BDDs: You Love ‘em, You Hate ‘em, You Cannot Live without ‘em (and here’s 1 reason why…)

Jessie Xu, Mark Williams, Hari Mony, Jason Baumgartner

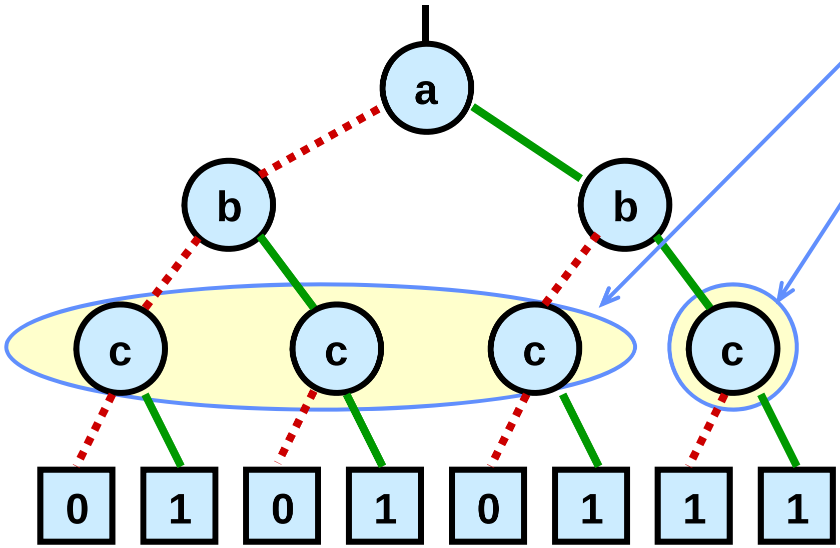
IBM Corporation

Outline

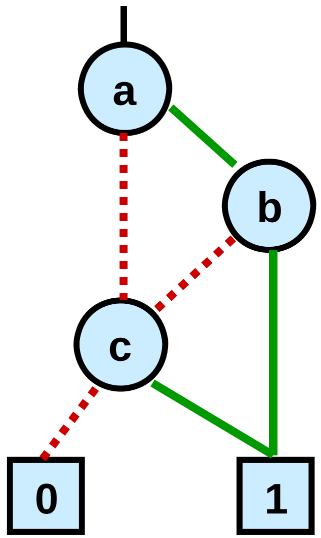
- Preliminaries: Background, Contemporary *Hint* Status Quo
- Technical Contributions: Automation, Stagnation
- Experiments: Utility of Hints, BDDs vs SAT
- Conclusion

Binary Decision Diagrams

- ***Please don't tell me you don't know what BDDs are…***

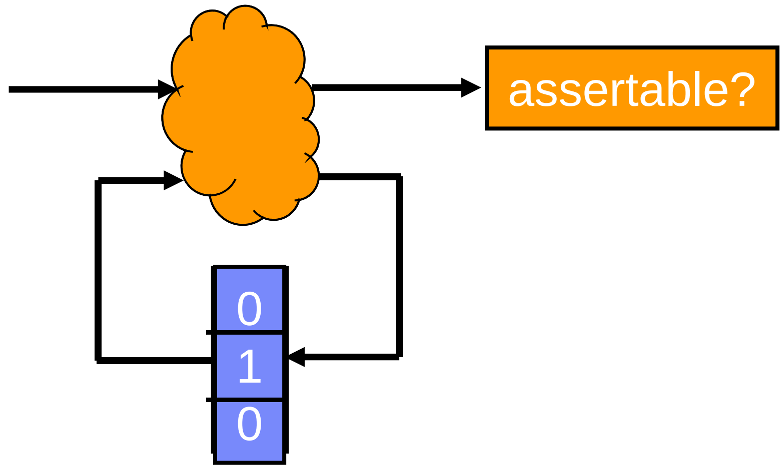


- Reduced Order BDD (ROBDD)
  - Merge isomorphic nodes
  - Remove redundant nodes



Hardware Verification Semantics

- A verification problem may be cast as a *sequential netlist*
  - Recall AIGER: *safety properties* synthesized into simple assertion checks
  - *Assumptions* synthesized as constraints or "input filters"

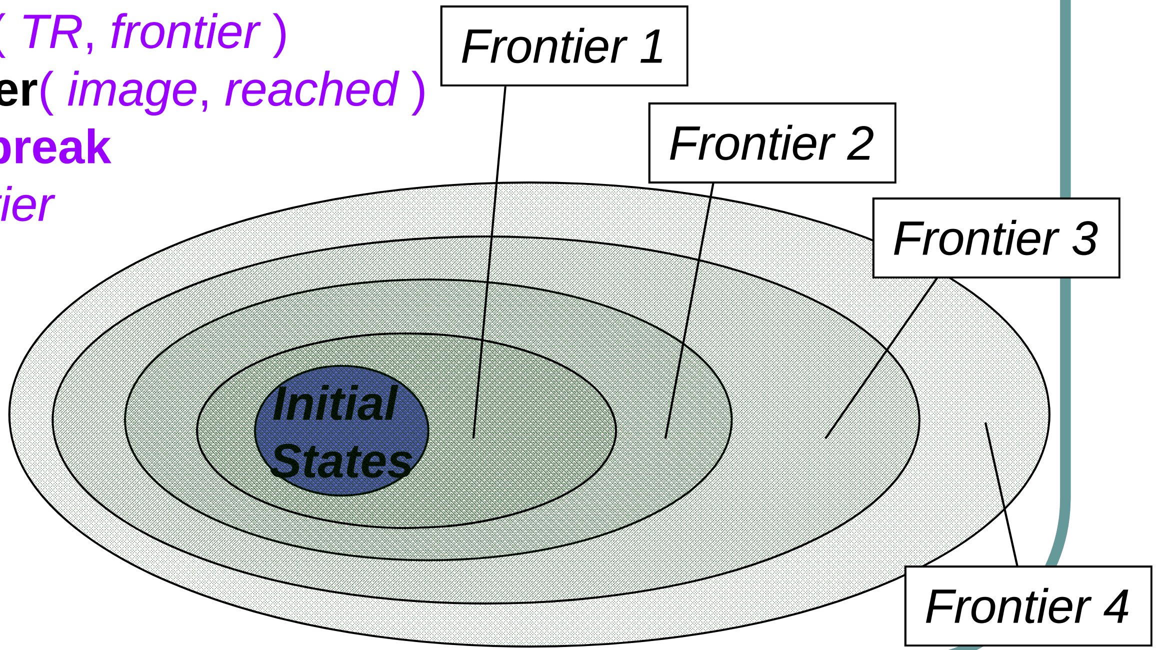


- A *state* is a valuation to the state variables
  - *Reachable state computation* will solve such verification problems

