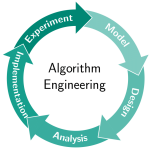
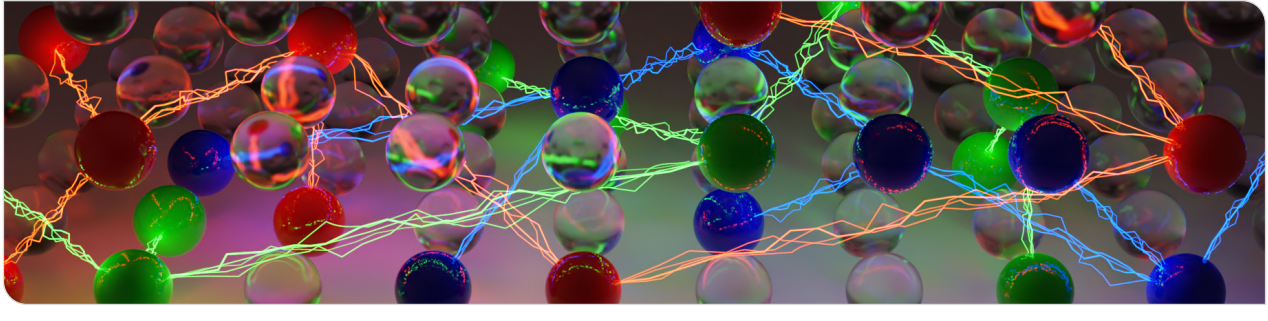
Karlsruher Institut für Technologie



Skalierbares SAT Solving und dessen Anwendung

Scalable SAT Solving and its Application

Dominik P. Schreiber | Kolloquium zum GI-Dissertationspreis 2023 | 6. Mai 2024



Motivation: SAT Solving

Karlsruher Institut für Technologie

Das NP-vollständige Problem **SAT** [Cook 1971]

Gegeben eine aussagenlogische Formel $F := \bigwedge_{c \in C} \left(\bigvee_{\ell \in c} \ell \right)$, finde eine erfüllende Variablenbelegung für F oder melde Unerfüllbarkeit.

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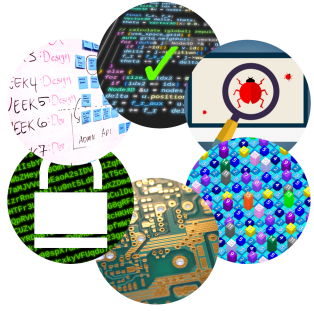
SAT Solving: Fundamentaler Baustein für eine Fülle von Anwendungen

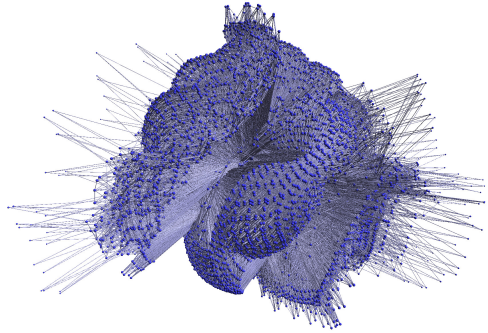
- Planung und Scheduling
- Formale Verifikation
- Testen und Debuggen
- Kryptographie
- Theorem-Beweisen
- Schaltkreis-Design



SAT: Grenzen der praktischen Lösbarkeit

Beispiel: Prüfe zwei arithmetische Schaltkreise auf Äquivalenz.

- Instanz A: 260k Variablen, 850k Klauseln
  - Schaltkreise sind nicht äquivalent
  - Gelöst in 1.33 s von KISSAT_MAB_PROP-NO_SYM [Gao 2023]



Knoten = Variablen;
Kanten = gemeinsame Klausel(n);
Variablen kontrahiert um Faktor ≈ 16

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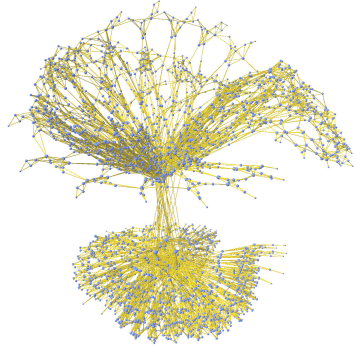
  - Schaltkreise sind äquivalent
  - Ungelöst von sequentiellen Solvern innerhalb von 5000 s



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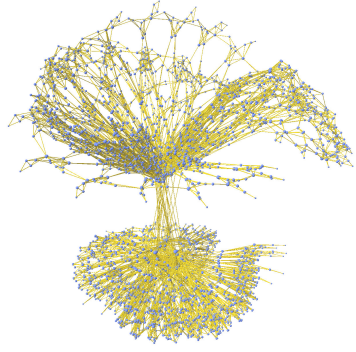
Beobachtung

Es ergeben sich stets praktisch relevante Probleme, die mit aktuellen Solvern nicht praktikabel lösbar sind.



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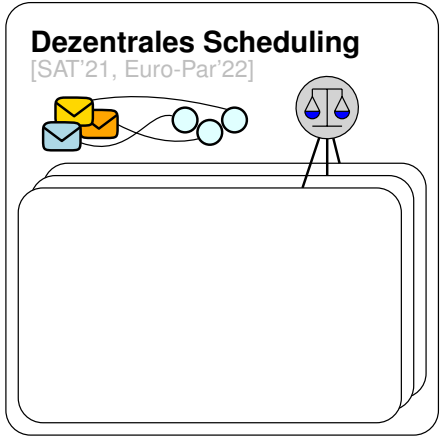
Übersicht



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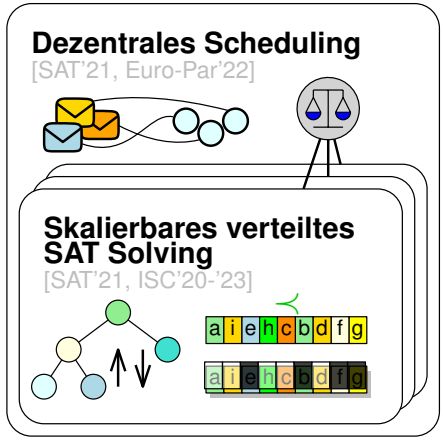
Dezentrales Scheduling
[SAT'21, Euro-Par'22]
Skalierbares verteiltes SAT Solving
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a i e h c b d f g
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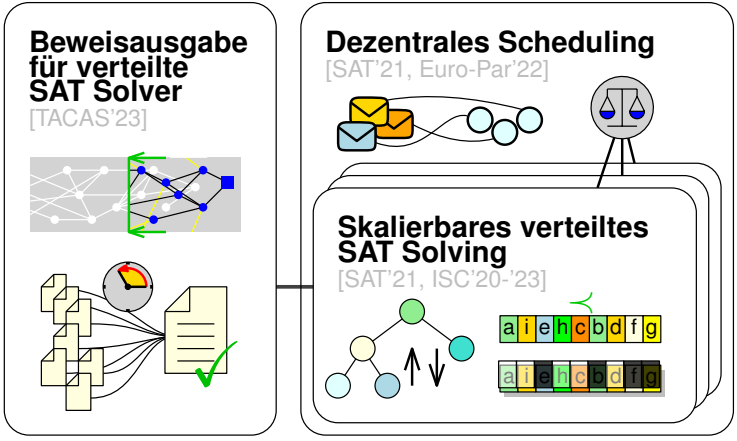
Beweisausgabe für verteilte SAT Solver
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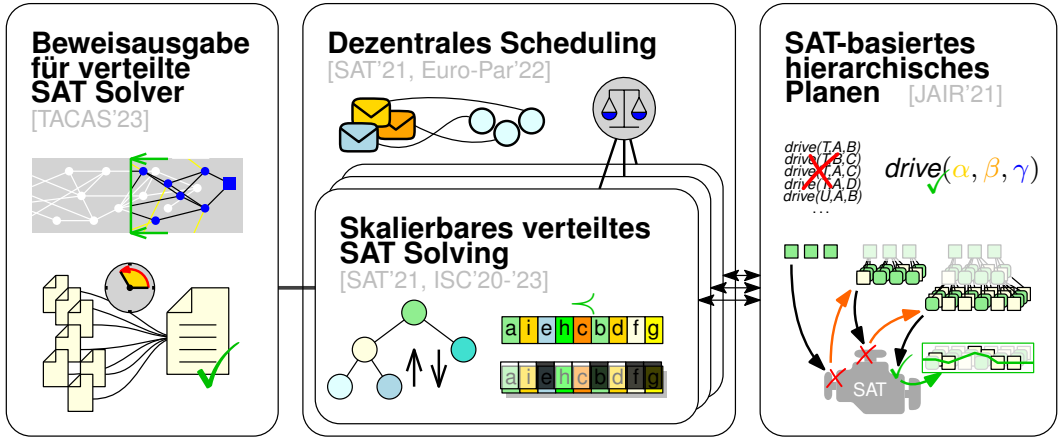
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SAT-basiertes hierarchisches Planen [JAIR'21]
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SAT

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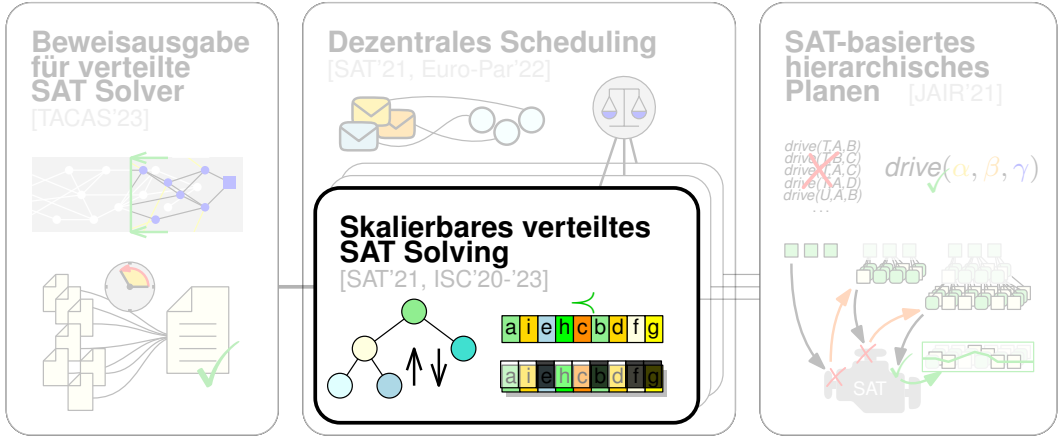
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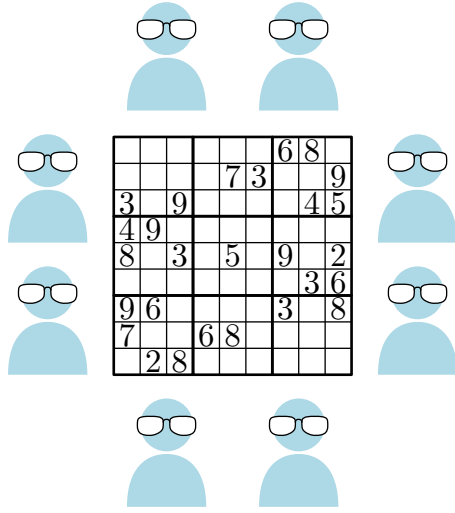
Paralleles Logisches Schließen

Die Versammlung der Logik-Experten

- Komplexes Logik-Puzzle
- *n* Puzzle-Experten möchten das Problem lösen
- Experten arbeiten ungestört am besten

Wie koordinieren wir unsere Experten?



