Fast Cone-Of-Influence Computation and Estimation in Problems with Multiple Properties

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joint work with

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Outline

- Introduction
- Standard Cone Of Influence(COI) computation
- Labeled COI computation
- Using COI
- Experimental results
- Conclusions

Introduction

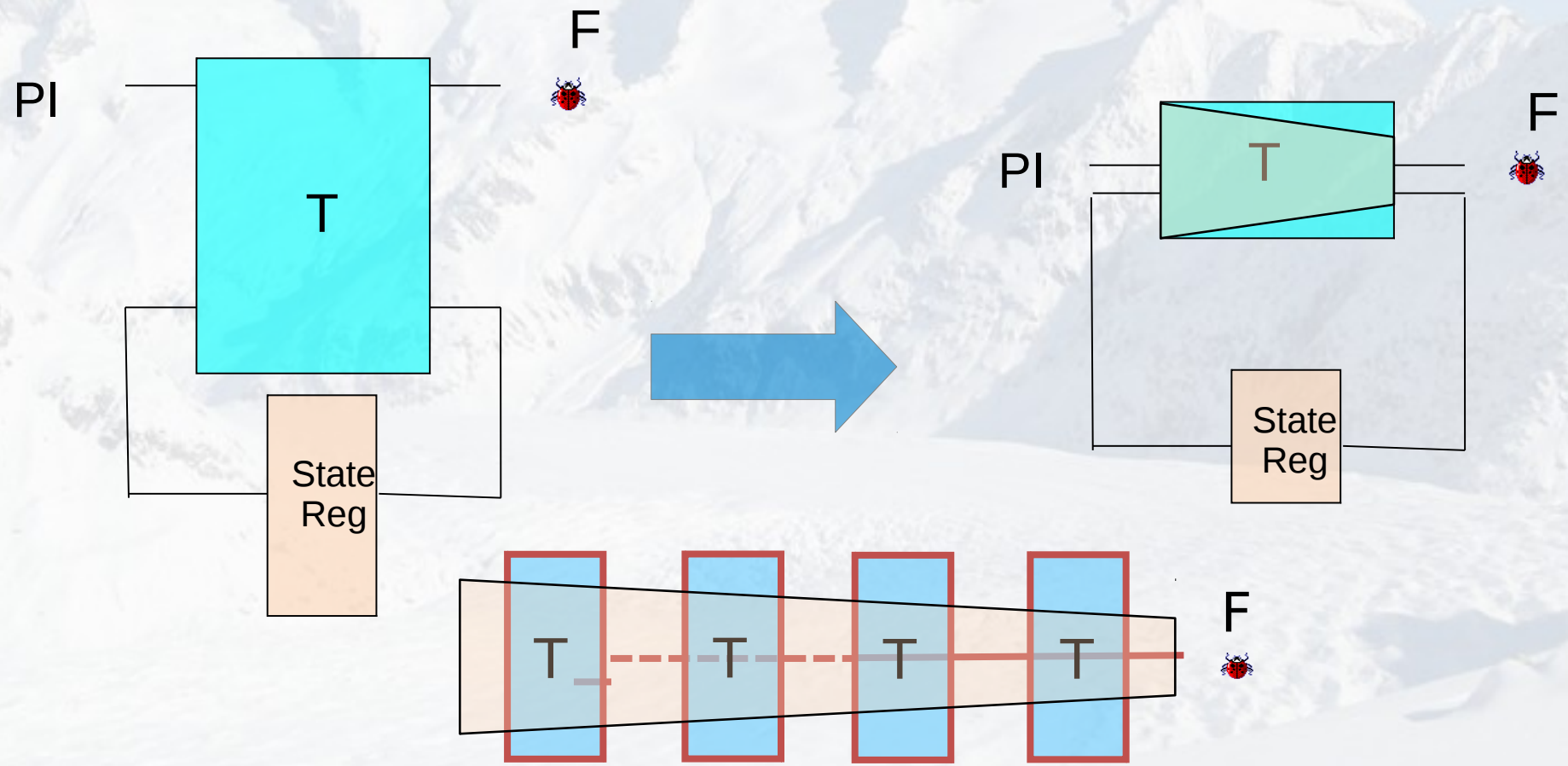
- The Cone of influence reduction(COI) is a fundamental technique to simplify designs in Hardware Model Checking
- Given a model represented as Finite State Machine (FSM)
  - specified using some state variables
  - the COI reduction simplifies the size of the model by eliminating variables not relevant to the property under verification