Reachability Analysis

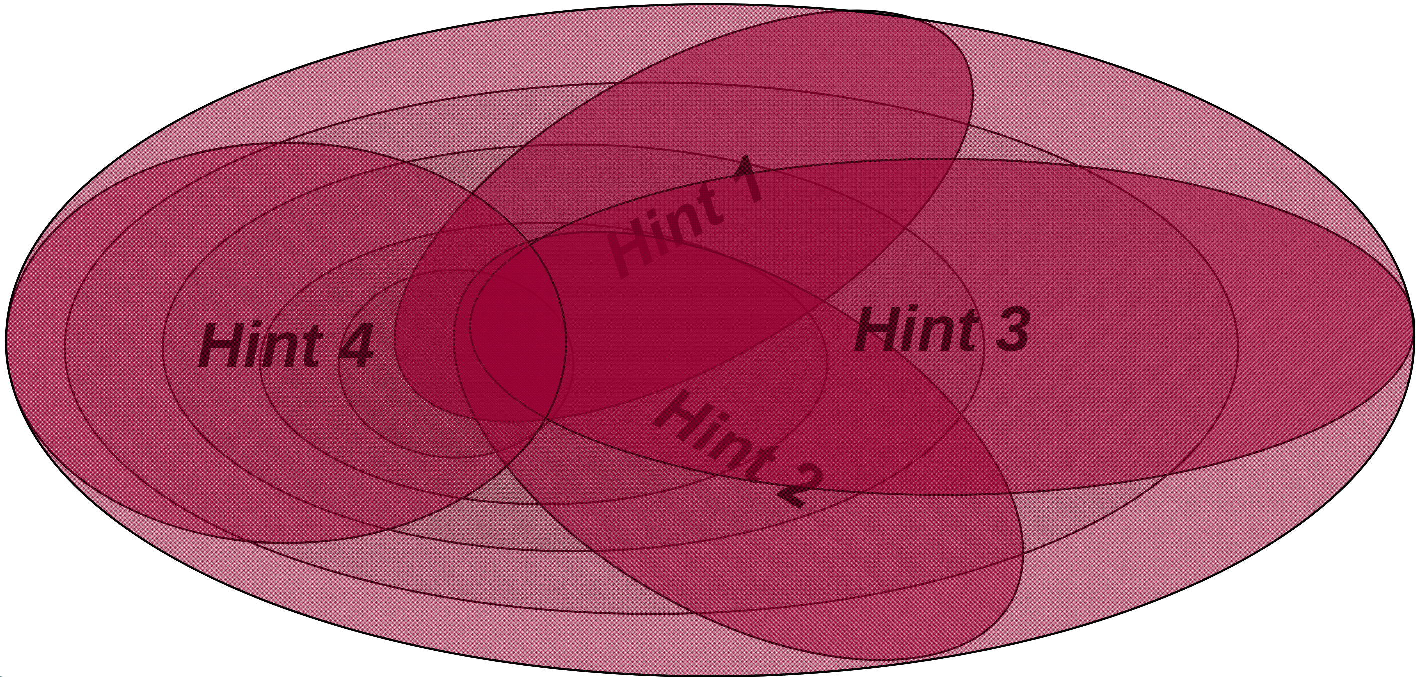
- Uses BDDs for efficient precise quantification; ***breadth-first search***

```
function FORWARDREACH( TR, init states )
  reached = frontier = initial states
  while (true)
    image = compute_image( TR, frontier )
    frontier = compute_frontier( image, reached )
    if (frontier is empty) then break
    reached = reached ∪ frontier
```

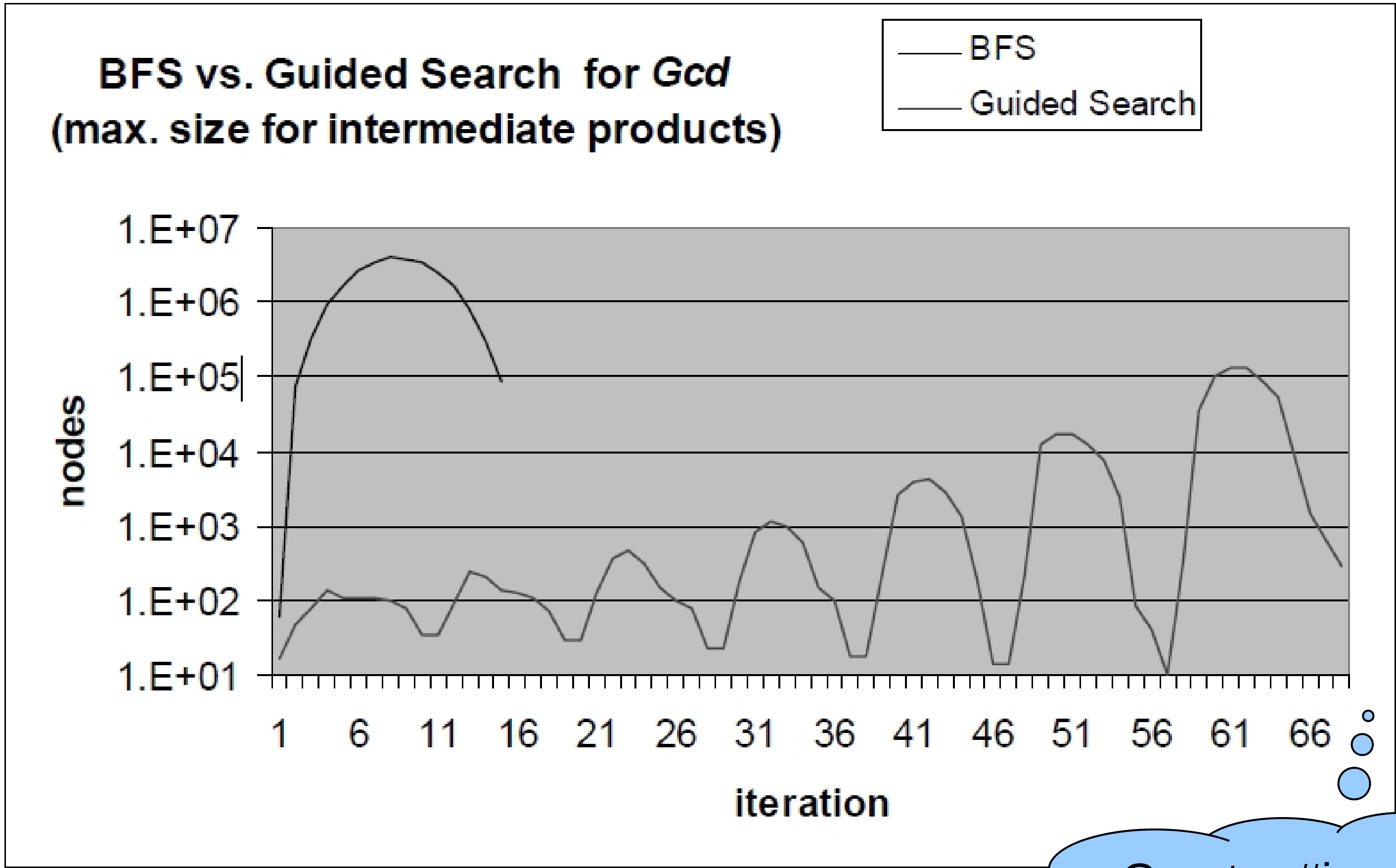


Reachability Analysis with Hints

- Problem: intermediate images result in large asymmetric BDDs
  - Final reached BDD may be compact
  - Intermediate blowup due to exploring distinct behaviors in parallel
- Solution: partition BFS into guided fixedpoints via ***hints***



Reachability Analysis with Hints



BFS: 1131s. Guided Search: 22s.

