois, Imperial College London, Iowa State, U Nebraska Lincoln, UT Austin, UT Arlington, Stanford, Stellenbosch, etc.
  - **Research communities**: software engineering, programming languages, systems, security, etc.

Challenge

Handling complex mathematical constraints

Example constraint generated with SE for a module from TSAFE (Tactical Separation Assisted Flight Environment)


```
sqrt(pow(((x1 + (e1 * (cos(x4) – cos((x4 + (((1.0 * (((c1 * x5) *
(e2/c2))/x6)) * x2)/e1)))))) – (((e2/c2)) * (1.0 – cos((c1 * x5))))),2.0))
> 999.0  & (c1 * x5) > 0.0 & x3 > 0.0 & x6 > 0.0 & c1 = 0.017… &
c2 = 68443.0 & e1 = ((pow(x2,2.0)/tan((c1*x3)))/c2) &
e2 = pow(x6,2.0)/tan(c1*x3)
```

CORAL: CONSTRAINT SOLVER FOR COMPLEX CONSTRAINTS

CORAL

- Target application of solver: SE of programs that
  - Use floating-point arithmetic
  - Call specific math functions

TSAFE example

Input: sqrt(pow(((x1 + (e1 * (cos(x4) – …

Output: {x1=100.0, x2=98.48…, x3=3.08…E-11, …}

Approach: combine meta-heuristic search and interval solving

Meta-Heuristic Search

- Explores candidate solutions
  - Start with random solutions
  - Refine candidate set based on *fitness function*

Inherently incomplete!

Meta-Heuristic Search

- Local search: Uses **one** single candidate solution
  - E.g., Alternating Variable Method (AVM), hill climbing, simulated annealing, etc.
- Global search: Uses **several** candidate solutions
  - E.g., Particle Swarm Optimization (PSO), genetic algorithms, etc.

Interval Solving

- Another method of constraint solving
- Applications in several domains. E.g., stability in control systems.

Input: sqrt(pow(((x1 + (e1 * (cos(x4) – …

Output: {x1=[99.9…, 100.0], x2=[99.9…, 100.0], …}, …

interval

Intervals may not contain solutions!

Our Approach: Combine Techniques

Meta-heuristic search	Interval solving
+ Good for finding exact solutions in large search spaces	+ Good for computing parts of solution space
- May get lost in local maxima	- Does not compute solutions

Seed meta-heuristic search
with inputs drawn from intervals
(intuition: better initial states)

Implementation

- For meta-heuristic search
  - Uses Opt4J (http://opt4j.sourceforge.net/)
- For interval solving
  - Uses RealPaver (RP) [Granvilliers & Benhamou, 2006]
- Also includes several optimizations
  - E.g., inference of variable domains, elimination of dependent variables, etc.