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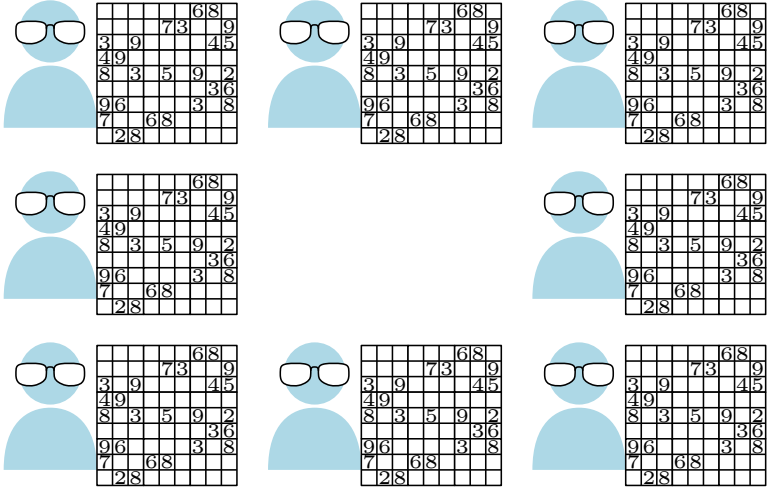

Paralleles Portfolio

- Alle bearbeiten originales Problem unabhängig voneinander

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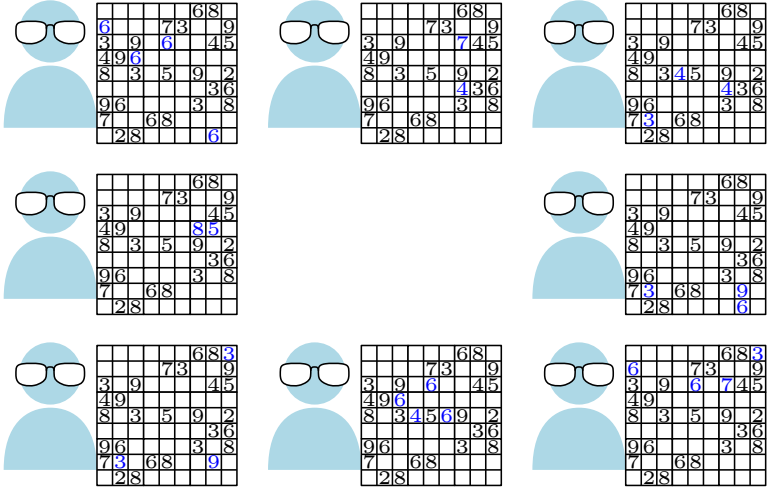

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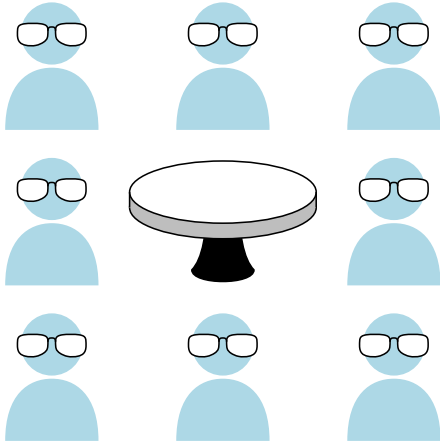

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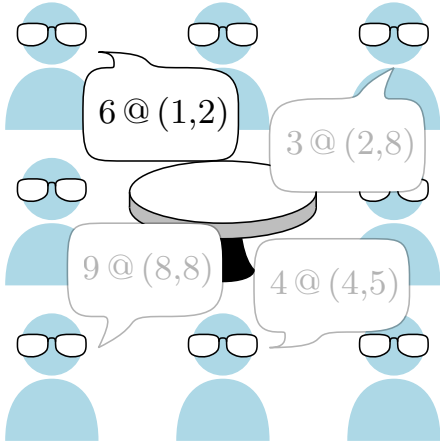

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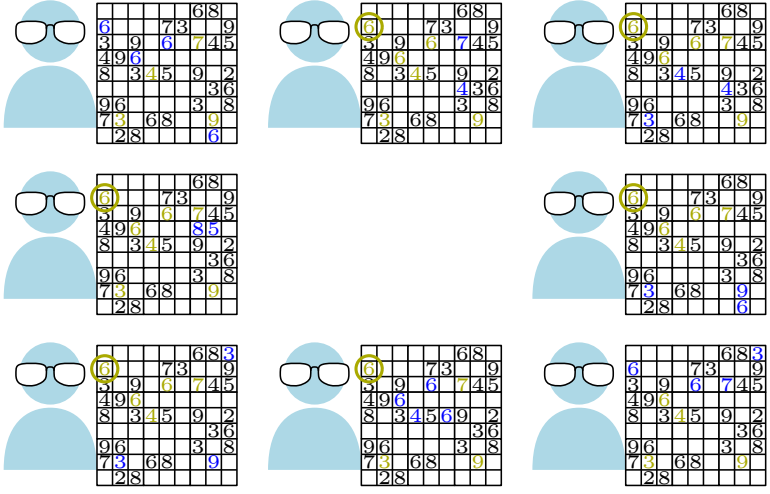

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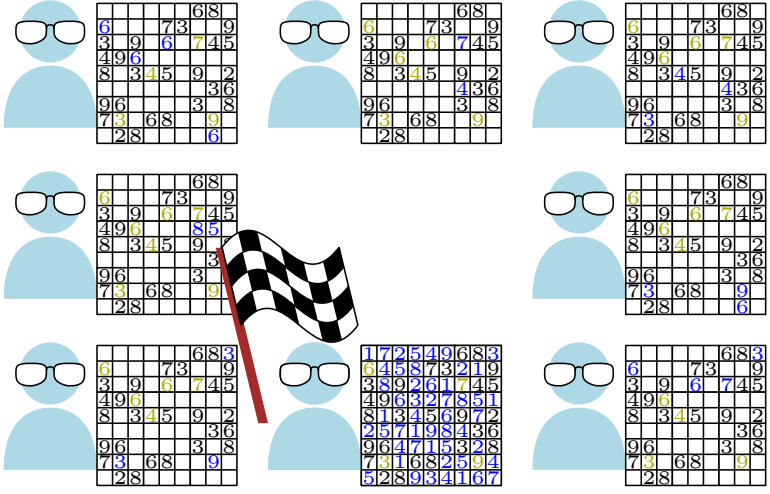

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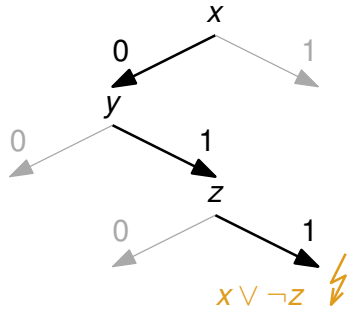
- Erkenntnisse beschleunigen das Lösen
- Nur ein Experte muss eine Lösung finden!

Verteiltes SAT Solving: Stand der Technik

Paralleles SAT Solving [Hamadi et al. 2010]

- Experten ≡ Sequentielle Suchalgorithmen



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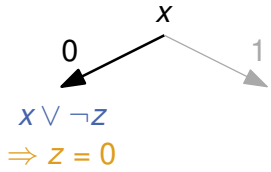

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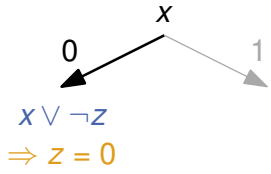

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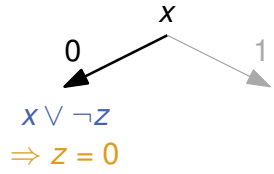

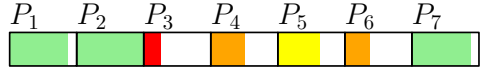

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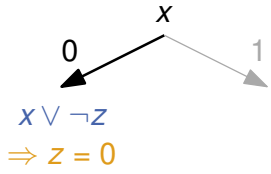
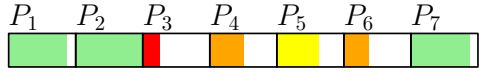
- Experimente mit $\leq$ 2048 Kernen
  - Individuelle super-lineare Speedups ($>$ 2048)
  - Median Speedup auf 2048 Kernen: 13 (Effizienz 0,6%)

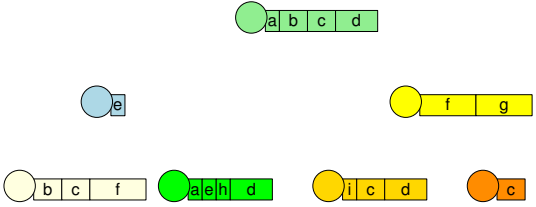




Klauselaustausch: Unser Ansatz [SAT'21, ISC'20-23]

Austausch nützlicher Klauseln

1.



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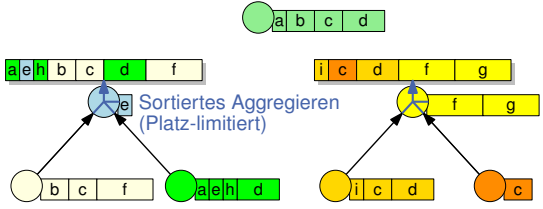

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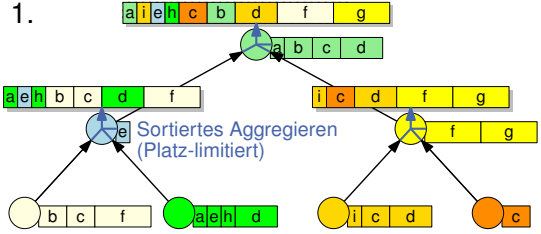

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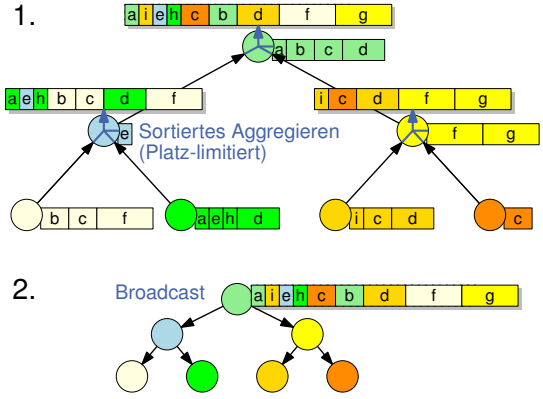