Greater #images; smaller BDDs

Borrowed from SRC review, covering "Hints to Accelerate Symbolic Traversal" CHARME '99

Original Reachability Algorithm with Hints

functio… EV… TH_HINTS(*TR*, *init states*, *hints*)

> Final hint ***must*** be ***true*** to ensure exhaustiveness

> Hints are *manually* provided and *static*

while (*hint* = pop(*hints*)) **do**

hint_TR = constrain(*TR*, *hint*)

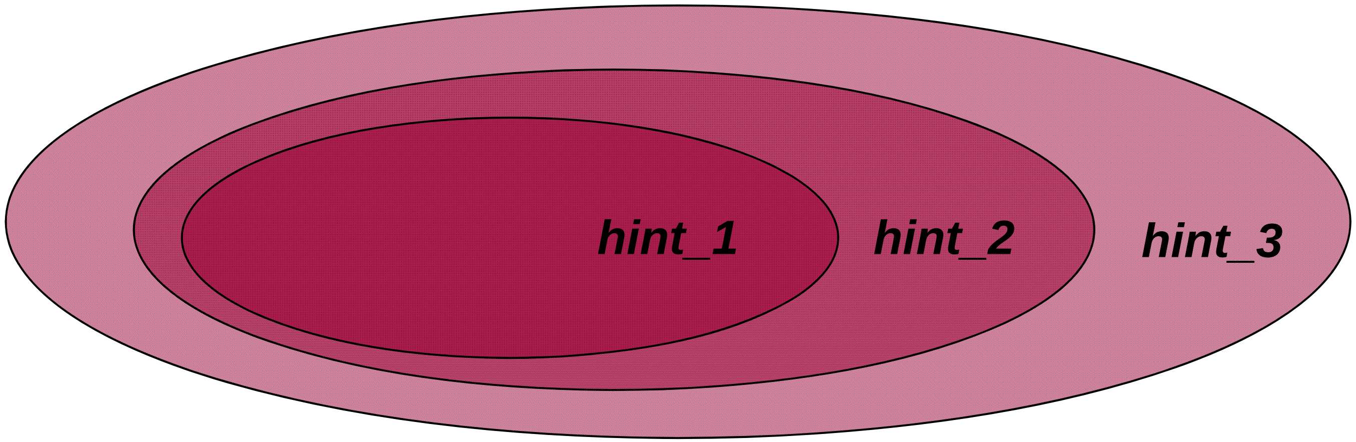
FORWARDREACH(hint_*TR*, *reached*)

> Goal: non-***true*** hints get close enough to true that final iteration is easy

Practical Observations

- *Arbitrary* hints often useful for *complex* problems

- Effective sequence: hint_1 $\subseteq$ hint_2 $\subseteq$ … $\subseteq$ hint_i
  - Then possibly hint_1' $\subseteq$ hint_2' $\subseteq$ … $\subseteq$ hint_j'



- Early work cited design insight to manually generate hints
  - Disable certain operations, limit address ranges, …

Outline

- Preliminaries: Background, Contemporary Hint Status Quo
- Technical Contributions: Automation, Stagnation
- Experiments: Utility of Hints, BDDs vs SAT
- Conclusion

Contribution 1: Netlist-Based Hint Generation

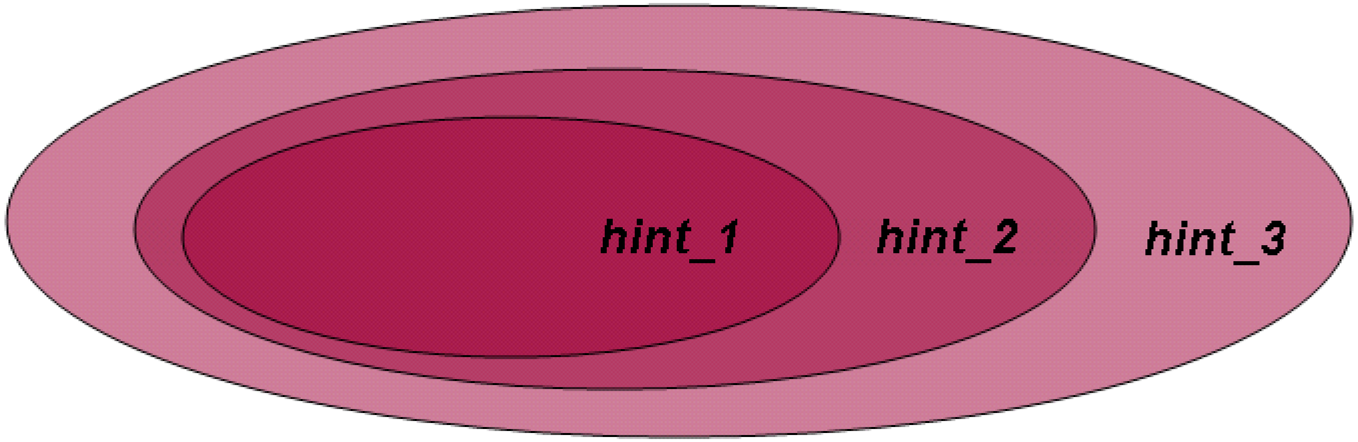
- Prior work focused upon manually-generated hints
  - Automated only to extract *branch conditions* in behavioral Verilog *CHARME 2005*
- Not applicable to:
  - Netlists of general format
  - Post-synthesis designs (equiv checking)
  - General types of designs
    - Pipelined, multithreaded, highly concurrent, arbitration, ...
  - A *transformation-based* tool (all HWMCC submissions)
    - Iterated with bit-level abstraction + reduction algorithms

Contribution 1: Netlist-Based Hint Generation

- Solution: derive hints directly from transition relation
- Rank inputs + state variables by how much they reduce *TR*
  - Select literal polarity with greatest reduction
- Greedily select best "N"
  - Proportional to design size; 10 – 15 works well
  - May prune N based upon to *TR* reduction threshold
- *Predicates* may be more effective than *literals*, though:
  - Nontrivial to determine effective predicates
  - Literals are more efficient to manage with BDDs: cofactoring