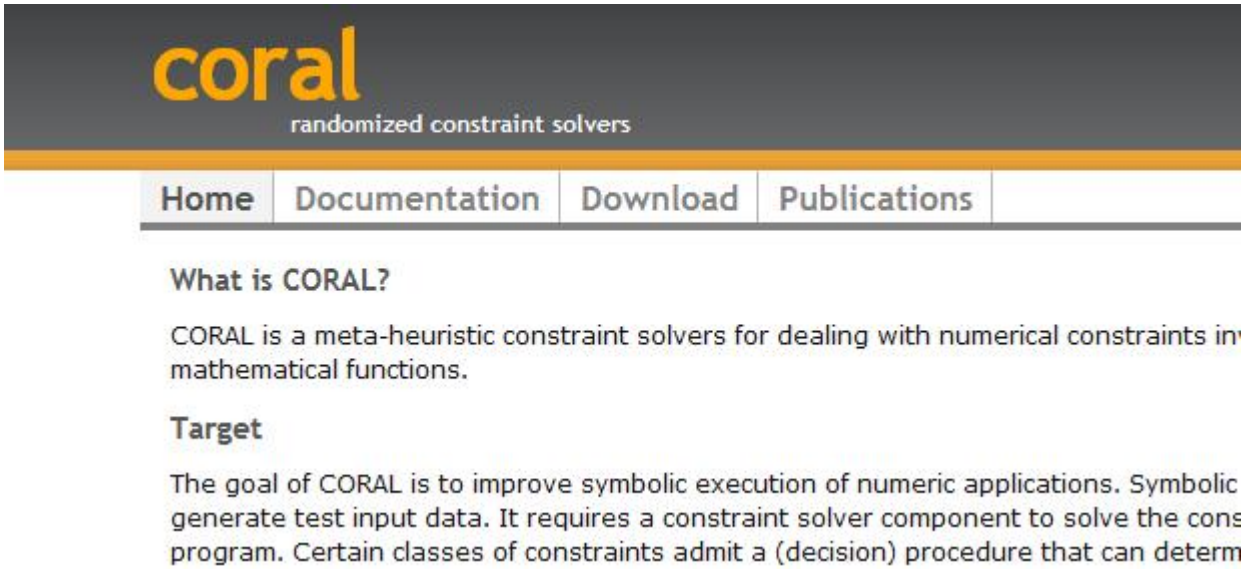
Tool

- Integrated with NASA's Symbolic PathFinder (SPF)

  http://babelfish.arc.nasa.gov/trac/jpf/wiki/projects/jpf-symbc

- Also available as a library

  http://pan.cin.ufpe.br/coral

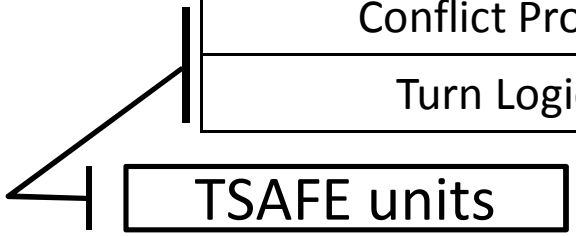


EVALUATION

Subjects

- Publicly available applications from the aerospace domain

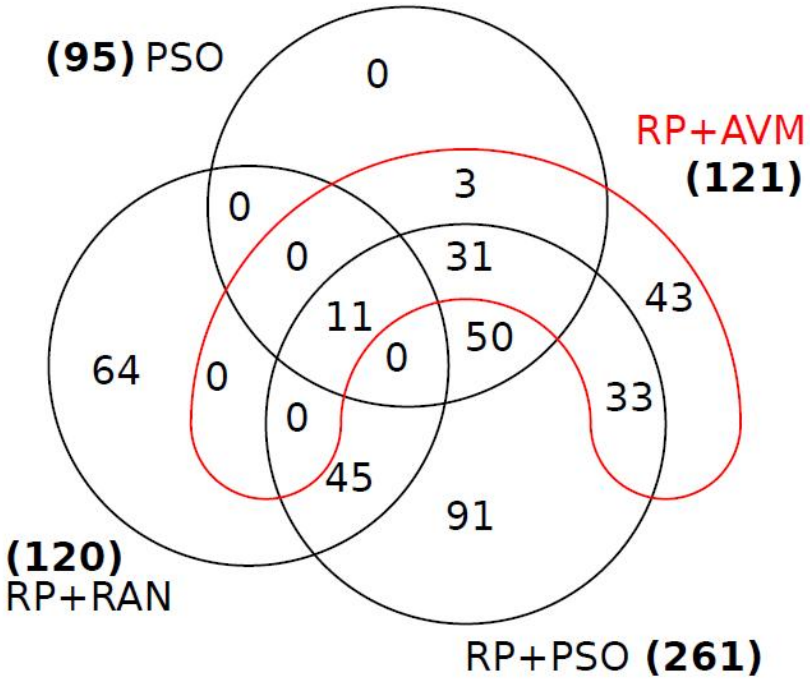
Subject	# constraints	# conjuncts	# functions
Apollo Autopilot	800	39	3
Collision Detection (CDx)	800	63	6
Conflict Probe	33	7	5
Turn Logic	329	3	20