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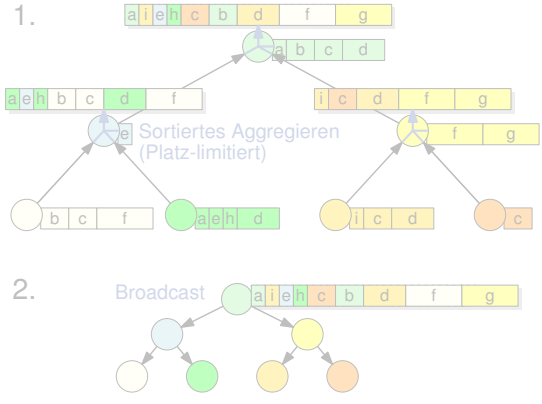
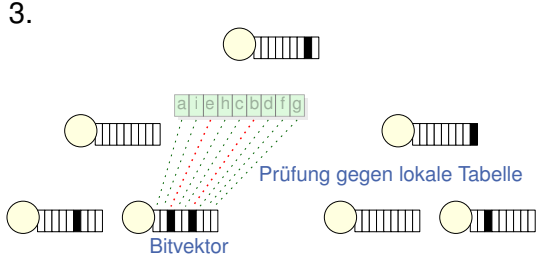


Filtern zuvor geteilter Klauseln



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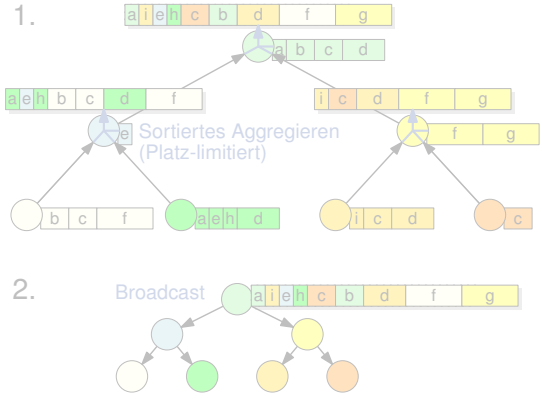

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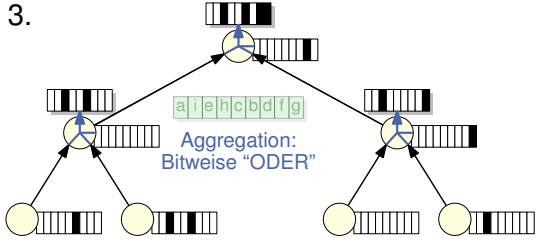

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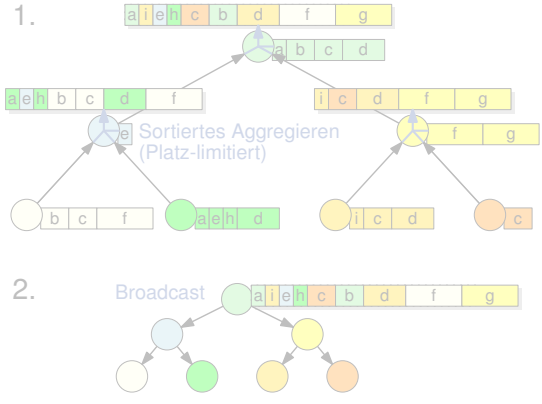

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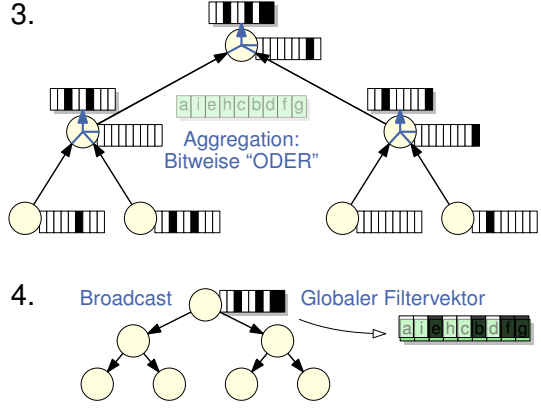
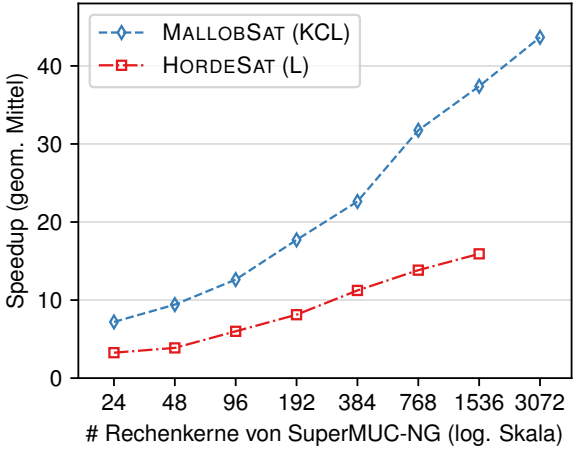


MALLOB: Ergebnisse



400 Probleme aus SAT Comp. 2021 · Seq. Baseline KISSAT_MAB-HYWALK · Seq. Zeitlimit 32 h (gelöst: 331) · Par. Zeitlimit 300 s

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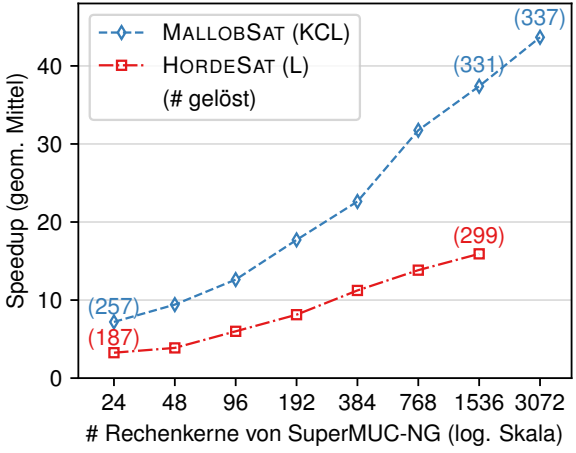

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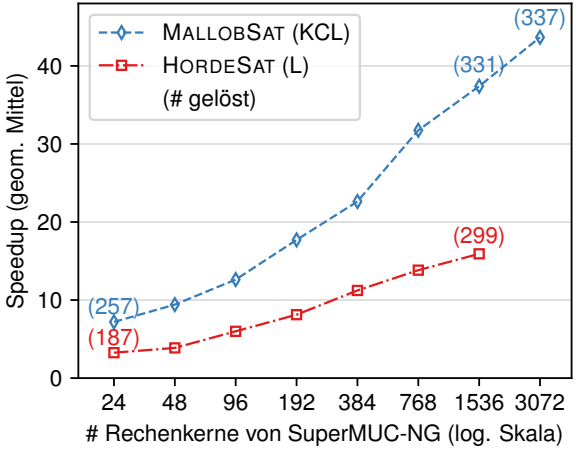

Seq. Laufzeit $\geq$ 1 h $\Rightarrow$ Speedup **419** auf 3072 Kernen

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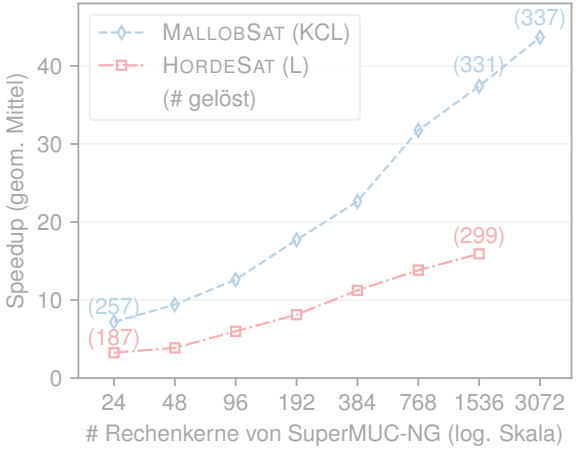


Seq. Laufzeit ≥ 1 h $\Rightarrow$ Speedup **419** auf 3072 Kernen

Flexible Ressourcenzuweisung

- 6400 Kerne, 2 h Laufzeit, 400 Formeln
- Starr: Jede Aufgabe erhält $\frac{6400}{400} = 16$ Kerne
  $\Rightarrow \varnothing$ Antwortzeit: 26.7 min
- Flexibel: Ressourcen fertiger Aufgaben werden an übrige Aufgaben umverteilt
  $\Rightarrow \varnothing$ Antwortzeit: 21.1 min (-21%)

400 Probleme aus SAT Comp. 2021 · Seq. Baseline KISSAT_MAB-HYWALK · Seq. Zeitlimit 32 h (gelöst: 331) · Par. Zeitlimit 300 s

MALLOB: Wirkung

/domschrei/mallob

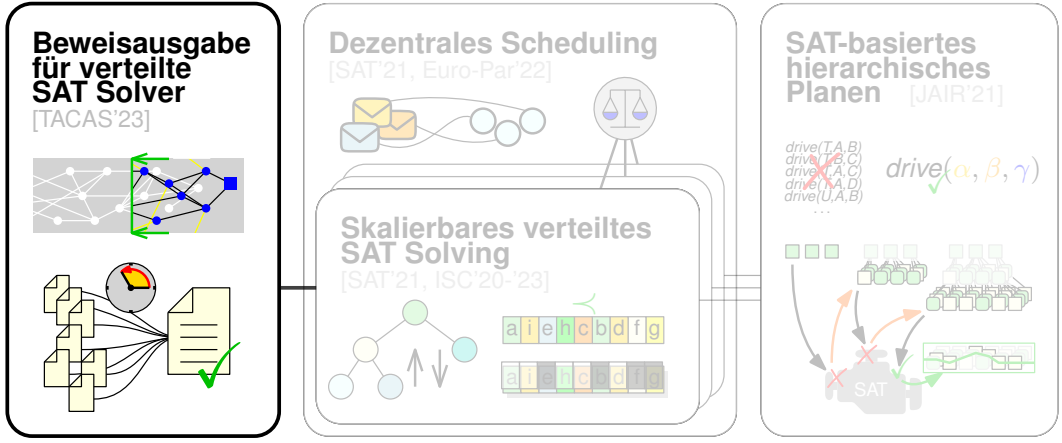
"*Mallob-mono is now, by a* wide *margin, the most powerful SAT solver on the planet.*"

—Byron Cook, Amazon Science, 2021

https://www.amazon.science/blog/automated-reasonings-scientific-frontiers

Int. SAT Competition
2020–2023

Übersicht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SAT

Motivation: Beweise für Unerfüllbarkeit

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Wie können wir sicherstellen, dass die Ausgabe eines SAT Solvers korrekt ist?