Contribution 2: Dynamic Hint Iteration

- Effective hint sequence hint_1 $\subseteq$ hint_2 $\subseteq$ hint_3 $\subseteq$ …
  - ***Conjunction of literals*** become hint
  - Each iteration eliminates one literal



- Literals re-ranked each time a victim is selected
  - DVO occurred since generated: re-ranked literals more apt
  - BDD ops involved in ranking are efficient (literals)

Contribution 2b: Vacuous Hint Elimination

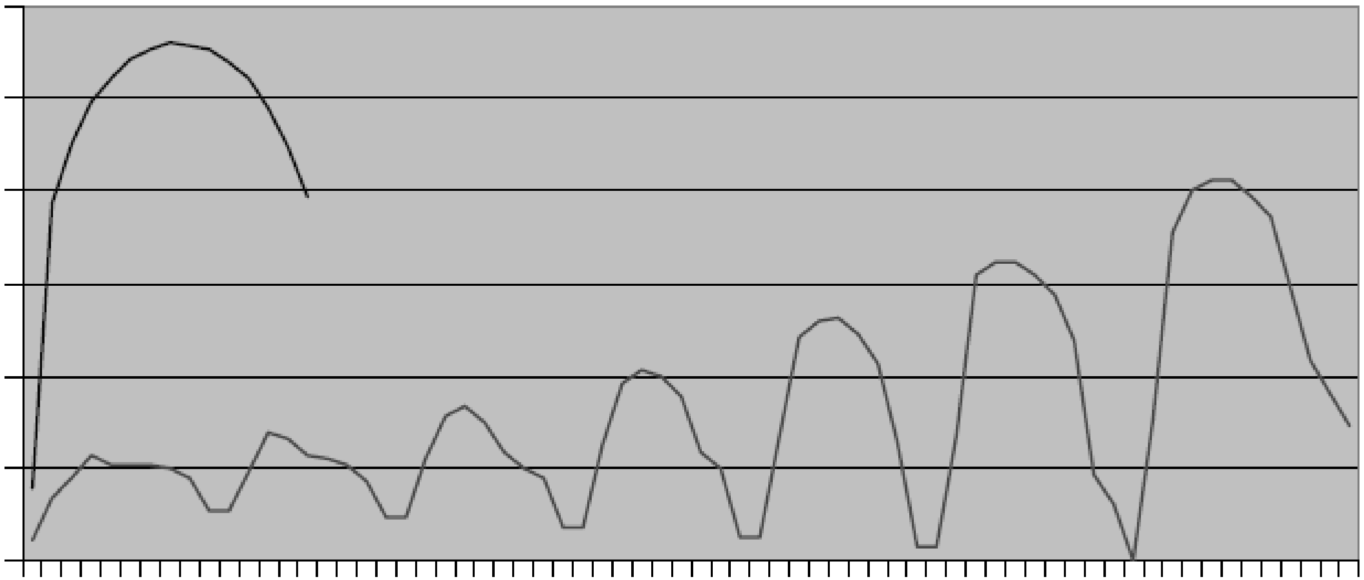
- Occasionally the *next* hint does not add any *new states*
  - E.g., the design transitions on a function of related inputs
- Wasteful to perform image + frontier computation
- if ***(next-hint AND reached)*** $\subseteq$ ***(current-hint AND reached)***
  - Skip next-hint as redundant
- ~15% speedup in overall reachability performance

Contribution 3: Dynamic Hint Introduction

- Hints may degrade performance:
  - Inadequate BDD simplification vs increased #images

- Easy problems: BDD ops already efficient; ~Linear slowdown

- Hard problems: hints may not adequately simplify



Contribution 3: Dynamic Hint Introduction

- Solution: set BDD node limits
  - Threshold exceeded: saturate BDD to *UNKNOWN* value
- Upon UNKNOWN: generate more hints, increase limit 150%
  - 350000 nodes a good starting threshold

1) Iterative generation superior to generating all hints at once
   - DVO likely occurred between calls
2) *Iterative* generation superior to re*start* with current var order
   - Existing hints already constraining current BDDs

Contribution 4: Hint Truncation

- Occasionally a hints >> diameter
  - Known issue: stagnation with sparse images
- Pathological example: counter with *parallel load* port
  - Hint may disable parallel load: exponential diameter increase
- Solution: place upper-bound on #images per hint
- Provably limits increased #images by worst-case linear factor