Introduction

- We address the frameworks where repeated COI computations are required for
  - multiple properties
  - Internal model nodes

  to avoid potentially quadratic slow down
- We wish to use COI information as property and/or variable scoring heuristics in various Model Checking algorithms

COI Reduction

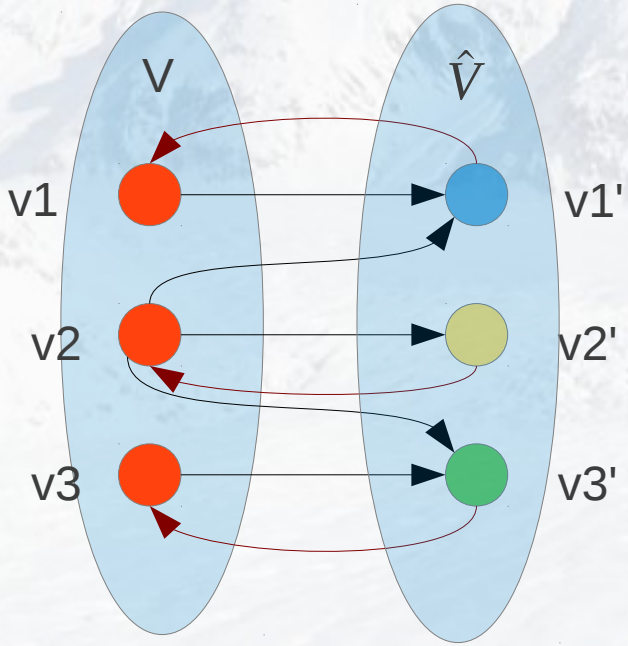


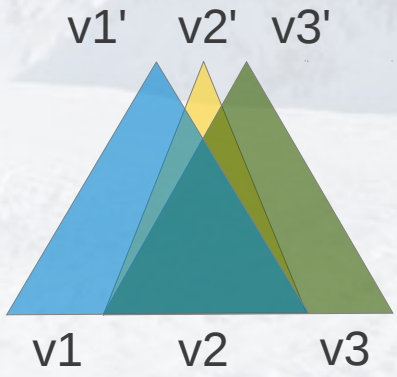
Standard COI computation

- The standard algorithm for computing COI(V) works on the variable dependency graph a bipartite graph where:
- V(present state) and V'(next state) variables are the nodes
- all (vj,vi') edges represent a dependency of the next state variable vi' upon present state variable vj

Standard COI computation

- The algorithm basically implements a backward traversal of the graph starting from all variables of $\hat{V}$
- The final COI is the subset of the reached V nodes





