Parallel Software Model Checking

Sagar Chaki

October 8, 2015

Software Engineering Institute
Carnegie Mellon University
Pittsburgh, PA 15213

Project Introduction and Overview

Scalability = fundamental challenge in software model checking (SMC)

- Model Checking: My 30-year Quest to Overcome the State Explosion Problem, Prof. Edmund Clarke

Most tools are sequential and do not use the abundant CPU cycles

- SMC is inherently difficult to parallelize
- SPIN has been parallelized, but is explicit-state

Develop a parallel symbolic software model checking algorithm

- Target multi-processors and clusters

Parallelize a recently developed SMC algorithm called Generalized Property Directed Reachability (GPDR)

- Has inherent parallelization opportunities (promising candidate)
- Being used in several SMC application domains (wide impact)

Intellectual and Scientific Merit

SMC Problem

```
void main() {
  int x = 0;
  while(x < 10) x++;
  assert (x == 10);
}
```

Constrained HORN-SAT (CHC) Instance

$$c_1 : x = 0 \Rightarrow P(x)$$

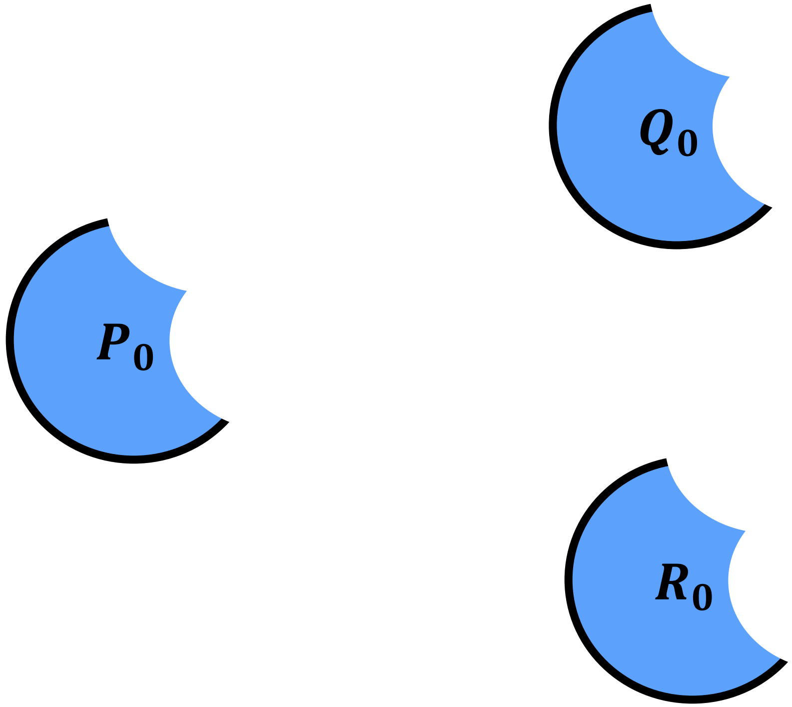
$$c_2 : P(x) \land x < 10 \land x' = x + 1 \Rightarrow P(x')$$