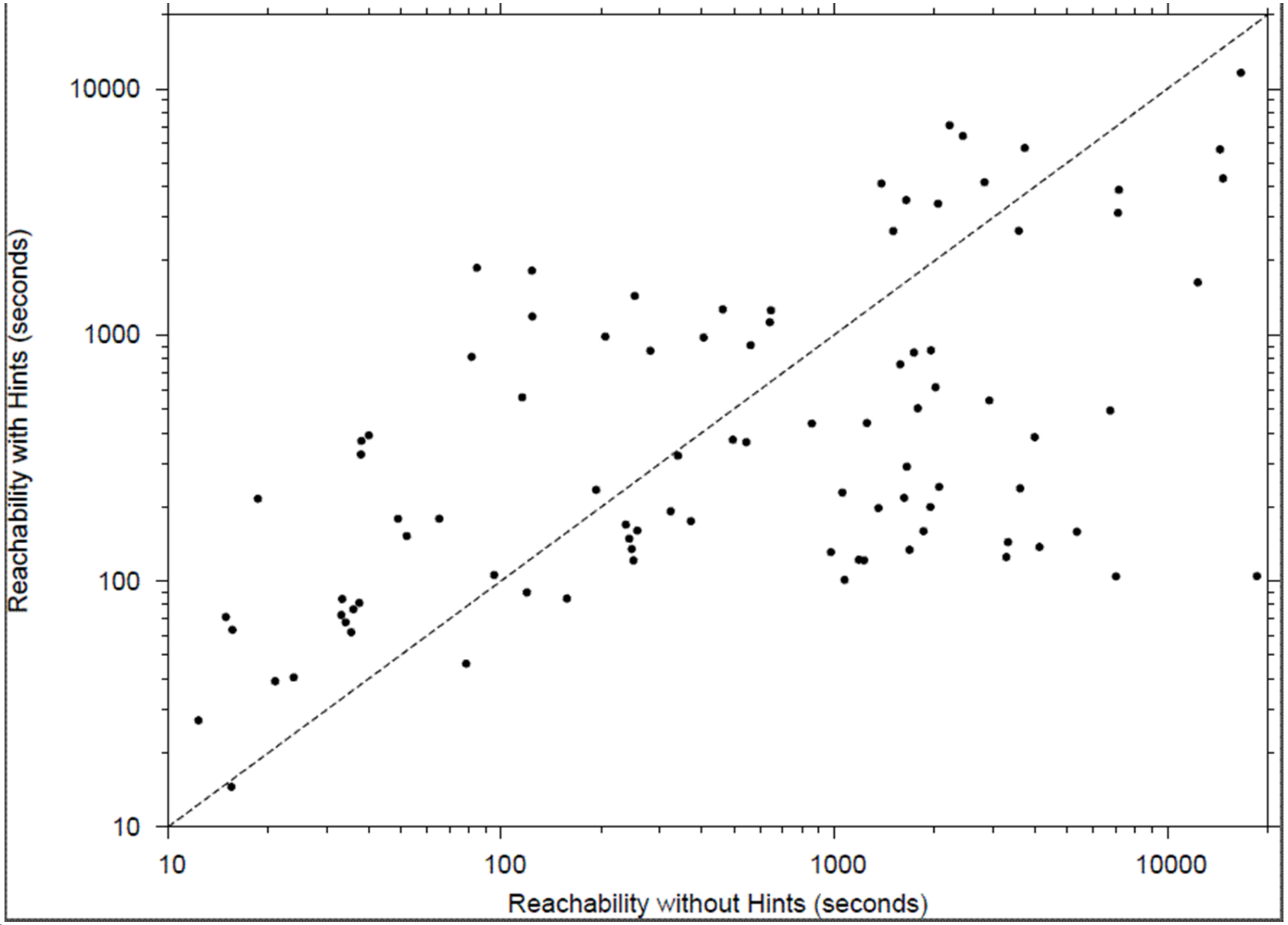
Outline

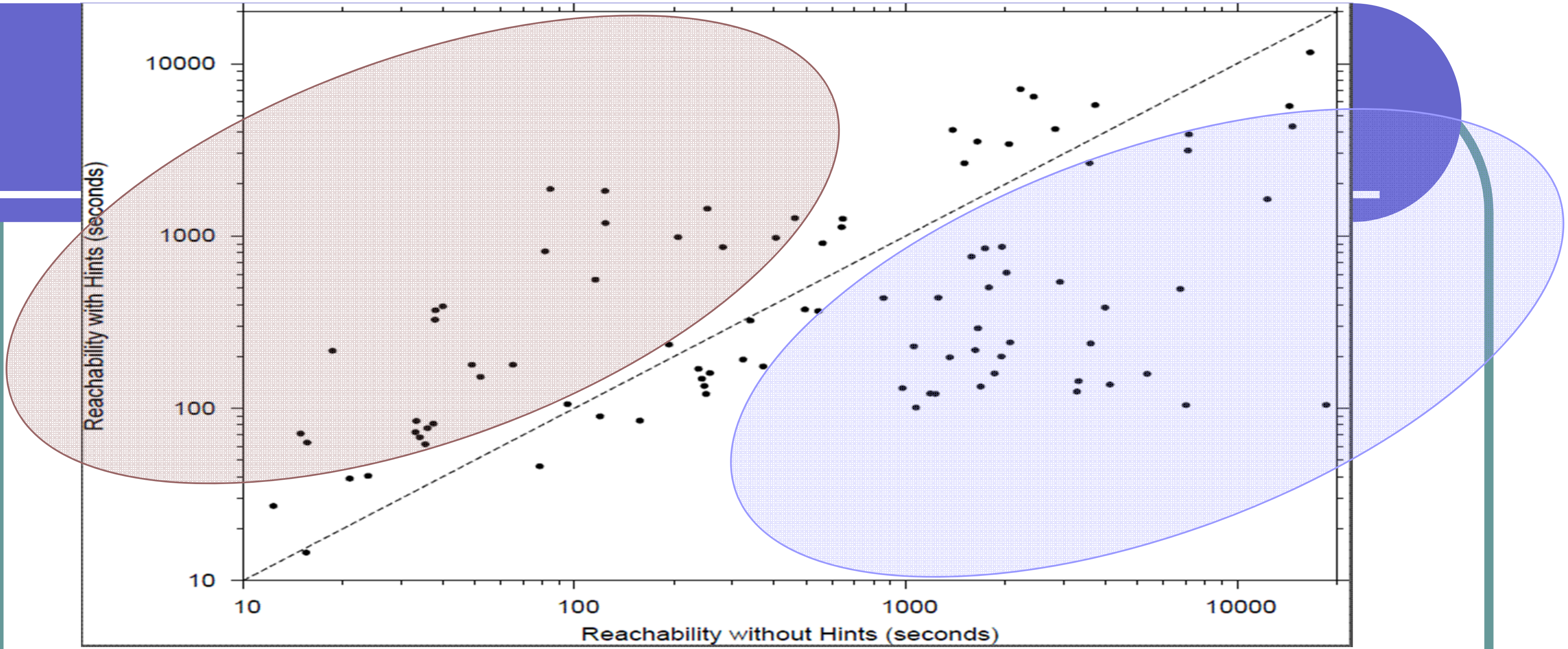
- Preliminaries: Background, Contemporary Hint Status Quo
- Technical Contributions: Automation, Stagnation
- Experiments: Utility of Hints, BDDs vs SAT
- Conclusion