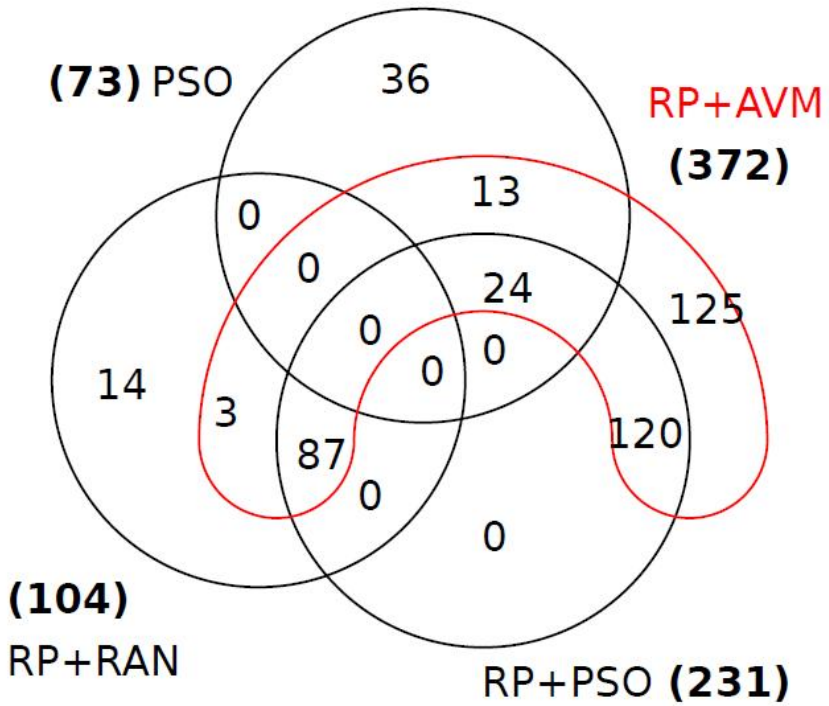
Evaluated CORAL Configurations

- Meta-heuristic search alone
  - AVM
  - PSO (previously found it better than GA)
- Interval solving w/ RealPaver (RP) alone
  - RP+RAN (choose random values from interval)
- Combinations of IS with global and local search
  - RP+AVM – optimistic on RP reported intervals
  - RP+PSO – not so optimistic