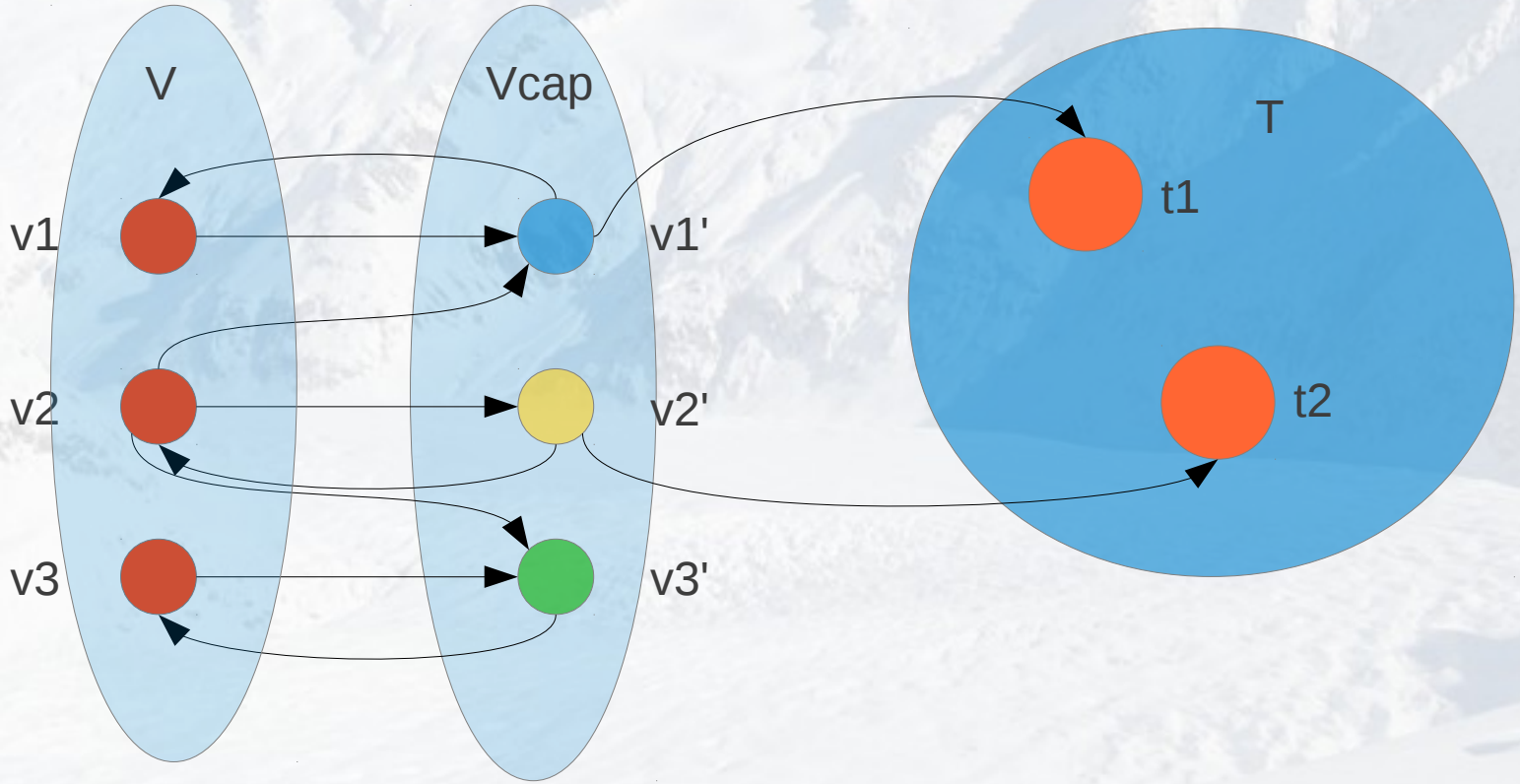
Standard COI computation

- Though computing each COI has a linear-time solution this process may become computationally expensive when repeated COI evaluations are necessary
- For example, when multiple properties need to be verified, and each requires an independent COI computation
- The base algorithm described would need to be applied repeatedly. This entails obvious overhead when multiple properties have overlapping COIs due to the sub-graph re-traversal
- The overall COI computation process may degrade to requiring quadratic resources

Labeled COI computation

- Our approach follows the graph labeling approach, in which graph nodes are assigned labels such that after labeling , the mutual reachability between nodes can be decided by inspecting labels alone.
- We associate to all nodes a visited flag and a bit array encoding → Bitmap where i-th bit correlates to the i-th present state variable vi
- Our bitmaps thus have one bit per state variable.