Experimental Setup

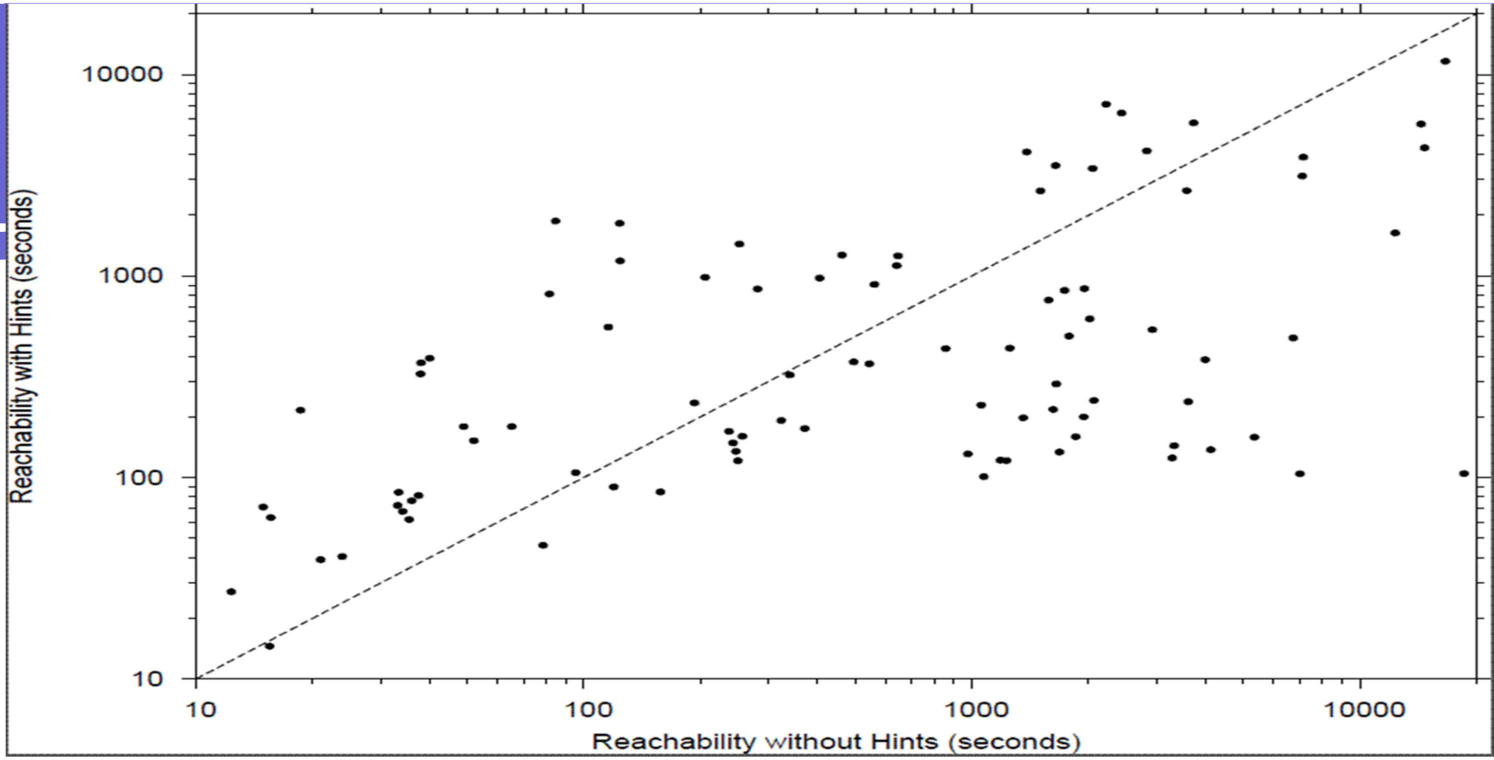
- Focused on HWMCC 2011 benchmarks which were
  - Not trivially solved by logic optimization or random simulation
  - Feasible for reachability analysis either with or without hints
  - And, hints were triggered (else no comparison)
- Time limit 4 hours; memory limit 4GB
- Implemented in IBM's SixthSense toolset

Experiments: Runtime



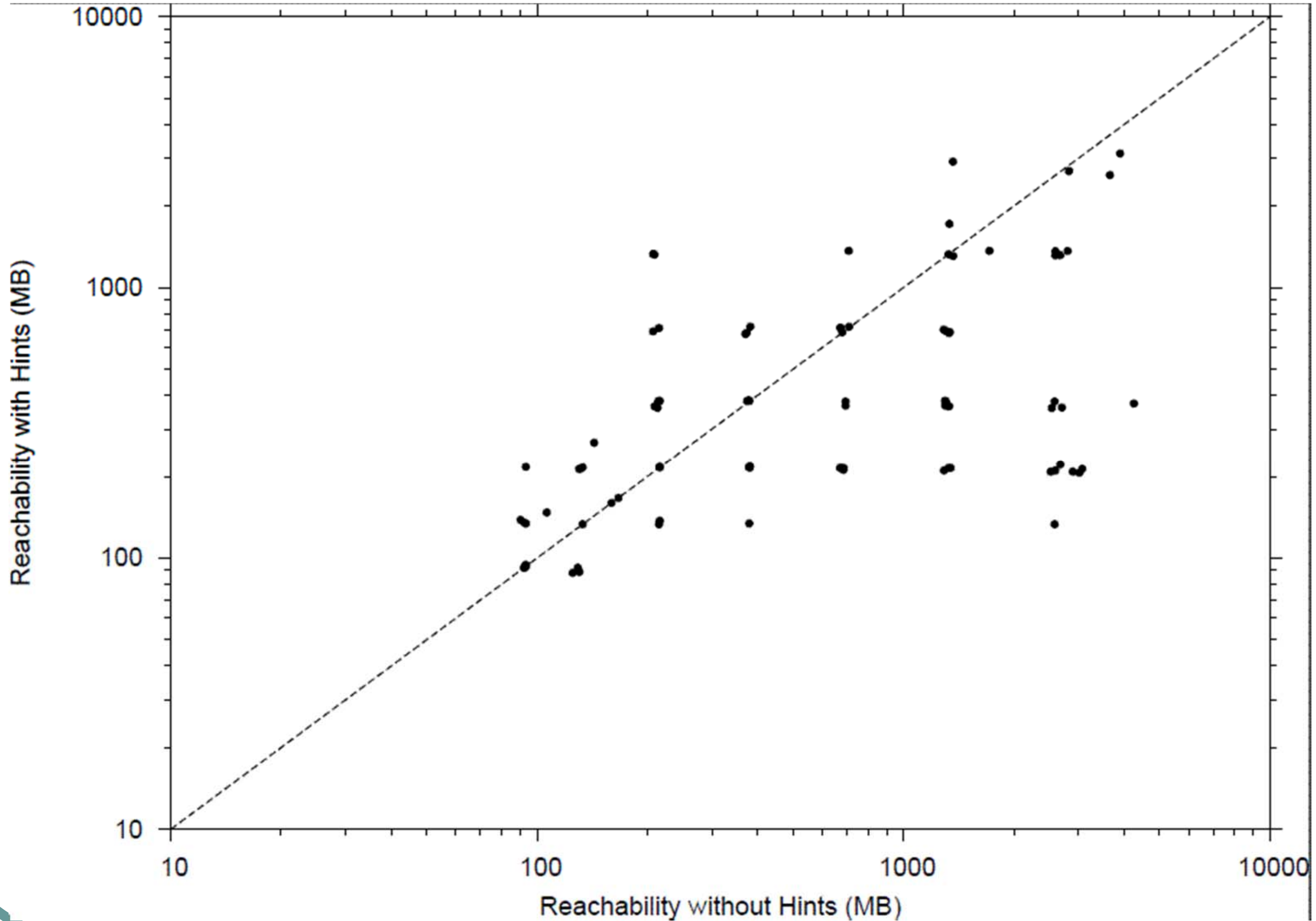


- Speedup proportional to benchmark complexity
  - Simpler problems slowed
  - Difficult problems sped up 1-2 orders of magnitude
    - 3 timeouts without hints; 1.8X cumulative speedup ignoring those
    - Often witness better trend in practice: hints *enable* reachability
- BDDs are heuristic! Variable orders, DVO + GC thresholds, …