Results for Apollo and CDx

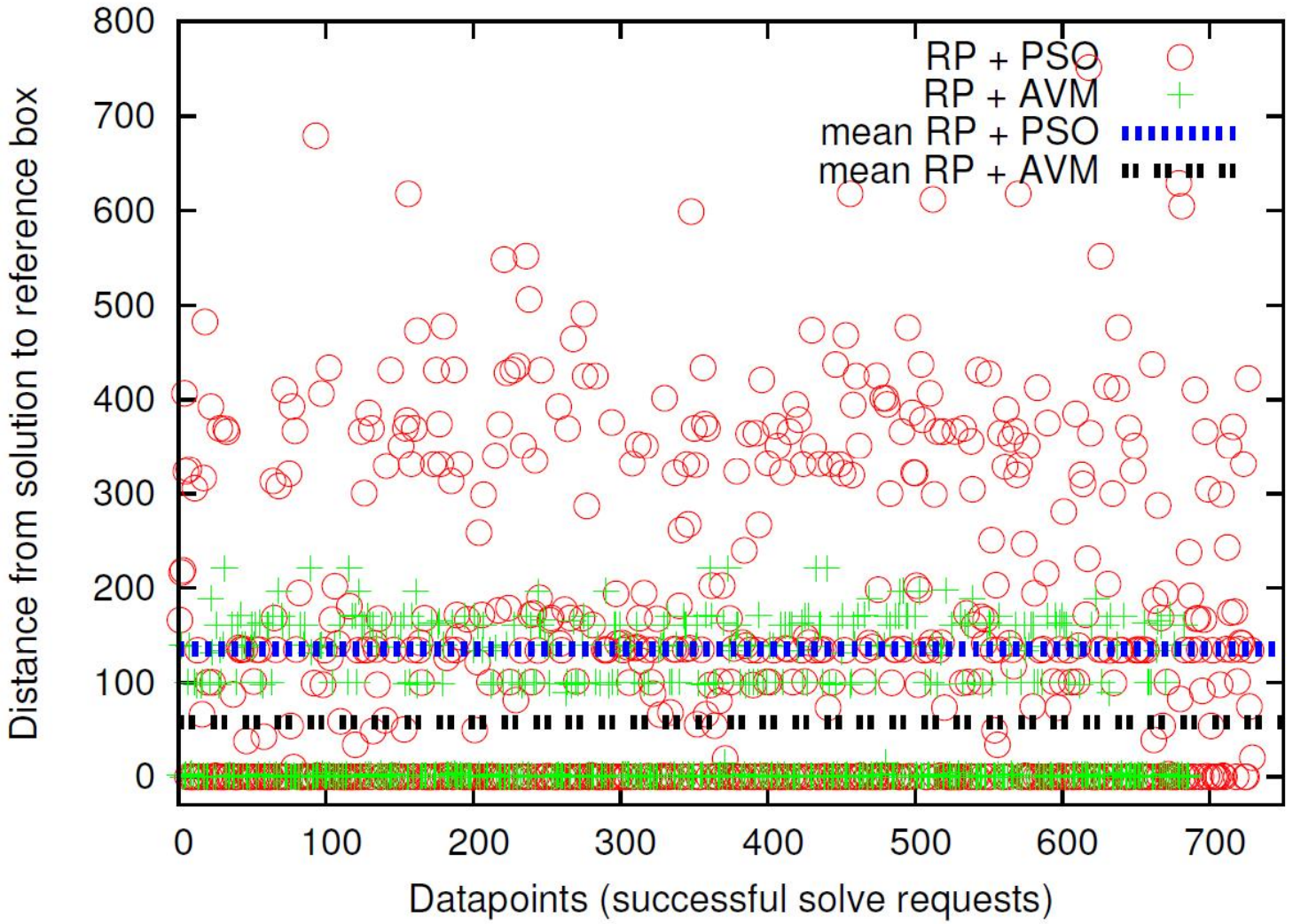


APOLLO

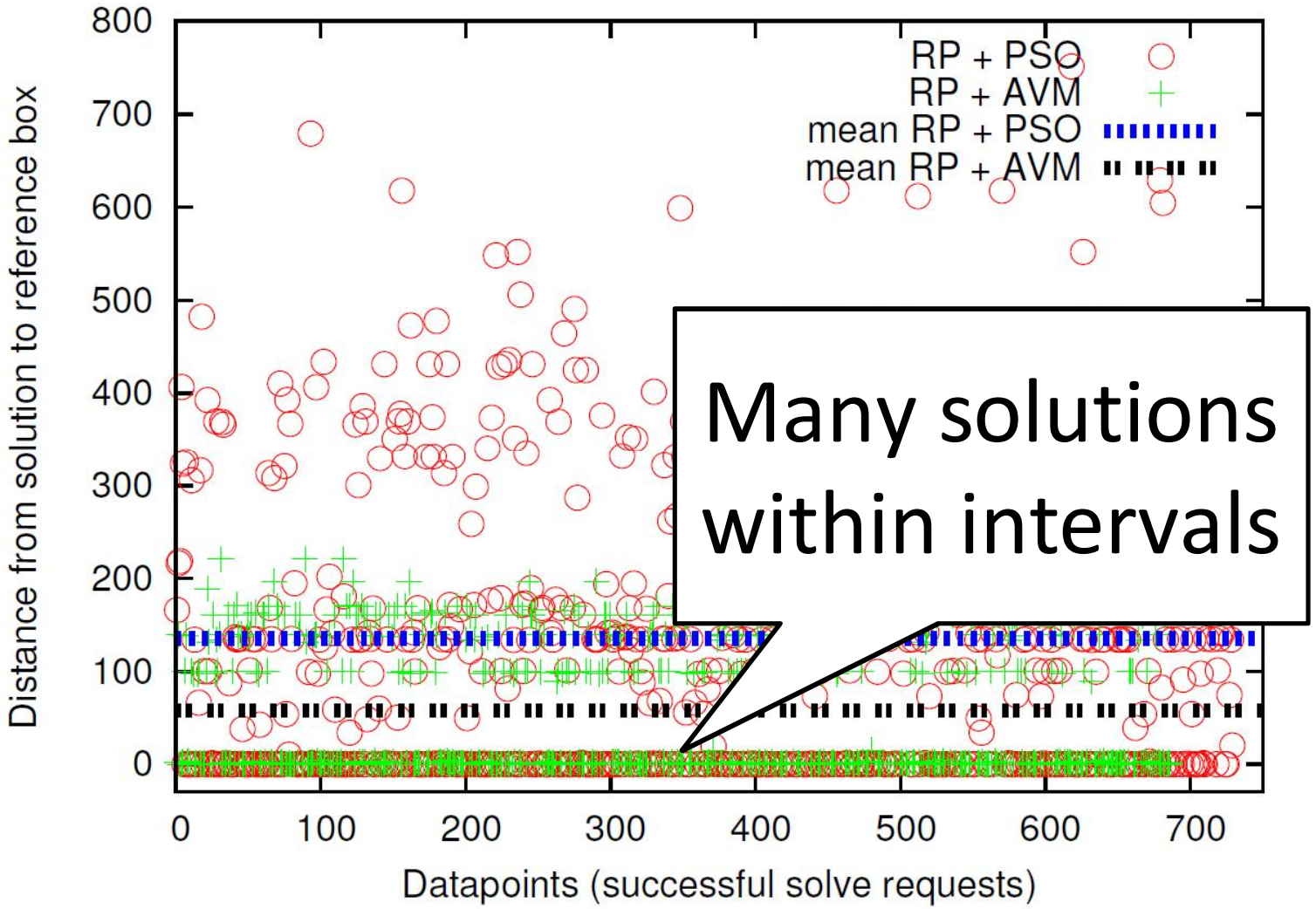


CDx

Distance from Solution to RP Box