Labeled COI computation



Labeled COI computation

- Initially all visited flag are set to false, and all nodes except present state are labeled with a 0 bitmap(Bmp)
- V nodes are labeled with a one-hot encoding of their variable index:

Bmp(vi)= OneHot(i)

OneHot(0)=..00001

OneHot(1)=..00010

Labeled COI computation

- For each target ti we perform a backward depth-first traversal of unvisited nodes.
- “backward” refers to the direction followed for edges in the dependency graph
- Bitmaps are propagated in the forward direction
- For each node, set the visited flag to true, and we recur for all adjacent fan in nodes

Labeled COI computation

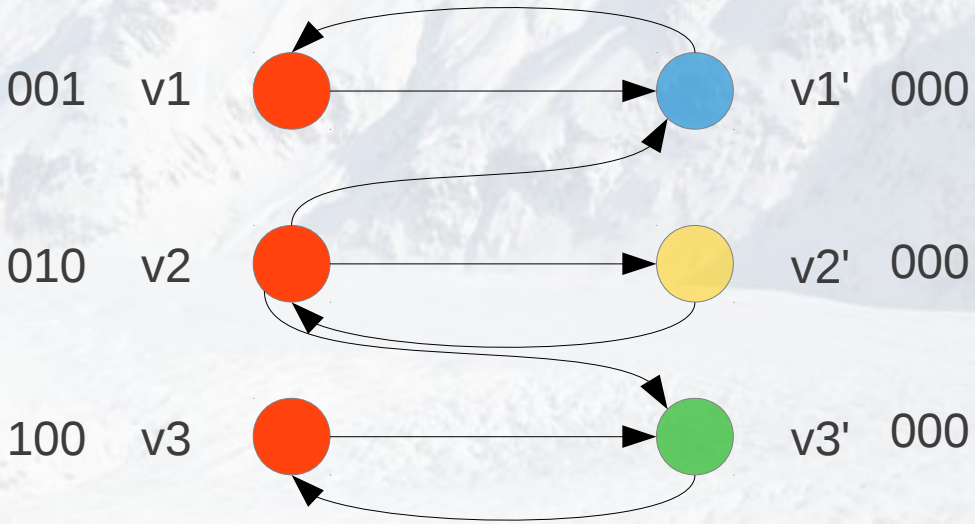
- Whenever node nj is reached by node ni the label of nj is bitwise Ored with the label of ni:

$$Bmp(nj)=Bmp(nj)|Bmp(ni)$$

- The topological order followed by the DFV guarantees that labels fully represent COI dependencies