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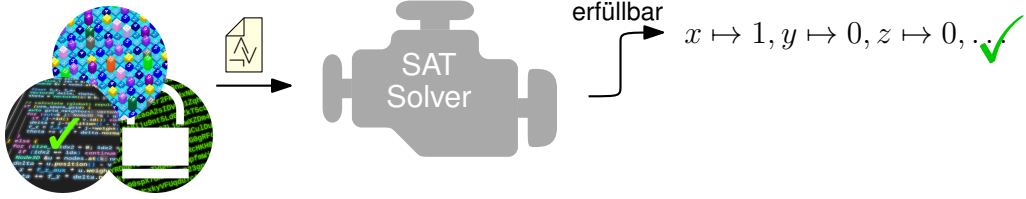

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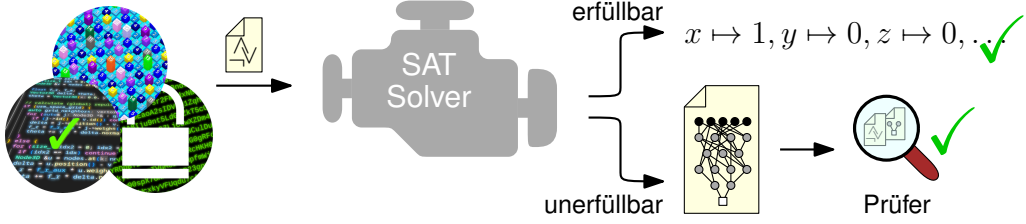

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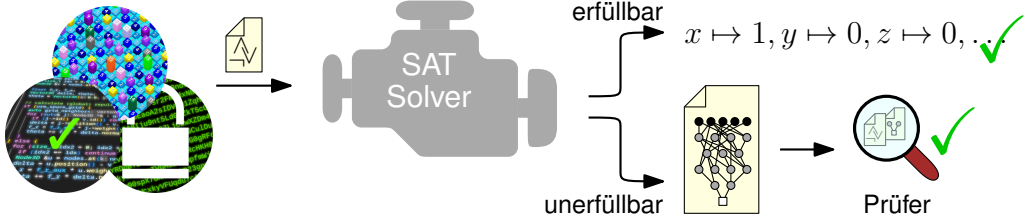
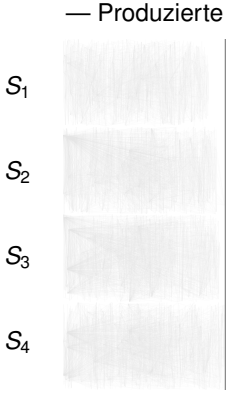


Unerfüllbarkeits-Beweise

- Sequentielle Solver: etablierter Standard, strikte Voraussetzung in Wettbewerben
- Parallele/verteilte Solver mit Klauselaustausch: keine praktikablen Ansätze

Verteilte Beweis-Rekonstruktion [TACAS'23]



Zuf. 3-SAT Formel, 180 Variablen. 4 Notebook-Kerne × 1.7 s. 300k Abhängigkeiten (ohne orig. Klauseln).

Solving: Herleitung und Austausch von Klauseln, Schreiben in partielle Beweise

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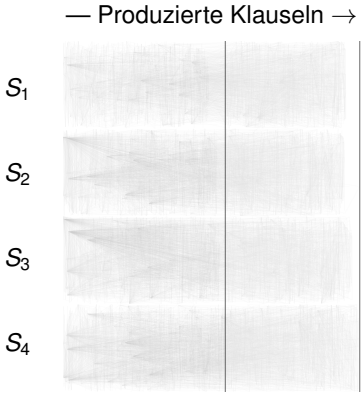

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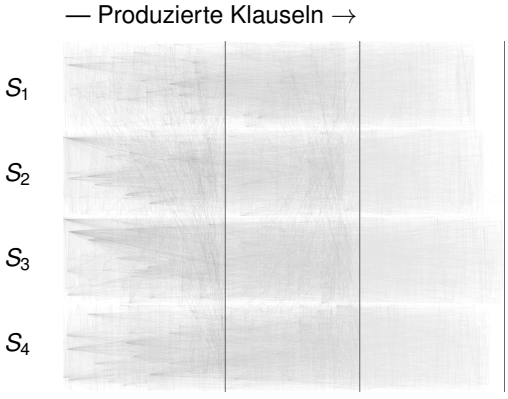

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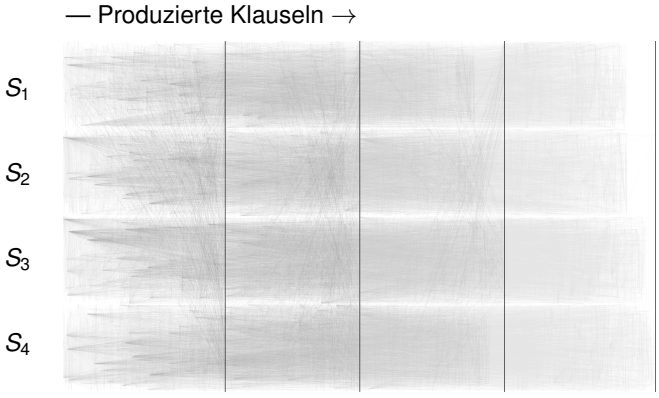

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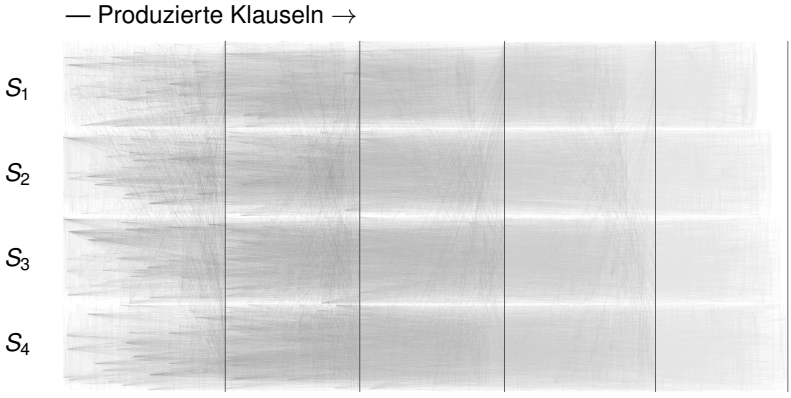

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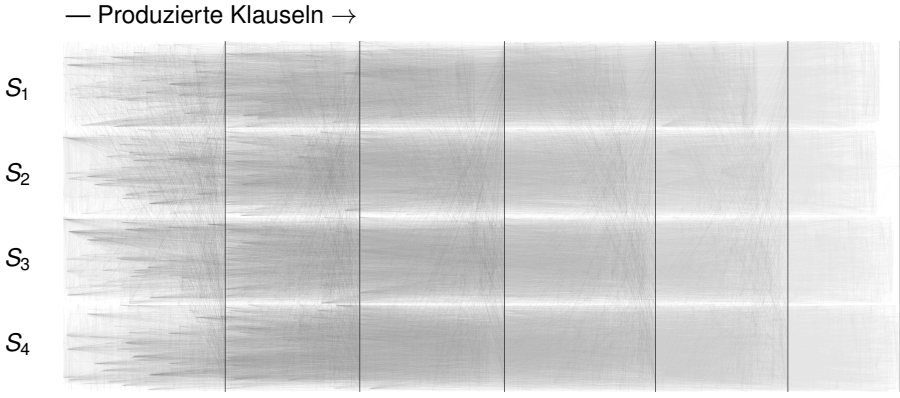

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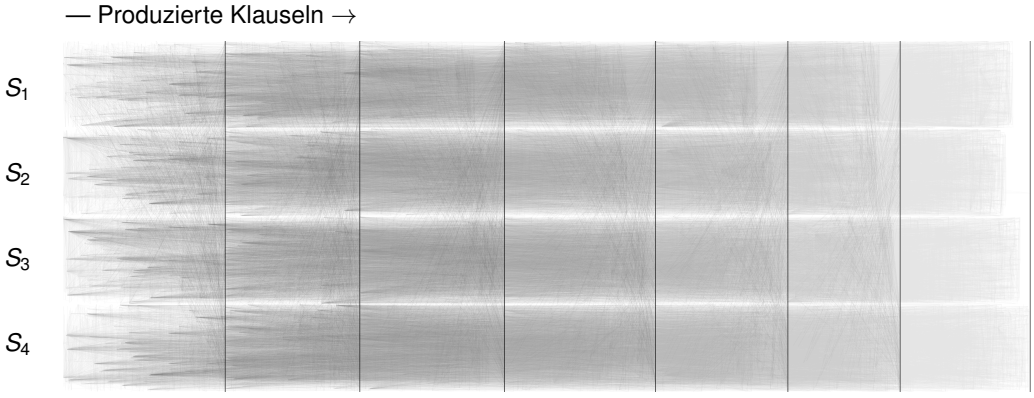

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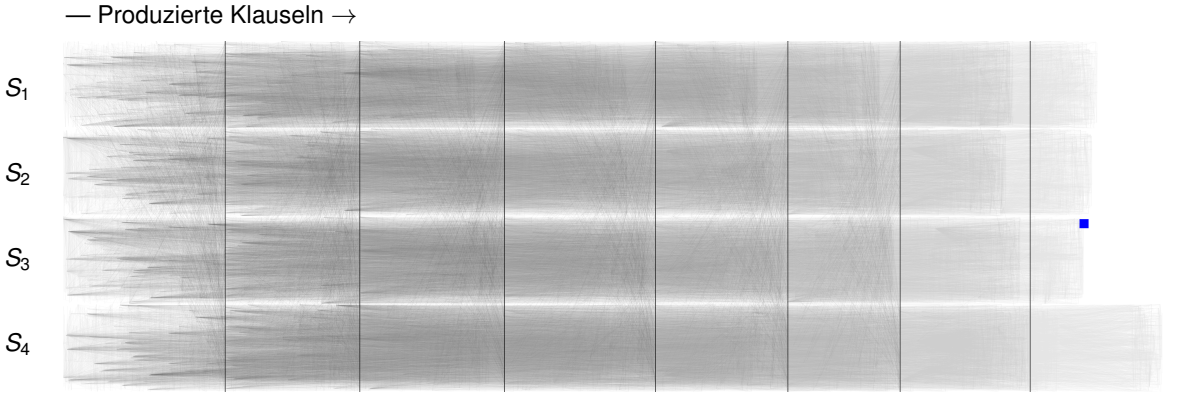

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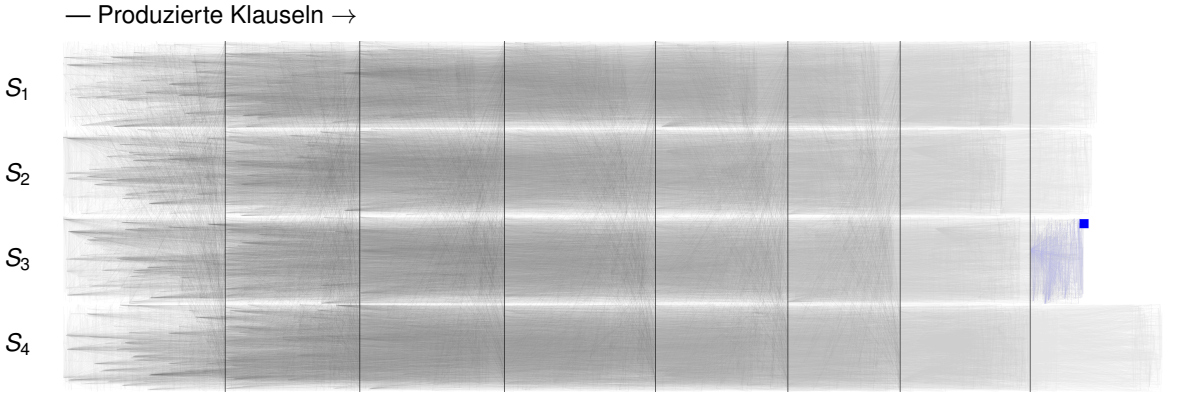