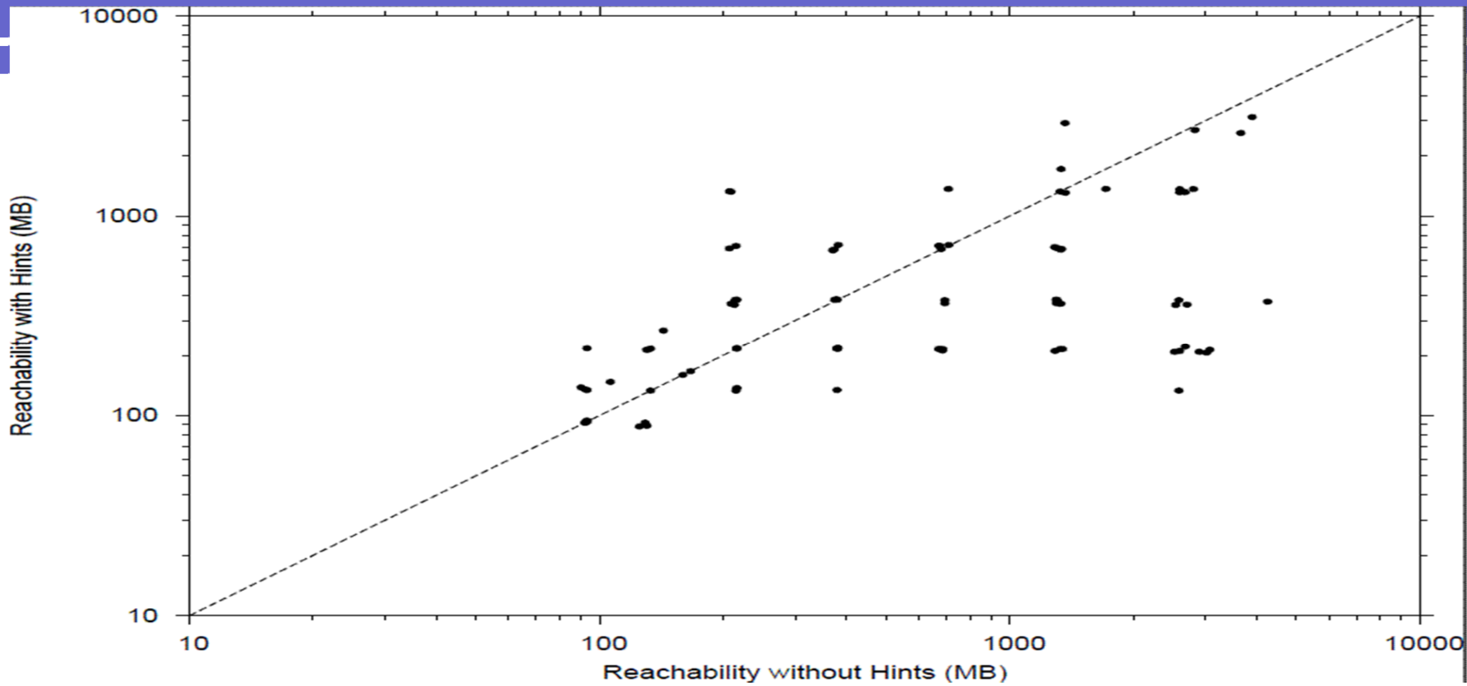


- *Should hint introduction occur only at larger depth?*
- No; if BDDs too large, ***much*** time wasted in DVO etc
  - Parallelizable strategy: more- vs less-aggressive hint generation
  - Simpler problems are not a significant practical concern