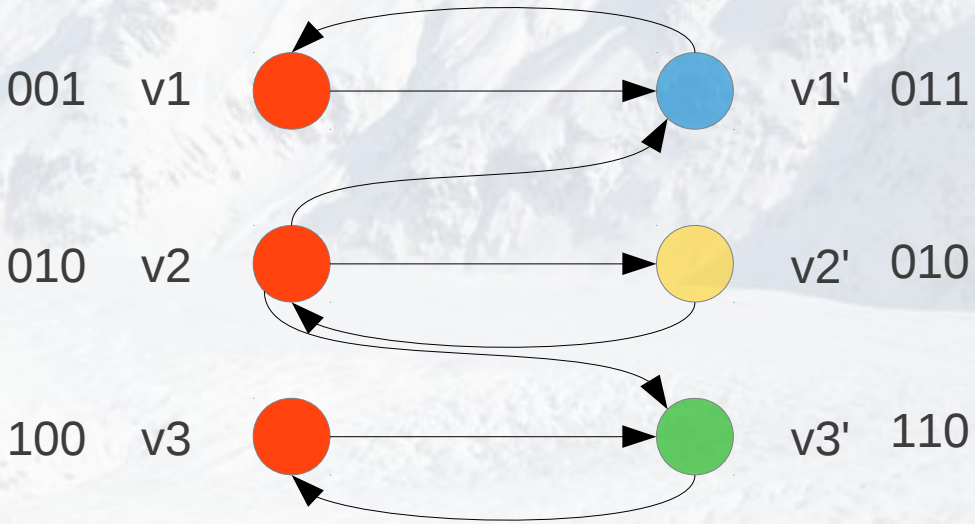
Labeled COI computation

Initializations

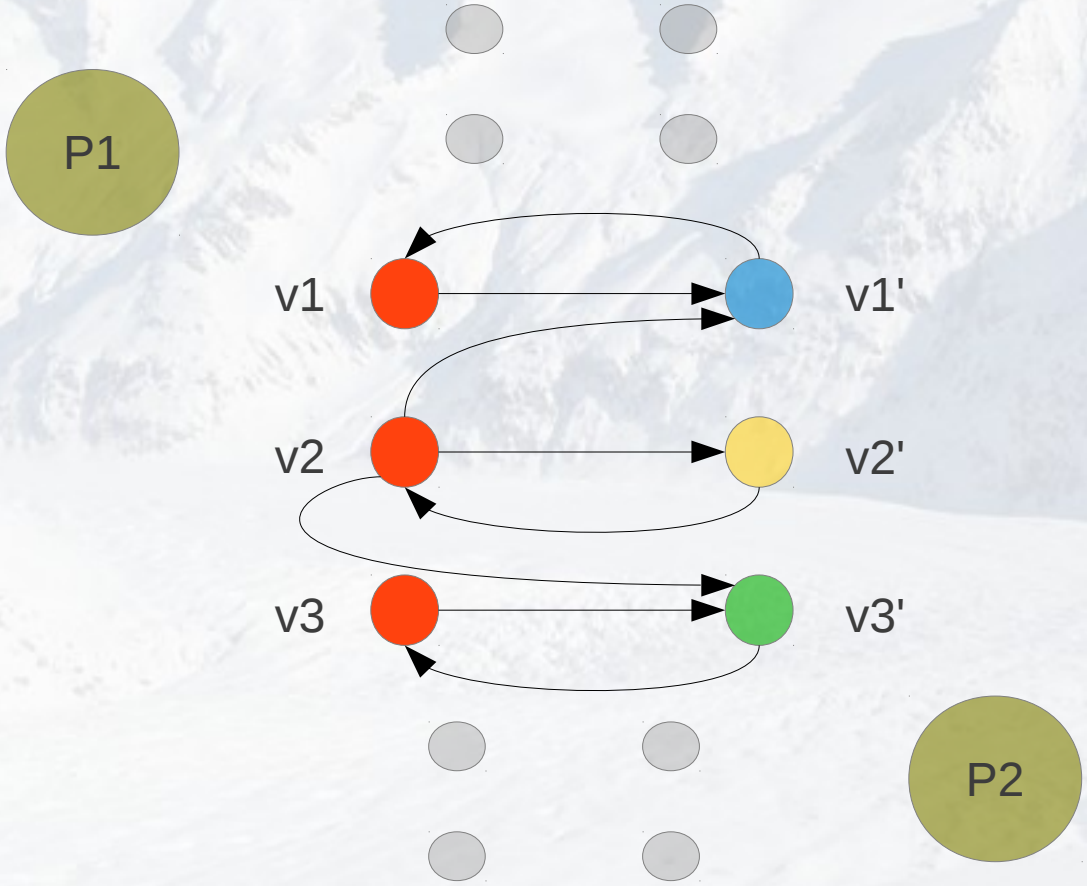


Labeled COI computation

Final result



Labeled COI computation



Strong Connected Component reduction

- Many circuits comprise one or more SCCs within each node may reach each other node
- SCC can be identified using Tarian's linear time algorithm
- Each SCC can be collapsed into a single representative node
- SCC can be used to avoid loops in the dependency graph

Using COI

Sorting and Grouping/Clustering Properties

- A first application of multiple COIs is the verification of multiple properties of the same model
- Whenever the number of properties is high COIs can be exploited for:
  - Sorting properties based on COI size
  - Grouping/clustering two or more properties into a single verification problem

Using COI

Sorting and grouping/clustering variables

- Another potential application for multiple COI analysis is to augment existing algorithms that statically and/or dynamically sort/group state variables, in BDD and SAT-based model checking
- We propose to compute COIs of individual state variables and consider COI statistics as a base for
  - Exploit heuristics for variable sorting
  - Partitioned transition relation management
  - Partitioned image computation