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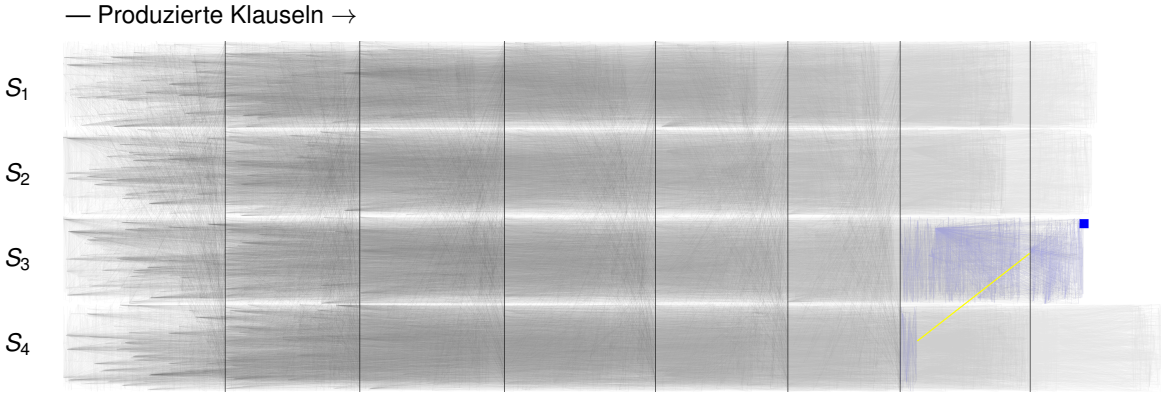

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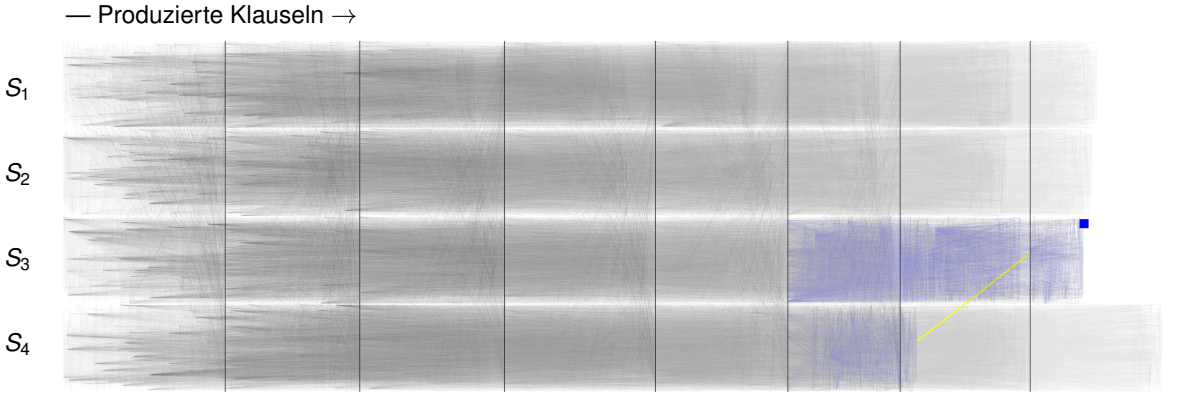

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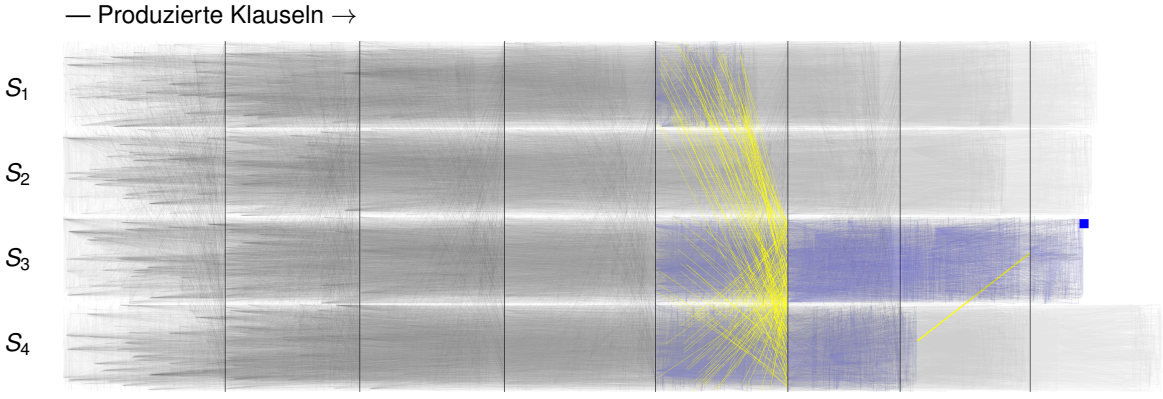

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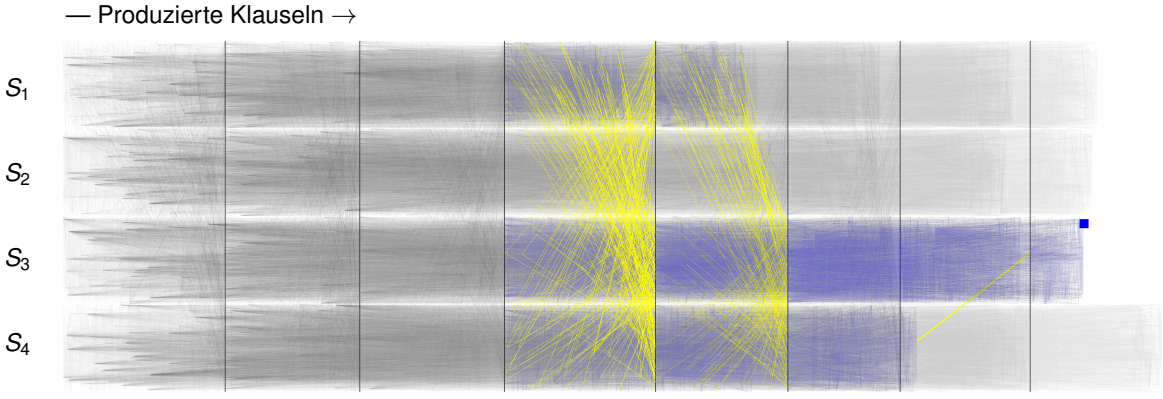

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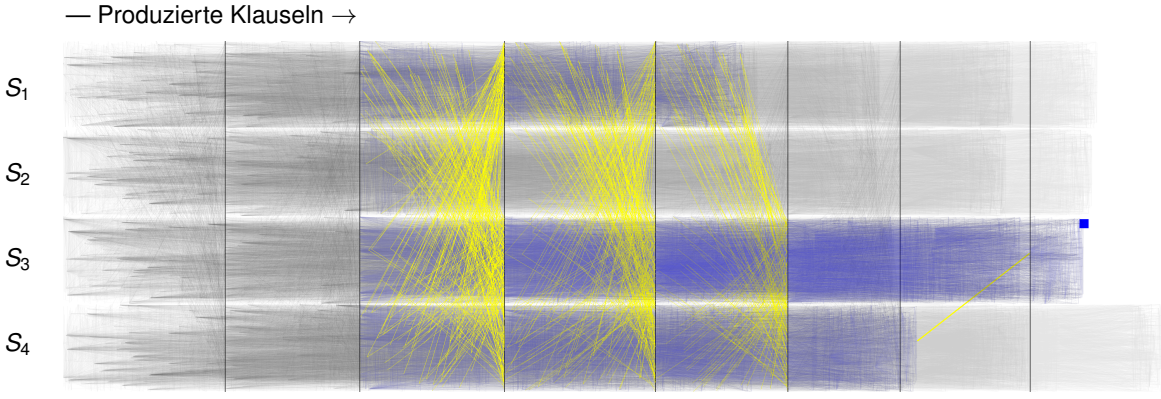

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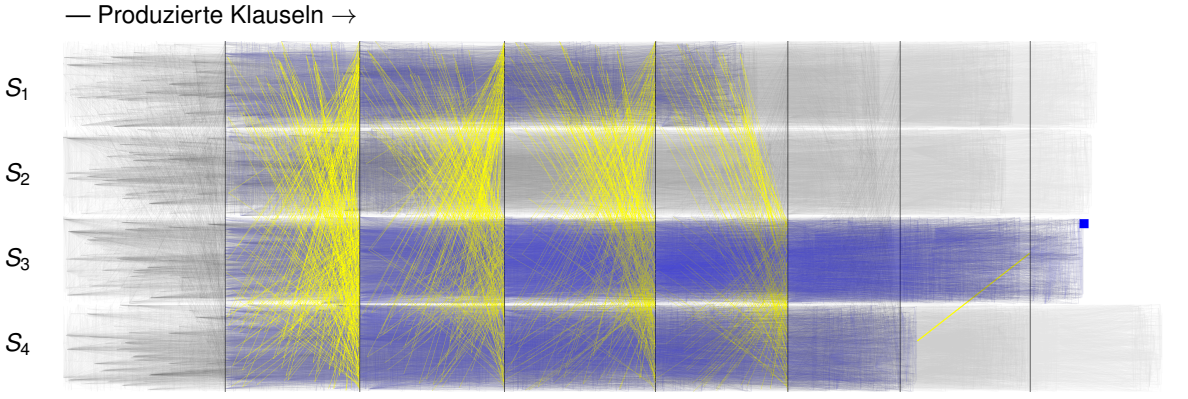

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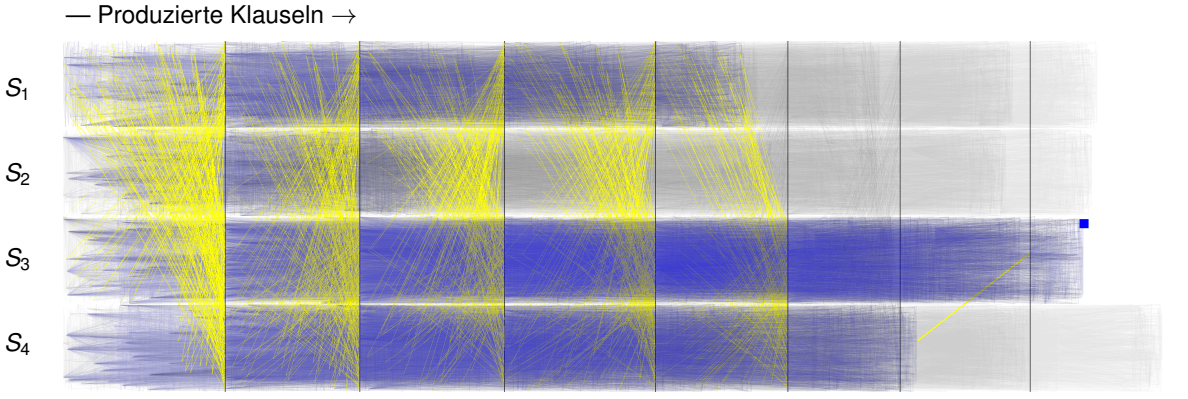

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Experimente [TACAS'23]

Wie teuer ist Beweis-Rekonstruktion & -Prüfung relativ zur Laufzeit des Lösens?

