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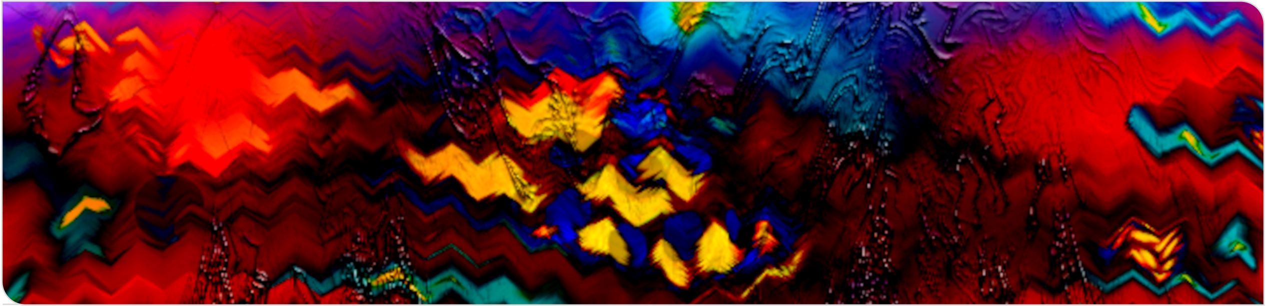
Empirical Evaluations for Hard Algorithmic Challenges

Algorithm Engineering

Markus Iser | March 7, 2025



Professional Background

GitHub

Scholar

- PostDoc at the Algorithm Engineering Group of Peter Sanders
- Organizer of International SAT Competitions
- Research Focus:

  Boolean Satisfiability and Optimization:
  Algorithms, Data Structures, Heuristics, Implementations, Applications, Encodings

  Empirical Algorithmics:
  Global Benchmark Database, Informed Benchmarking, Explainable Algorithm Selection, Research Automation

- Focus of this Talk:

  Empirical Evaluations for Hard Algorithmic Challenges

Some Algorithmic Challenges

Efficiency: Asymptotic runtime and memory usage.

Scalability and Communication: Parallelizability and overheads in parallel and distributed computing.

Correctness: Verification and correctness guarantees.

Empirical Evaluations:

Analytical methods are insufficient to predict the performance of algorithms in practice.

Empirical evaluations are essential for understanding algorithm performance.

Runtime experiments form the cornerstone of **measurement** in empirical algorithmics.

Hard Problems: Boolean Satisfiability and Optimization

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Problems are given as a set of (linear) constraints of the form $\sum_{i=1}^{n} c_i x_i \circ b$.

$\rightarrow$ Boolean variables x_i, integer coefficients c_i, bound b, and operator $\circ \in \{\leq, \geq, =\}$

Goal: Find an assignment to the variables x_i that satisfies all constraints (or prove that none exists).

Problem Variants: Pseudo-Boolean Satisfiability (PBS), Propositional Satisfiability (SAT), Pseudo-Boolean Optimization (PBO), Maximum Satisfiability (MaxSAT), . . .

Applications: Verification, Placement/Routing, Product Configuration, Explainability, Planning, Scheduling, . . .

Complexity: NP-complete / NP-hard

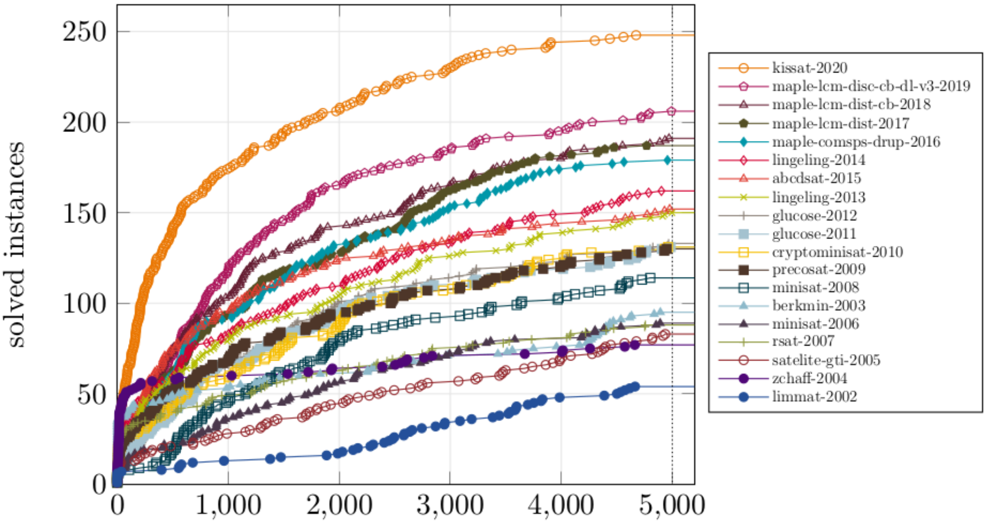
NP = Nondeterministic Polynomial Time: The class of problems where a given solution can be verified efficiently (in polynomial time), but finding a solution may not be feasible in polynomial time.