Using COI

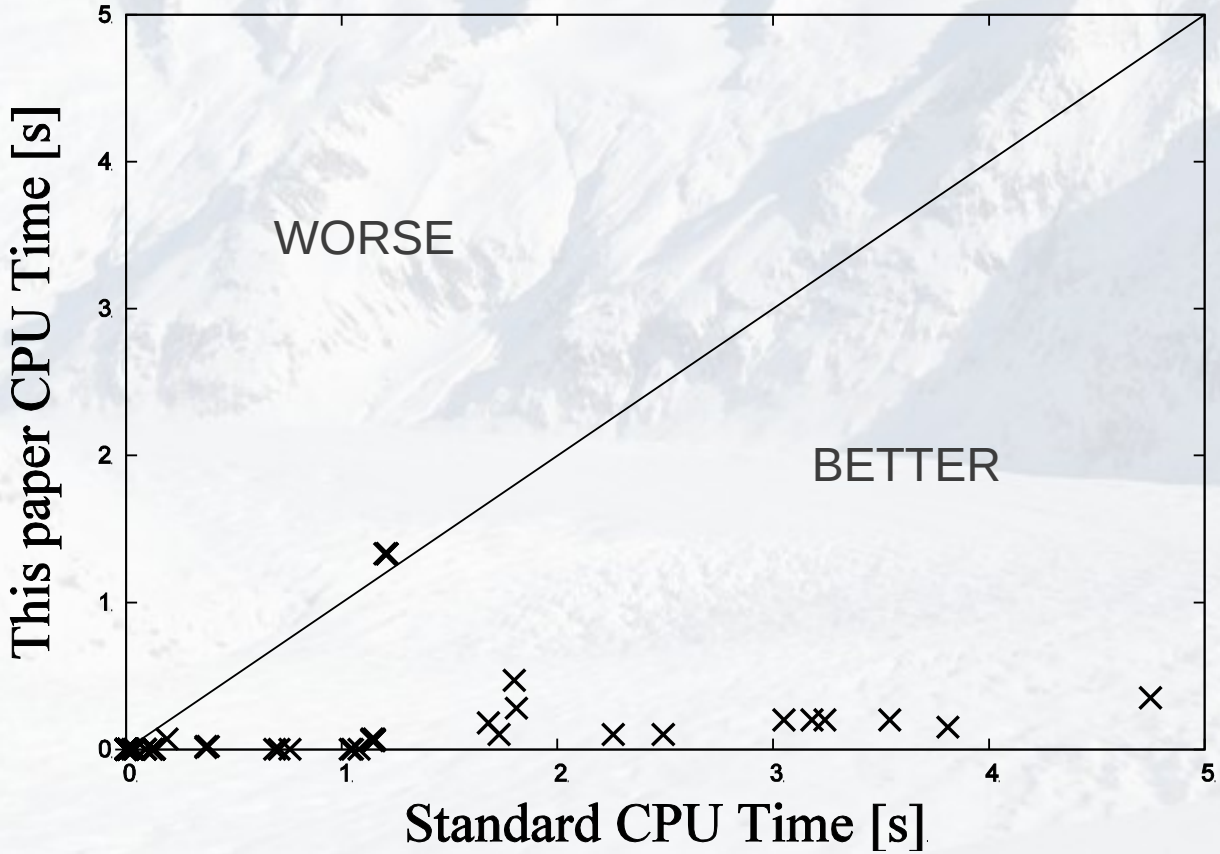
Partitioned transition relation management using COI (On going work)

- We are investigating the question of how to perform partitioning in reachability based verification using COI informations
- Clustering algorithms
  - K-means
  - Hierarchical
    - Single
    - Complete
    - Average

Experimental Results

- We run experiments on the multi-property suite of the HWCC'11
- HWCC'11 consists of 24 benchmarks a some of them with more than 1000 properties
- Our prototype ran an Intel i7 860470/2010 Workstation with 8 MB cache memory, a clock speed of 2.8 G Hz, 4 cores 8 threads, 8 GB of main memory DDR III 1333, and hosting a Ubuntu 12.04 LTS Linux distribution

Experimental Results



Conclusions

- The work introduces new techniques for a fast computation, estimation , and application of the COI of multiple properties
- In order to avoid multiple repeated traversals of the same some sub-graph our algorithm is based on graph node labeling, and it performs a single visit of the variable dependency graph
- It costs is linear in time but quadratic in memory

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