AWS Cloud · 400 Probleme aus SAT Comp. 2022

- **64 Threads**: $\approx 1.1\times$ (135 Beweise rekonstruiert & geprüft)
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Karlsruher Institut für Technologie

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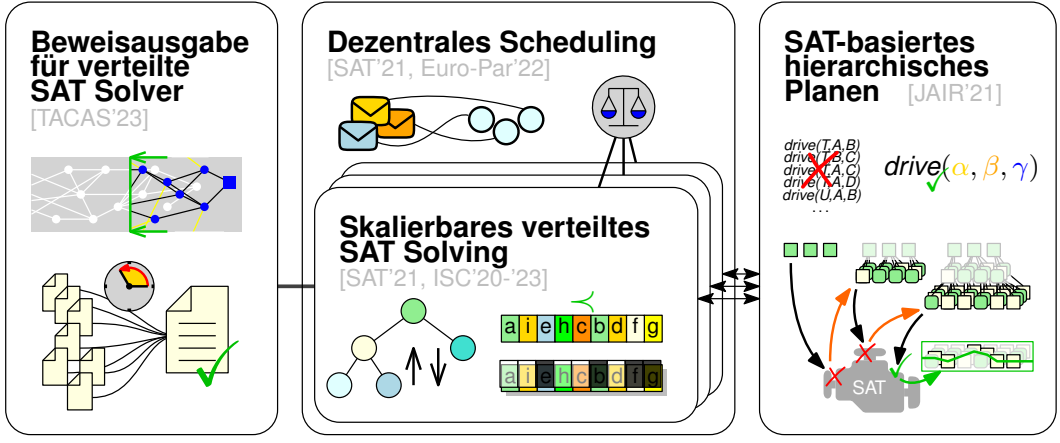
Fazit

Erster praktikabler und skalierbarer Ansatz für verteilte Beweiskonstruktion mit Klauselaustausch

Abschluss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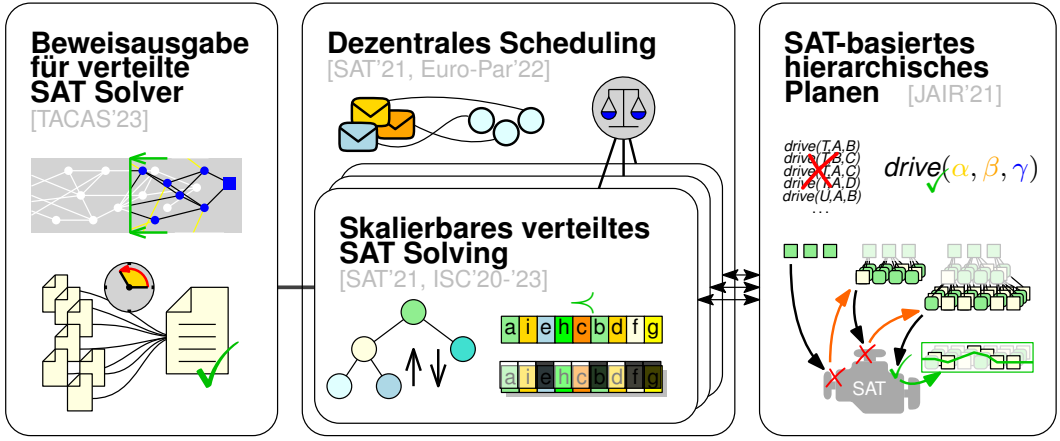


⇒ Horizont der praktisch & zuverlässig lösbaren Probleme erfolgreich erweitert.

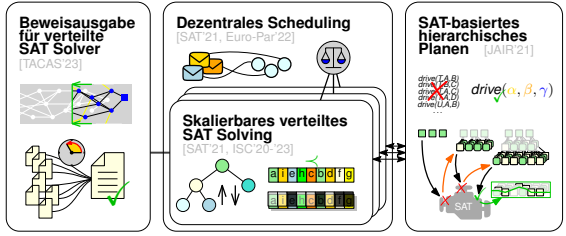
Anhang

(deutsch / englisch)

Ausblick & Publikationen

Ausblick

- Nutzen-maximierende Algorithmen für Ressourcenzuteilung
- Verringerung redundanter Arbeit zwischen sequentiellen Solvern
- Heterogene Systeme (v.a. GPUs)



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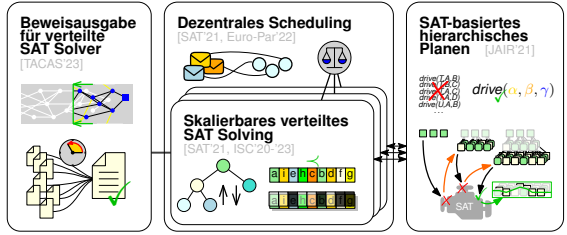

Einbezogene Publikationen

[Euro-Par'22] Sanders, Schreiber: *Decentralized Job Scheduling of Malleable NP-hard Jobs* ∗

[SAT'21] Schreiber, Sanders: *Scalable SAT Solving in the Cloud*

[TACAS'23] Michaelson, Schreiber et al.: *Unsatisfiability Proofs for Distributed Clause-Sharing Solvers* ∗

[JAIR'21] Schreiber: *Lilotane: A Lifted SAT-based Approach to Hierarchical Planning* (auch auf IJCAI'21)

[ISC'20-23] Technische Berichte für Int. SAT Competitions

Weitere Publikationen

[ICAART'19, ICAPS'19] SAT-basiertes hierarchisches Planen *mit Grounding*

[SoCS'19] Klassisches Planen mit SAT-basierten Techniken

[HPCSE'21] Fortschrittsbericht zu Hochleistungsrechnen

[JOSS'22] Artikel zu MALLOB(SAT) in Software-Journal

[2×Sparkle'19, 2×IPC'20] Diverse Technische Berichte

∗ Für Best Paper Award nominiert

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Behnke, Gregor, Daniel Höller, and Susanne Biundo. “totSAT – Totally-ordered hierarchical planning through SAT.” AAAI 2018.

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Audemard, Gilles and Laurent Simon. “Predicting learnt clauses quality in modern SAT solvers.” IJCAI 2009.

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Biere, Armin. “CaDiCaL, Lingeling, Plingeling, Treengeling and YalSAT entering the SAT competition 2018.” SAT Competition 2018.

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Heule, Marijn J. H., Norbert Manthey, and Tobias Philipp. “Validating Unsatisfiability Results of Clause Sharing Parallel SAT Solvers.” POS 2014.

Zheng, Jiongzhi, Kun He, Zhuo Chen, et al. “Combining Hybrid Walking Strategy with Kissat MAB, CaDiCaL, and LStech-Maple.” SAT Competition 2022.

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2 · Schaltkreis: https://www.rawpixel.com/image/5907876/photo-image-background-public-domain-technology

2 · Planung/Scheduling: https://www.pexels.com/photo/blue-printer-paper-7376/

2 · Kryptographie: https://pixabay.com/vectors/computer-encrypt-encryption-1294045/

2 · Gefärbtes Gitter: https://www.quantamagazine.org/the-number-15-describes-the-secret-limit-of-an-infinite-grid-20230420/

2 · Debugging: https://technofaq.org/posts/2017/12/heres-everything-you-need-to-know-about-software-testing/

Problemstellung

Zentrale Problemstellung

Wie können wir den Horizont der praktisch lösbaren SAT-Instanzen erweitern?

Wichtige Aspekte: Effiziente Kodierung von Problemen; Nutzung von paralleler Hardware.

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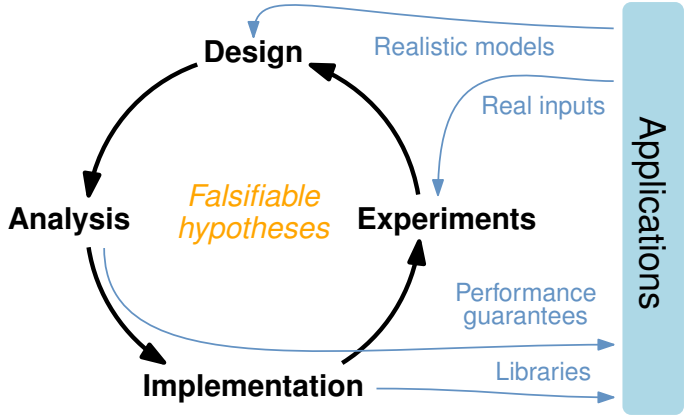
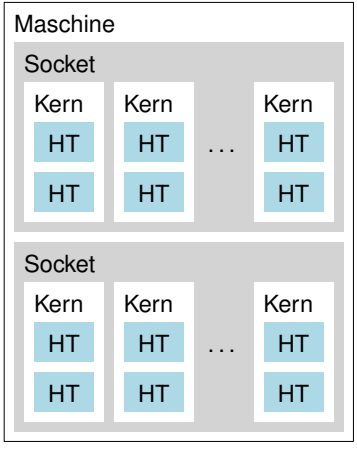
Leitfragen:

1. Wie können wir moderne verteilte Rechenumgebungen effizient für SAT Solving nutzen?
2. Wie können wir Systeme für SAT Solving in derartigen Umgebungen vollständig vertrauenswürdig machen, um deren Einsatz für kritische Anwendungen zu ermöglichen?
3. Wie können komplexe Anwendungen effizienteren Gebrauch von SAT-Solvern machen, damit zuvor unlösbare Probleme bewältigt werden können?

Methodology: Algorithm Engineering



Grundlage: Rechenumgebung



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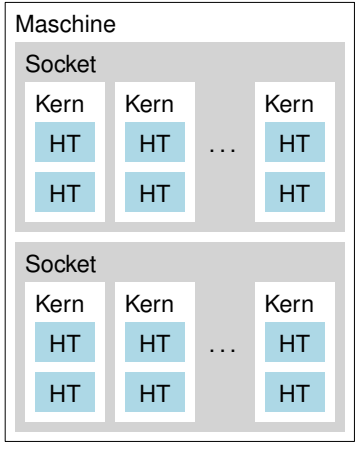

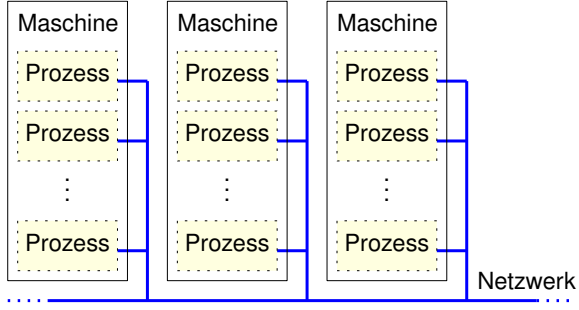

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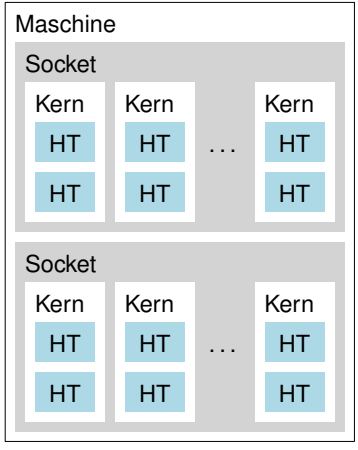