$$c_3 : P(x) \land x \geq 10 \land x \neq 10 \Rightarrow Error()$$

$$Q : Error()$$

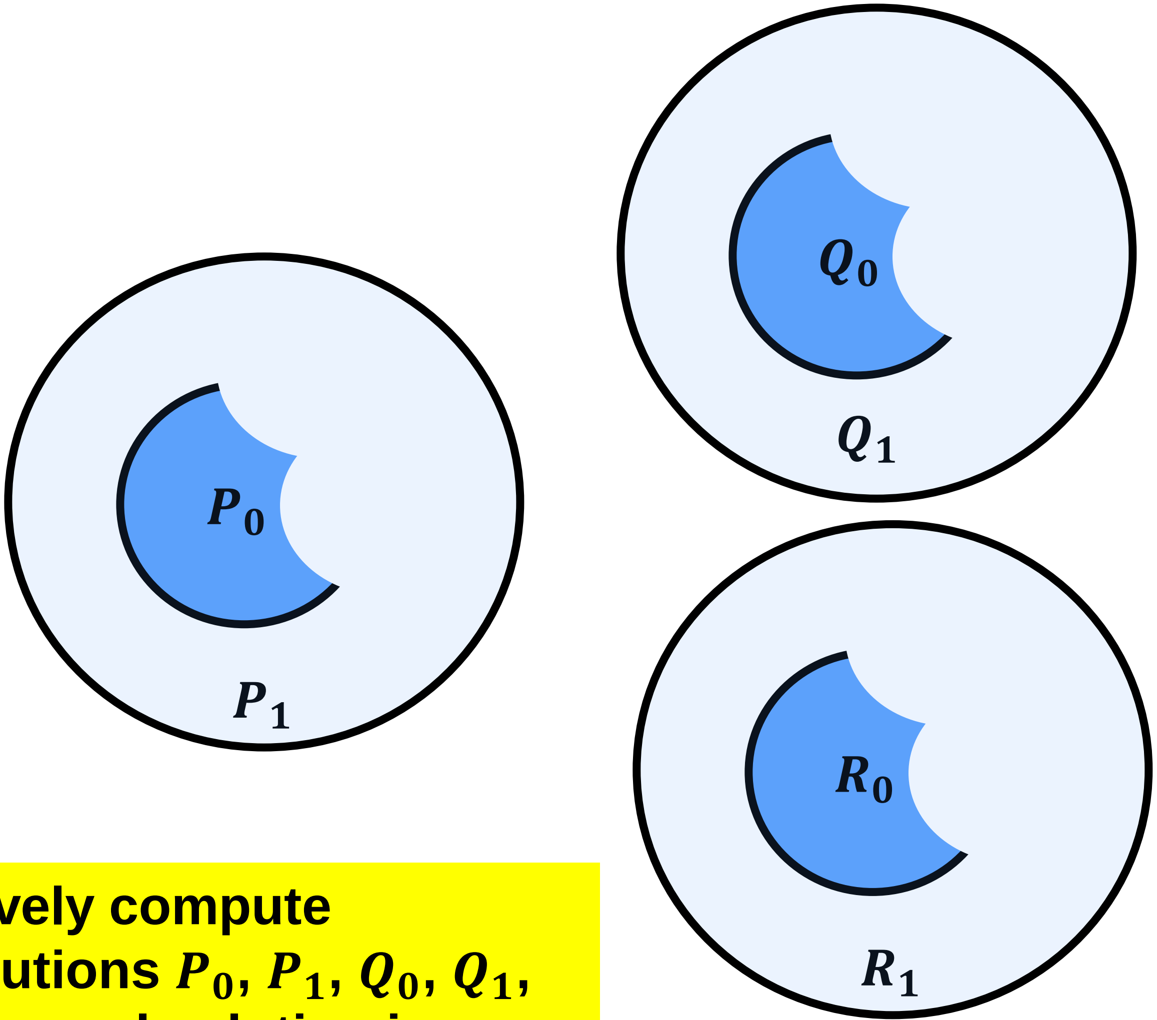
- **CHC = Predicates () + Clauses () + Query ()**
- **Solution = Assignment to predicates that satisfies the clauses such that the Query predicate is assigned**
- **Claim : Solution exists for CHC iff main() never violates assertion**
- **SMC for concurrent programs, real-time software, Lustre programs etc. also being reduced to CHC**
- **Idea: parallelize a recently developed algorithm (GPDR) for solving CHC**

Intellectual and Scientific Merit



GPDR: Iteratively compute candidate solutions P_0, P_1, Q_0, Q_1, R_0, R_1 etc. till a real solution is found, or it is proved that no solution can exist.