Distance from Solution to RP Box



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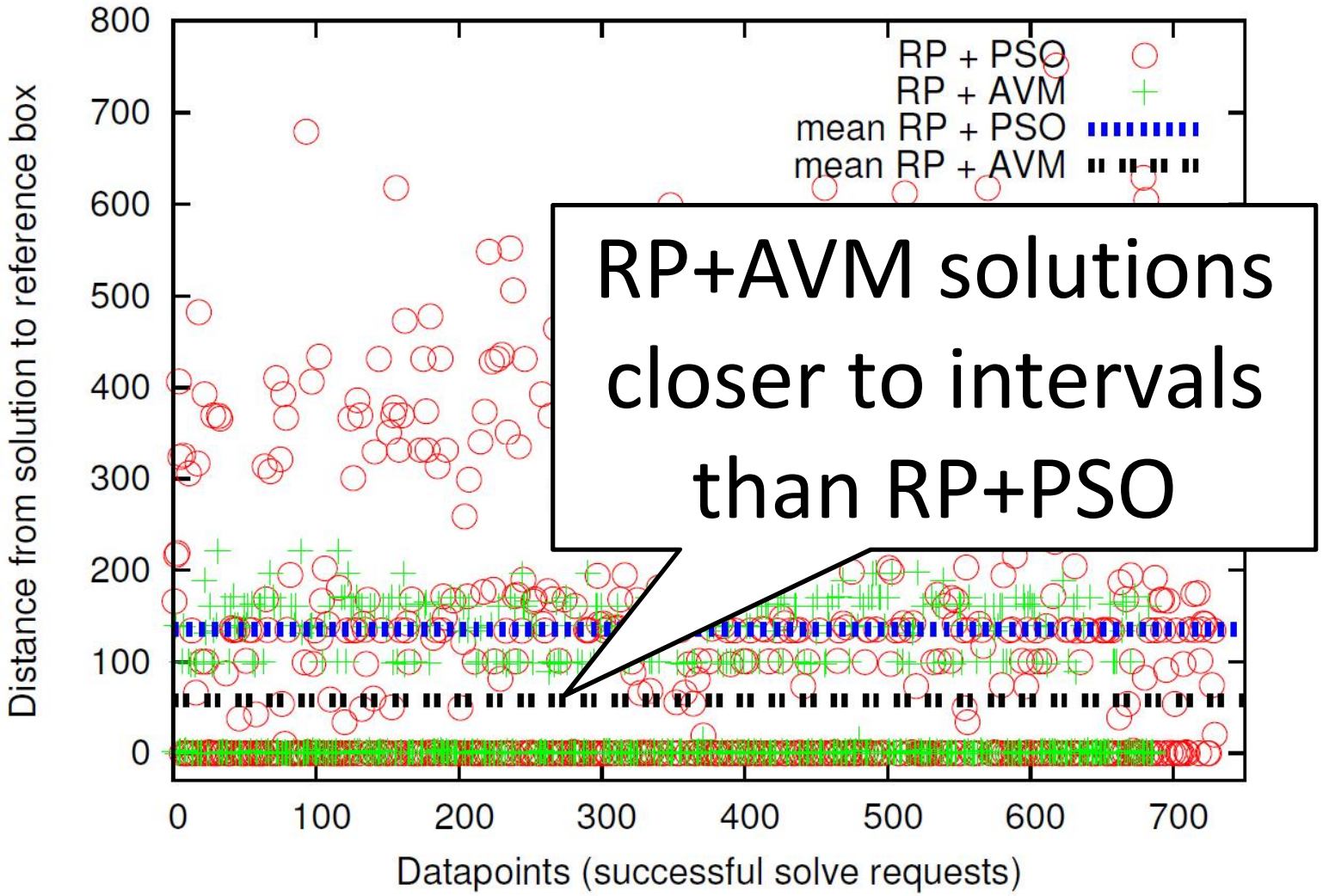