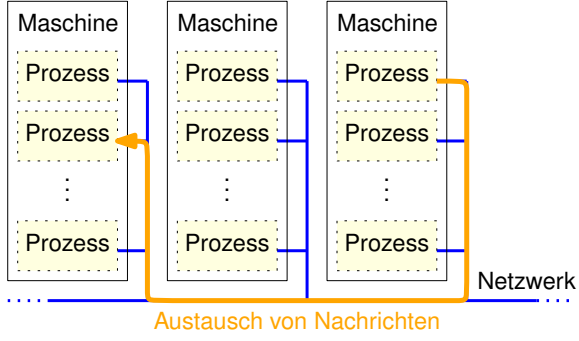

Prerequisites: Communication Primitives

Collective operations with $\mathcal{O}(\log m)$ *span* / *depth*:

- **All-reduction** – e.g., broadcast value, compute maximum

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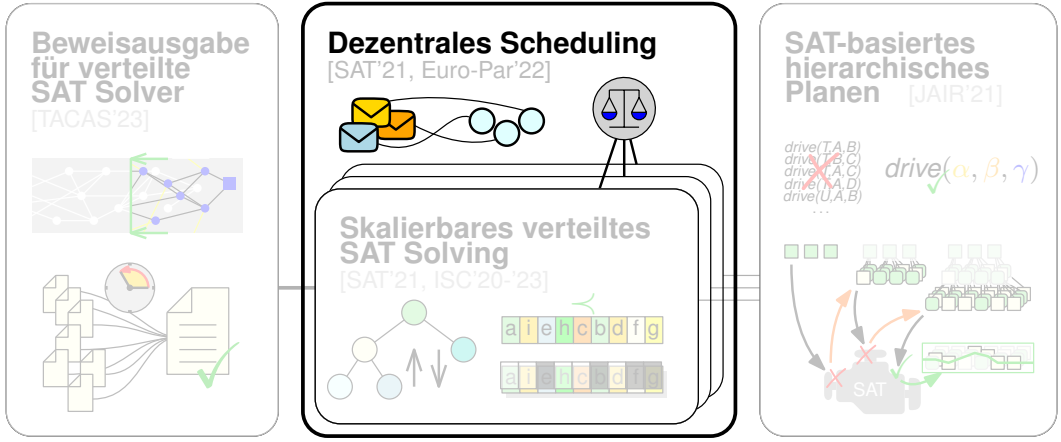
Übersicht


Beweisausgabe für verteilte SAT Solver
[TACAS'23]
Dezentrales Scheduling
[SAT'21, Euro-Par'22]
Skalierbares verteiltes SAT Solving
[SAT'21, ISC'20-'23]
SAT-basiertes hierarchisches Planen [JAIR'21]
drive(T,A,B)
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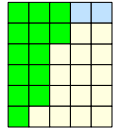
SAT

Scheduling: Motivation

Definition: Verformbarkeit (*Malleability*) [Feitelson 1997]

Eine parallele Rechnung ist **verformbar**, wenn sie zur Ausführungszeit eine fluktuierende Anzahl von Recheneinheiten unterstützt.



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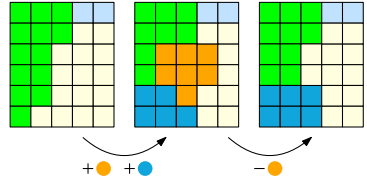

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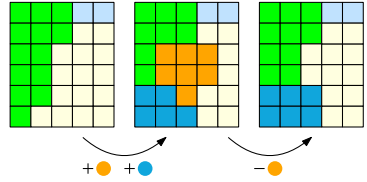
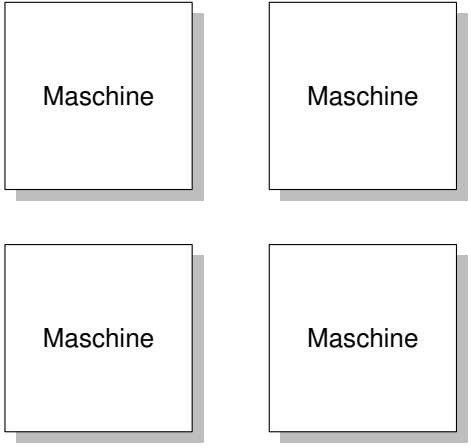


Warum verformbares Scheduling für SAT Solving?

- Ausführungszeit einer Aufgabe unbekannt ⇒ Flexibles Reagieren von Vorteil
- Sublineare Skalierung ⇒ Gleichzeitiges Bearbeiten mehrerer Probleme erhöht Effizienz
- Einfach umsetzbare Verformbarkeit → Nächster Themenblock

Ausführungsumgebung



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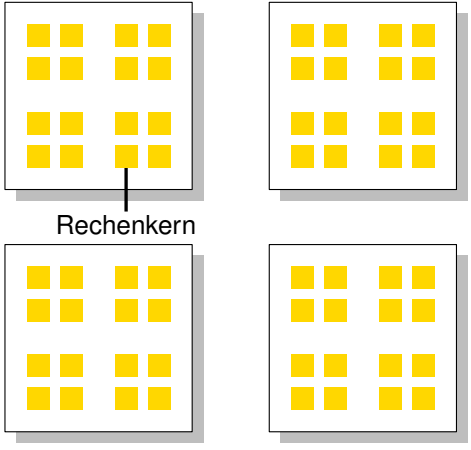

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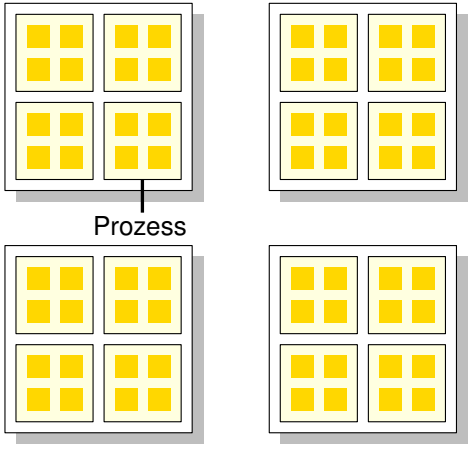
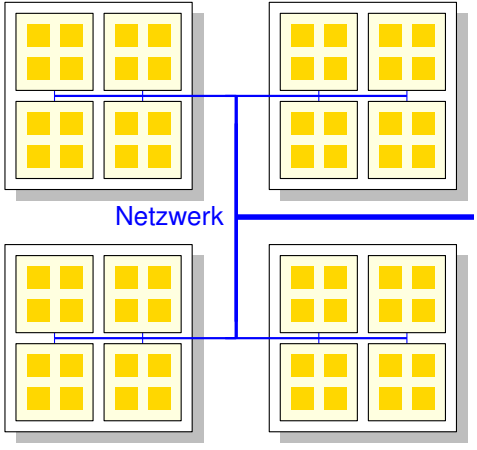


Verteilte Rechenumgebung des Schedulers

- *m* verteilte Prozesse

Ausführungsumgebung



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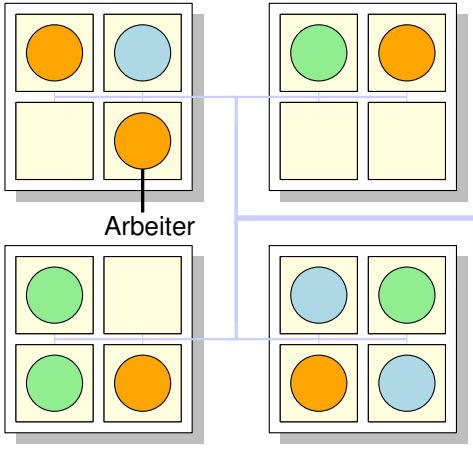

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- Arbeiter: Ausführungskontext einer bestimmten Aufgabe auf einem bestimmten Prozess
- Je Prozess:
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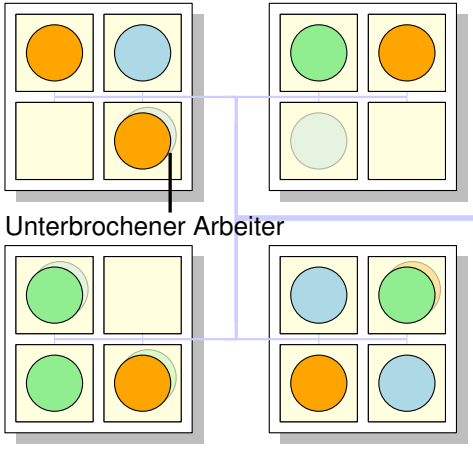

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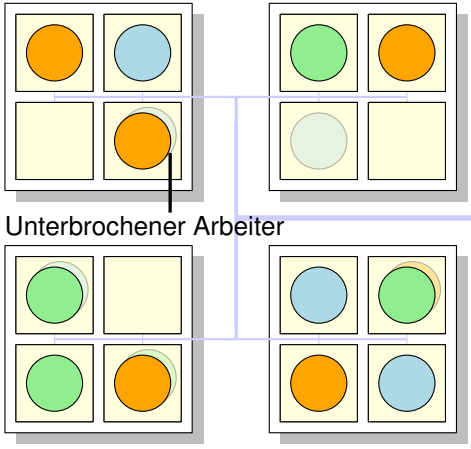

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  - Priorität $p_j \in \mathbb{R}^+$
  - Max. Ressourcen-Bedarf $d_j \in \mathbb{N}^+$

Mallob: Scheduling-Ansatz [Euro-Par'22]

Problem 1: Bestimme für jede Aufgabe j faire Anzahl $1 \leq v_j \leq d_j$ von Arbeitern, sodass $v_j \propto p_j$

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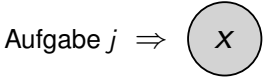

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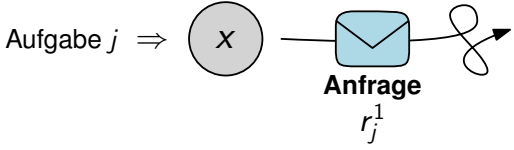

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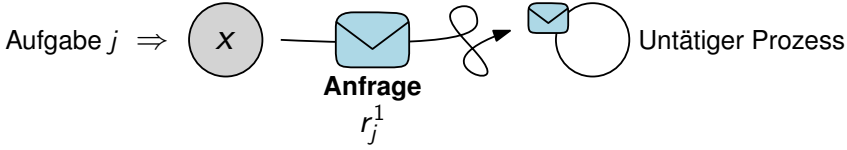

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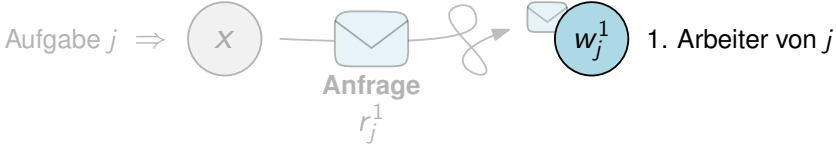

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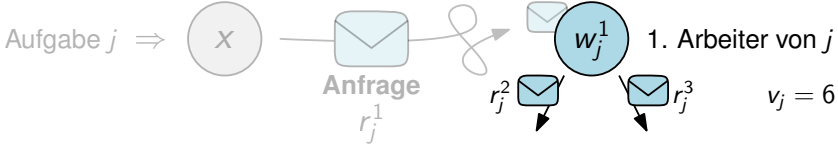