Intellectual and Scientific Merit



GPDR: Iteratively compute candidate solutions P_0, P_1, Q_0, Q_1, R_0, R_1 etc. till a real solution is found, or it is proved that no solution can exist.

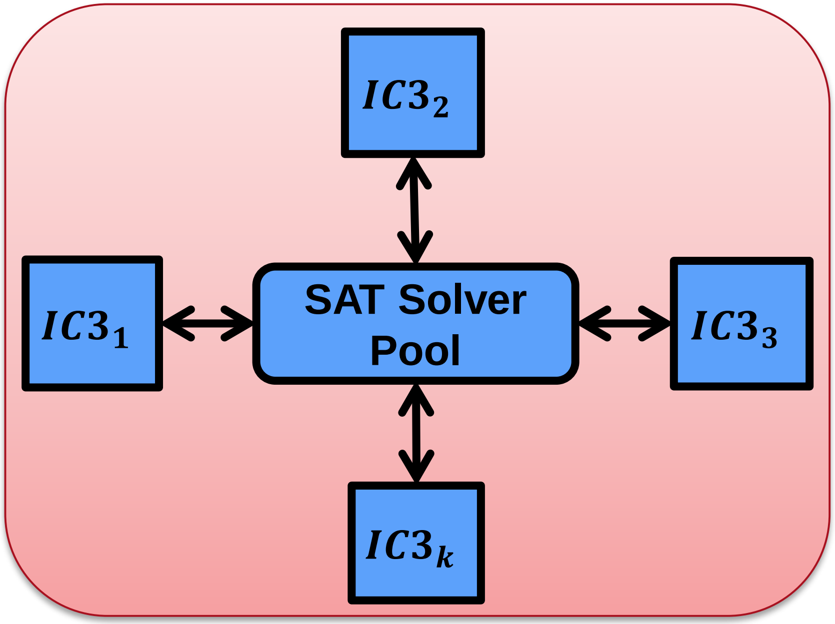
Parallel PDR with Lemma Sharing

PDR = GPDR with a single negative predicate per clause

- Used for hardware model checking
- Also known as IC3

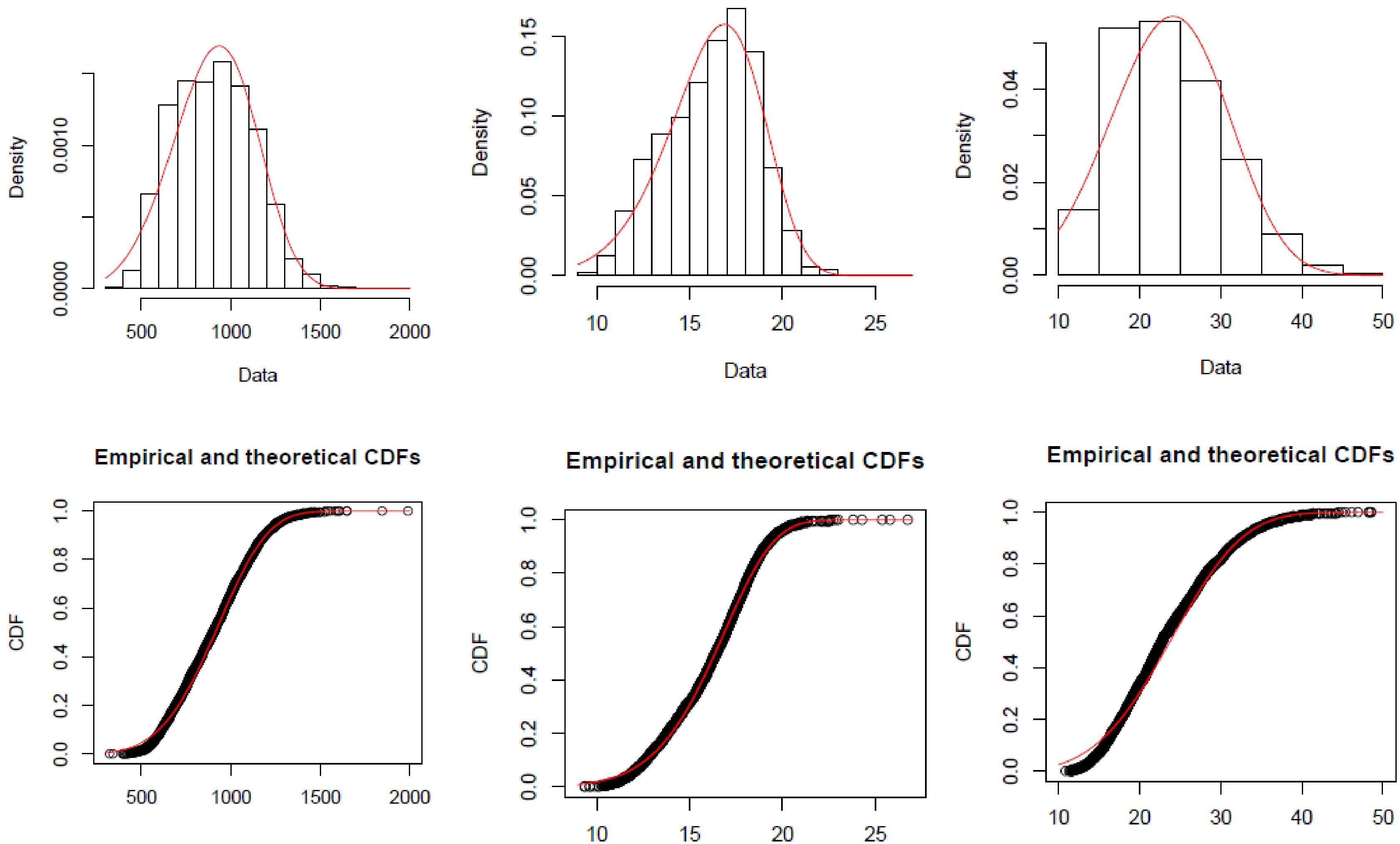
Parallelized a publicly available reference implementation of IC3

- Several copies of IC3 running in parallel
- Sharing facts learned about reachable states (lemmas)
- Three variants: synchronous, asynchronous, proof-checking
- Evaluated on benchmarks from the Hardware Model Checking Competition 2014
- Average speed up over 2x, in some cases over 300x



$Parallel\ PDR$

Unpredictability in Runtime of Parallel PDR