Experiments: Memory

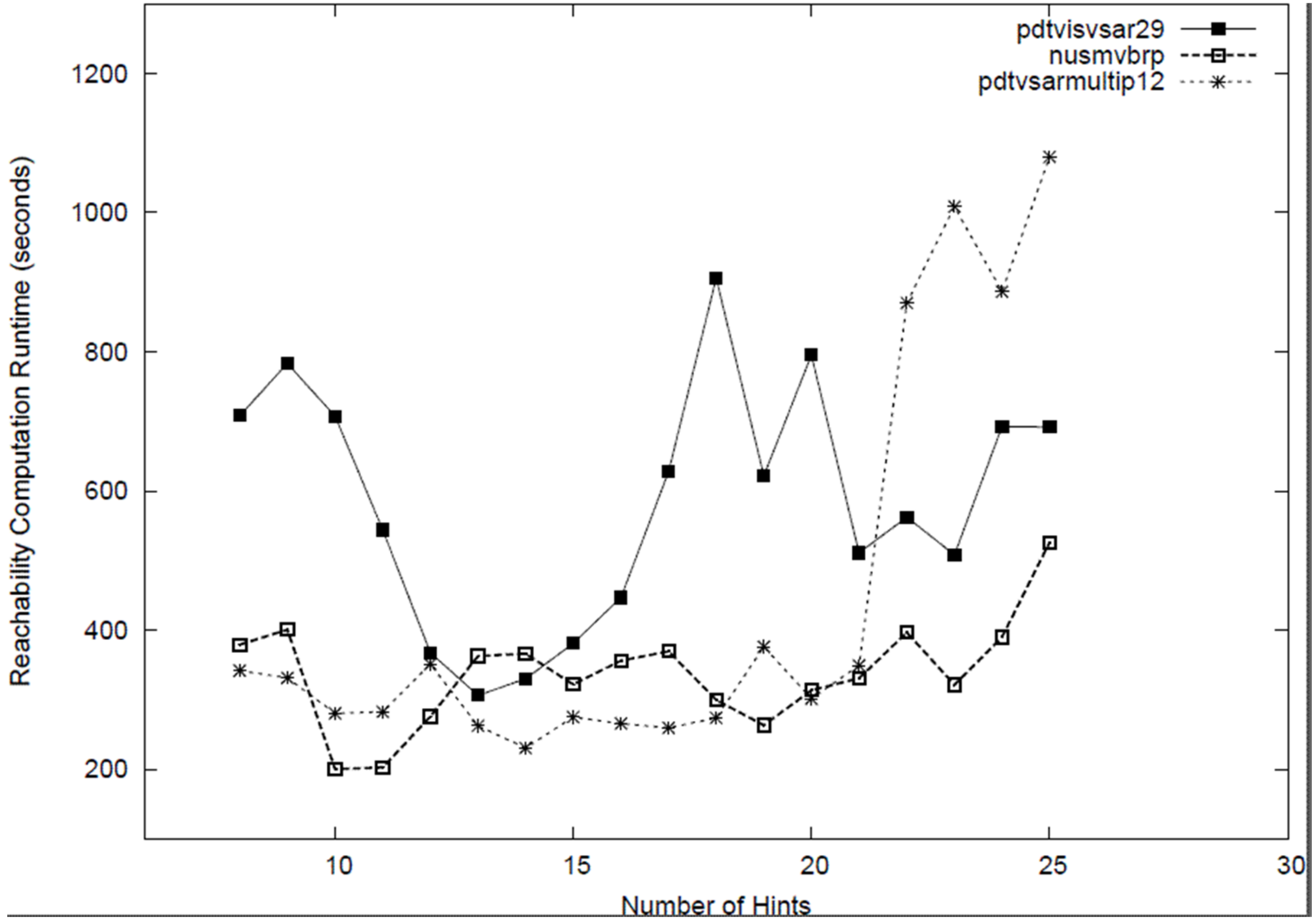


Experiments: Memory

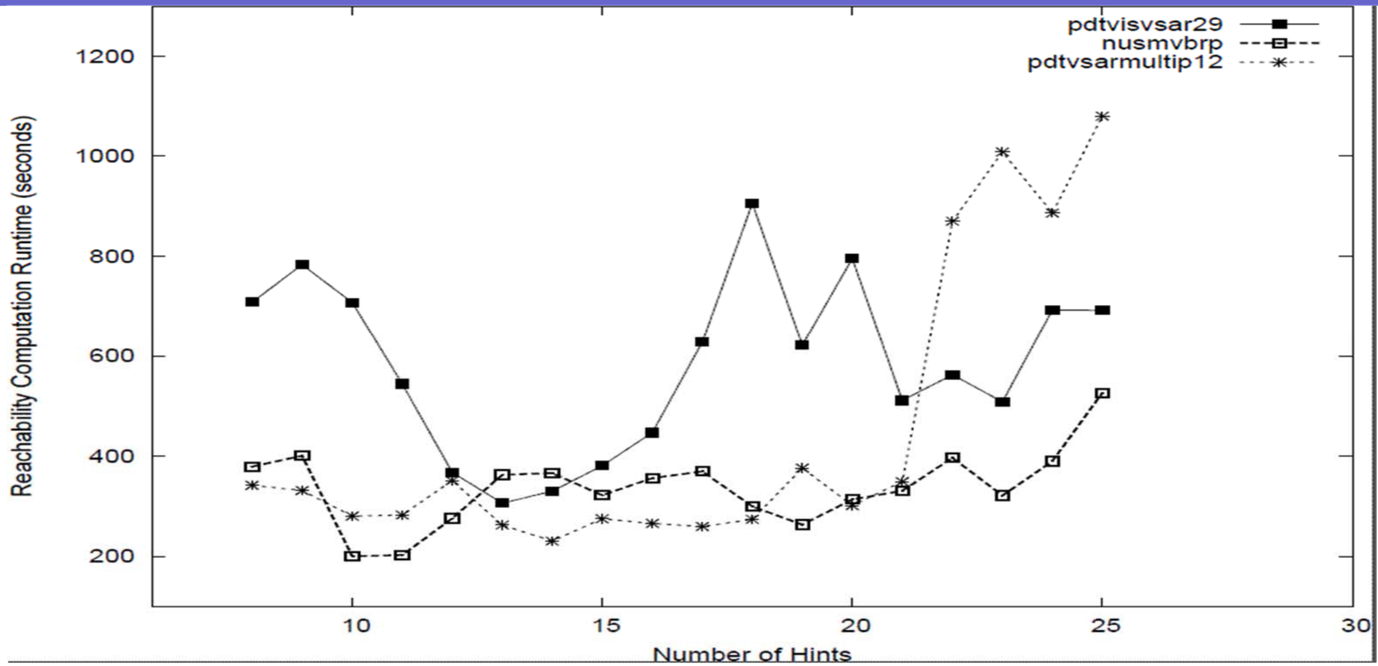


- Significant clustering due to DVO + GC thresholds
- Simpler problems degrade, difficult problems benefit

#Hints vs Runtime



#Hints vs Runtime



- Noisy U-shaped pattern
  - U reflects: BDD simplification vs increased #images
  - Noise is intrinsic in BDD-based reachability…

Importance of Reachability Analysis

- SOTA verification tools leverage a large variety of algos
  - Certain algos better-suited to certain problems than others
  - ***Relentless push for 100% automation***
  - Algos include: reductions, abstractions, proof, falsification
    - *Many* flavors of each
- SAT-based techniques often held as being most scalable
  - Falsification: BMC, semi-formal extensions, …
  - Verification: induction, interpolation, IC3, …
- Experiment 2: assess performance of BDD vs SAT provers

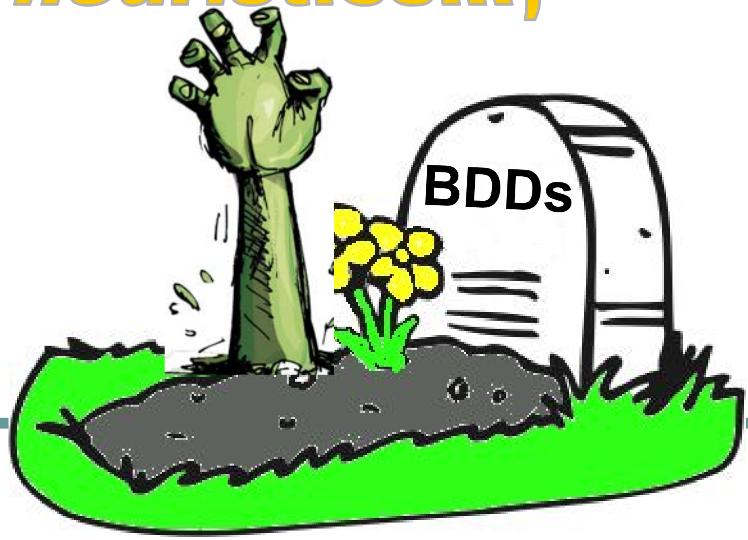
Importance of Reachability Analysis

- On this benchmark suite:
  - Reachability with hints solved all 92 benchmarks
  - Reachability without hints has 3 timeouts (3.2%)
  - IC3 has13 timeouts (14.1%)
  - Interpolation and induction each have 41 timeouts (44.6%)
- Not bad! Though…
- Practical verification tools leverage light-weight time-constrained algos before heavier-weight algos

The Return of the Son of the Curse of the Ghost of BDDs…

- Filtered out benchmarks solvable within 10 seconds
- Of the 29 benchmarks remaining
  - 7 using IC3 (24.1%)
  - 3 using induction (10.3%)
  - 19 solved most quickly using reachability (65.5%)

BDDs Live! (With the proper engineering + heuristics…)



Outline

- Preliminaries: Background, Contemporary Hint Status Quo
- Technical Contributions: Automation, Stagnation
- Experiments: Utility of Hints, BDDs vs SAT
- Conclusion

Conclusions

- Huge disparity in runtime vs. benchmark for various algos
- SAT dominates easy problems
- BDDs Live! For complex problems
  - Easy to discount “Easy for technique X“ as easy…
  - ***Hard*** problems underrepresented in research?
- Hints are critical to enable complex reachability computation