Boolean Satisfiability and Optimization
Ingredients of Efficient Solvers

Relevance has stimulated research to the extend that modern solvers can efficiently solve real-world instances.

- *Paradigms*: Local Search, Backtrack Search, Resolution-based Learning, ...
- *Algorithms and Data Structures*: Solvers are complex systems with many interacting components.
- *Heuristics and Configuration*: combinatorial explosion of choices
- *Implementations*: Bare-metal implementation skills are crucial, take the hardware architecture into account
- *Encoding*: devise efficient representation as set of constraints

SAT Competition Winners on the SC2020 Benchmark Suite



data produced by Armin Biere and Marijn Heule

Empirical Evaluations
Challenges in Benchmarking

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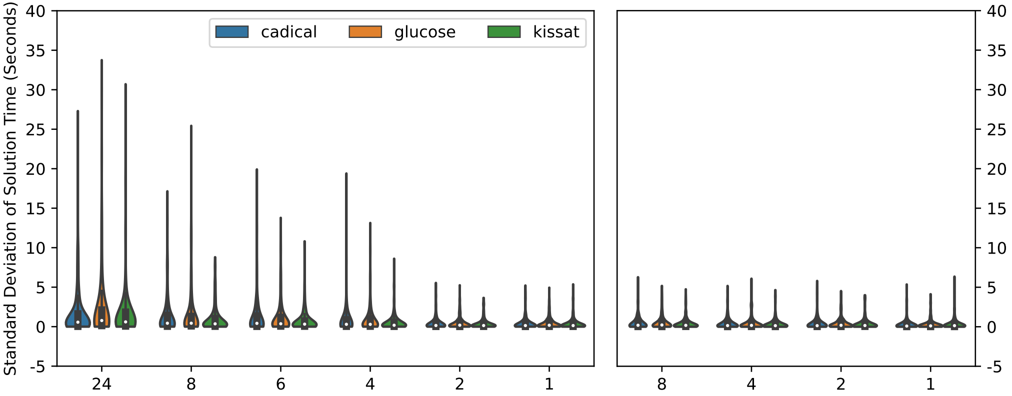
- **Reproducibility**: Ensuring that results can be reproduced by others.
- **Consistency**: Ensuring that results are consistent across different runs.
- Evaluations in the past ran on a large amount of nodes (one job per CPU)
- Modern CPUs have a hierarchical memory structure
  - Non-uniform memory access (NUMA) in multicore architectures
  - Shared caches among cores on the same socket
  - Sharing of resoruces can lead to interference and unpredictable memory access patterns.

Empirical Evaluations

Reproducible and Reliable Measurements

Result of enforcing non-overlapping caches using Resource Control (resctrl) on Intel Xeon E5-2650v4.



From: Parallel Empirical Evaluations: Resilience despite Concurrency, Fichte et al., AAAI-24

Global Benchmark Database (GBD)

Turn to the Extension of an Algorithmic Problem

- Overcome working with sets of mostly anonymous benchmark instances
  $\rightarrow$ with 'meaningful' names like: `44-114583.cnf`
- Dataset interoperability and integrability through computable instance IDs
  $\rightarrow$ Computable ID serves as primary key for GBD datasets
  - Extensible, Decentralized Architecture
  - Identify identical benchmark instances
  - Join instance metadata from different sources
- Track domain, or author of instances, relationships between instances, isomorphism classes, etc.
- Tools for the seamless integration of benchmark data into existing workflows

Richer Evaluations of Runtime Data

Evaluation per Instance Domain (Example: SAT Competition 2023 Dataset)

Family	Count	BreakID-Kissat	SBVA-Cadical	Kissat-MAB-prop
interval-matching	20	10000.00	10000.00	**0.15**
or_randxor	5	103.93	**21.82**	10000.00
hashtable-safety	20	10000.00	797.46	**194.75**
satcoin	15	10000.00	**1395.53**	10000.00
set-covering	20	**262.39**	722.01	5761.57
cryptography-ascon	20	2673.77	**356.82**	5628.35
grs-fp-comm	17	8258.64	3649.90	**3435.82**
reg-n	5	10000.00	10000.00	**6295.16**
mutilated-chessboard	12	5135.77	3194.54	**1656.50**
production-planning	20	5031.37	**2470.42**	3946.63
hardware-verification	8	3964.51	2832.05	**1558.52**
register-allocation	20	2016.39	101.20	**5.50**
...	...	...	...	...

Goals

Systematize Algorithmic Ground Truth in NP-hard Problem Domains

- User-defined Domains, Feature Extractors, and Instance Transformers
- Relations between Domains, Relations between Encodings
- Track Instance Equivalence Classes, e.g., for Isomorphism Classes: isomorphism-invariant hashes
- Generic Toolset for Algorithmic Evaluation
- Rolling Competitions and Automated Benchmarking
- Data-driven Algorithmic Research