Matches Weibull Distribution = Minimum of iid random variables under Extreme Value Theorem
Solvers "compete" and the fastest one "wins"

Portfolio of Parallel PDRs

Parallelization leads to random runtime

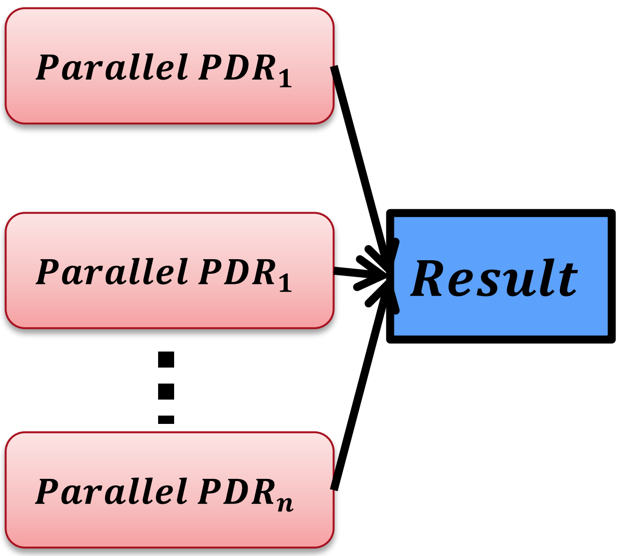
- Information from other copies perturbs the SAT solver and alters the search path in unpredictable ways
- Solution: Use a portfolio
  - Run many solvers in parallel
  - Stop as soon as one finds solution
- How big should the portfolio be?
  - Answer: 20 gives you a .99999 probability of hitting the expected runtime of a single solver
  - Derived using statistical analysis and extreme value theory
    - Runtime of portfolio = min (runtime of solvers)
    - Minimum on iid random variables converge to Weibull distribution

Paper under submission. Tools publicly available.