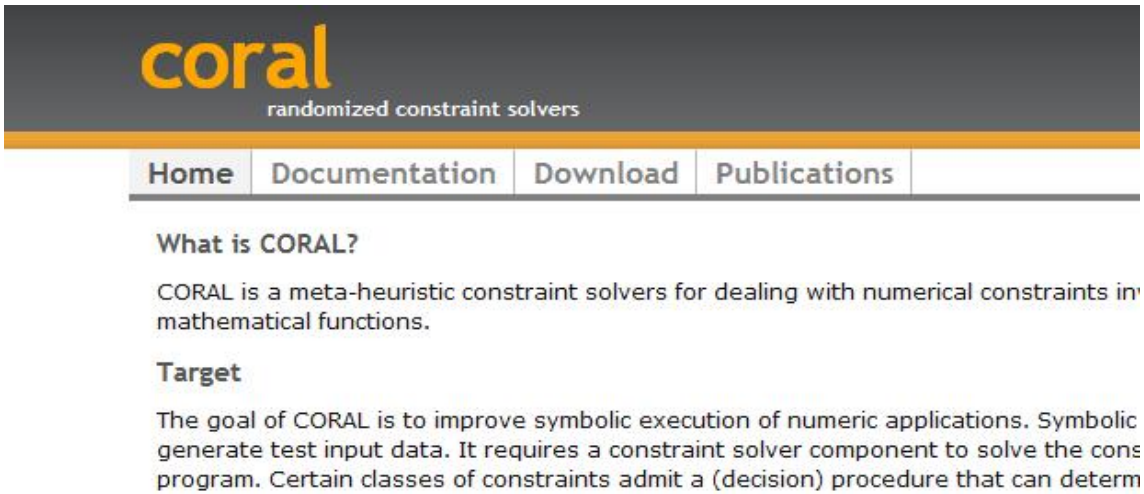
Time Results

- Solvers typically respond very fast
- The most extreme case: ~40s
- We limit the # of iterations not execution time
- Random solving slower than others (10^6 iterations vs 600 PSO)

Conclusions for CORAL

- Combination solved more constraints than meta-heuristic search or interval solving alone
  - Both global and local search help interval solving
  - Complementary: should be run together in parallel

http://pan.cin.ufpe.br/coral



Related Work

- Combining interval solving and SAT solving.
  - iSAT [Franzle *et al.,* JSAT'10]
- Using meta-heuristic search.
  - FLoPSy [Lakhotia *et al.,* ICTSS'10]
- Optimizing solving with constraint propagation.
  - Choco [Jussien *et al.*, EMNTR'10]
- Use concrete values and randomization to simplify complex constraints.
  - DART [Godefroid *et al.*, PLDI'05],
  - EXE [Cadar *et al.*, CCS'06]

Conclusions

- CORAL
  - Solver for complex mathematical constraints generated by symbolic execution
  - Combines meta-heuristic search with interval solving
    - Techniques are effective and complementary
- Future Work
  - Robustness analysis [Majumdar & Saha, RTSS 2009]
  - Overflow and round-off error bounds analysis

THANK YOU!