Probability that a portfolio of m parallel PDRs will finish in expected running time of a single parallel PDR

$$p(m) > 1 - e^{-\frac{m}{e^{\gamma}}}$$

$\gamma \approx 0.57721$ *is the Euler-Mascheroni constant.*



Results: Parallel PDR (4)

		IC3SYNC		IC3ASYNC		IC3PROOF		IC3RND	
$\mathcal{B}$	$\lvert\mathcal{B}^*\rvert$	Mean	Max	Mean	Max	Mean	Max	Mean	Max
HWCSAFE	31	1.30	5.61	1.58	5.47	1.60	4.08	1.17	4.64
HWCBUG	14	2.49	18.7	14.3	151	25.1	309	1.07	1.49
TIPSAFE	14	1.28	4.50	2.61	11.1	2.29	12.8	1.37	3.80
TIPBUG	9	2.23	5.35	2.82	7.32	3.50	12.1	1.16	2.17
SAFE	44	1.30	5.61	1.93	11.1	1.83	12.8	1.24	4.64
BUG	23	2.38	18.7	9.58	151	16.3	309	1.11	2.17
ALL	67	1.67	18.7	4.74	151	6.79	309	1.19	4.64

Results: GPDR Strategies

Rewrote our implementation of GPDR (called Spacer)

- Re-design and re-implementation
  - improved the original code written by a student
  - new architecture is similar to IC3 allowing to reuse our existing work on parallelizing IC3
- Implemented three different solution strategies
  - Differ in the way priorities queues are populated and cleared
  - Results indicate that strategies are complementary
  - Each performs well on different subset of benchmarks
  - Good idea to run in parallel with “loose” coupling
- Tool is publicly available

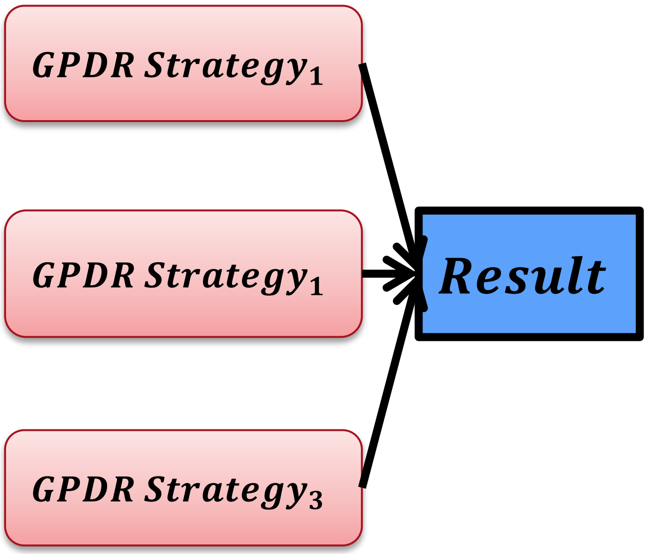
Results: Parallel GPDR

Run different strategies on different machines/cores and share inductive invariants and reachable states (partial solutions)

Use restarts to weed out bad strategies

Observed speedups in some cases, approach has potential

- Insufficient data to draw solid conclusions



Summary

Parallel Software Model Checking

Sagar Chaki (chaki@sei.cmu.edu)
Arie Gurfinkel (arie@sei.cmu.edu)
Derrick Karimi (dhkarimi@sei.cmu.edu)