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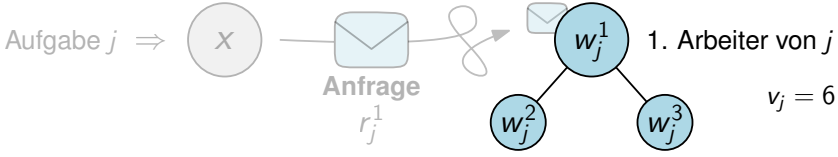

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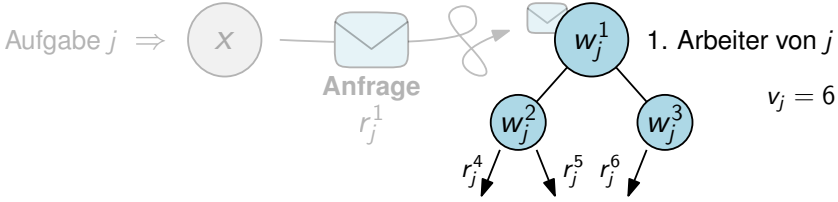

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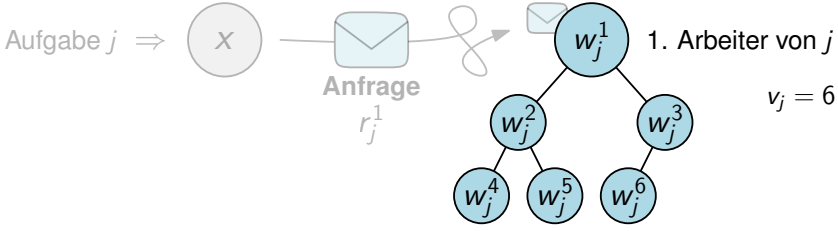

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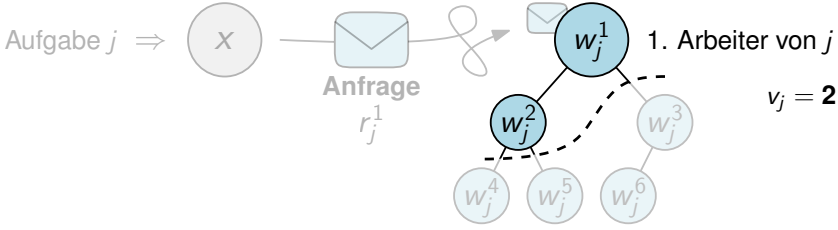

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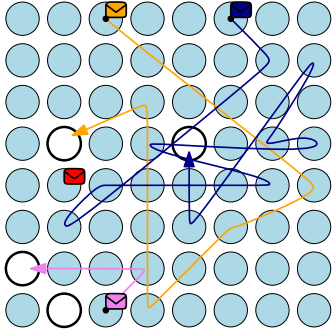

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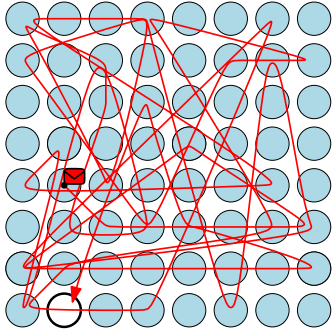

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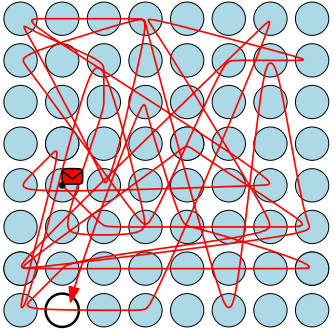

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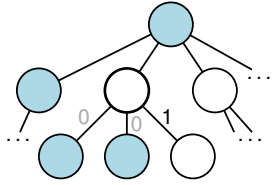

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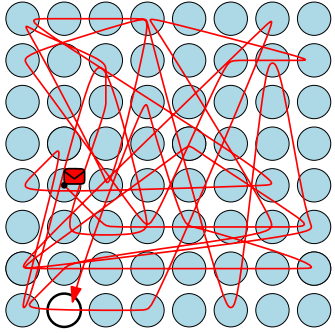

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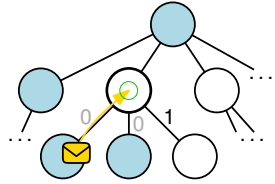

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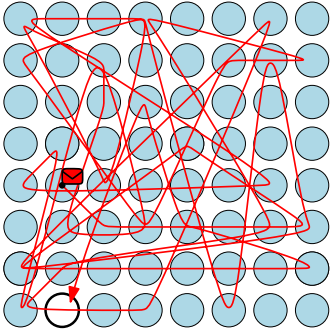

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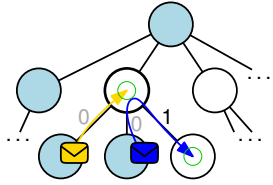

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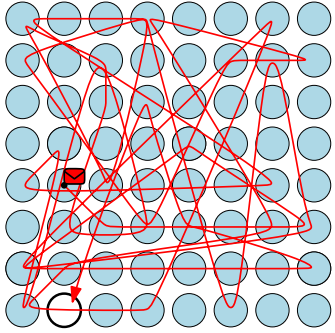

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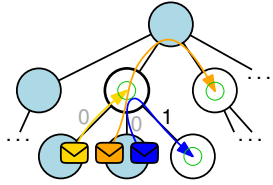

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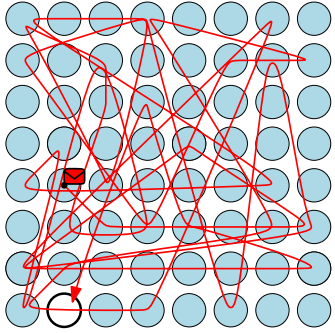

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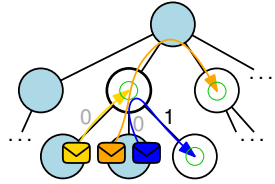
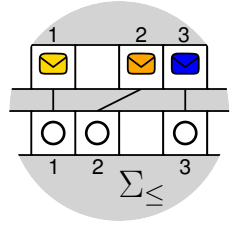


Async. Präfixsummen



Scheduling: Experimente [Euro-Par'22]

- 128 Maschinen von **SuperMUC-NG**
  – 1536 Prozesse $\times$ 4 Kerne
- Zufälliges Eintreffen von SAT-Aufgaben
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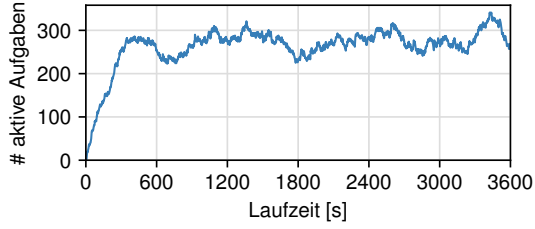

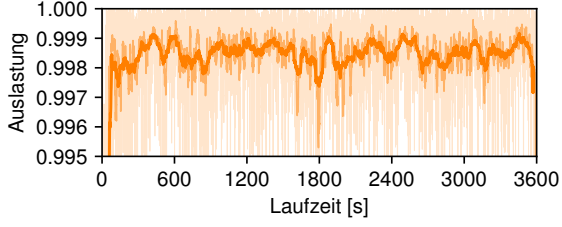

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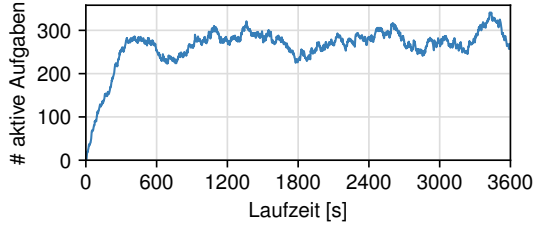
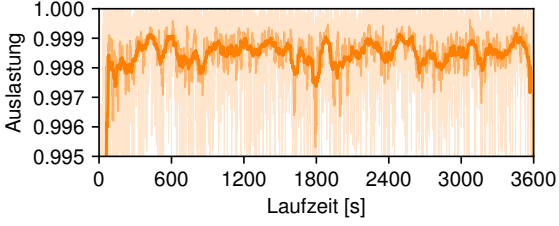


Durchschnittliche Latenzen

$\approx$ 10 ms für Scheduling des 1. Arbeiters
$\approx$ 1 ms für Berechnung fairer Volumen
$\approx$ 6 ms für Hinzufügen neuer Arbeiter



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Map each job $j \in J$ to a fair number of workers, the volume $v_j \in \mathbb{N}^+$, s.t.

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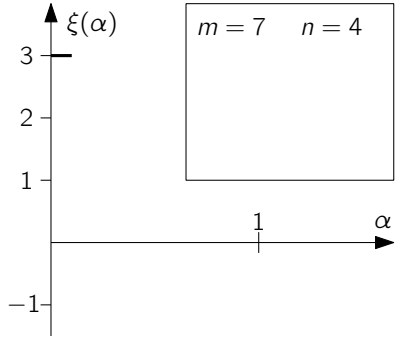

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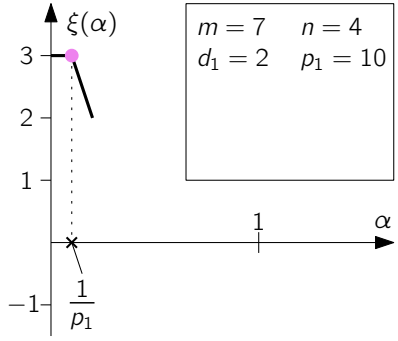

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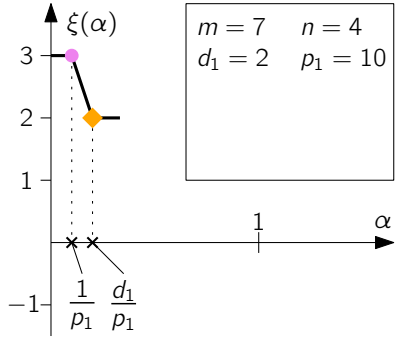

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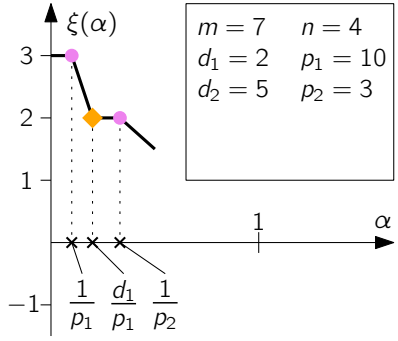

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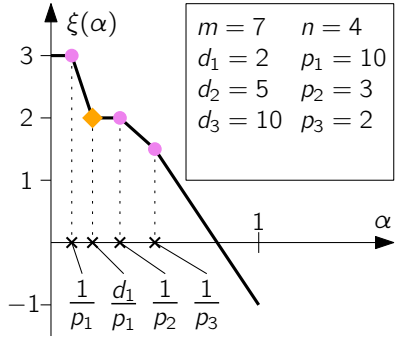

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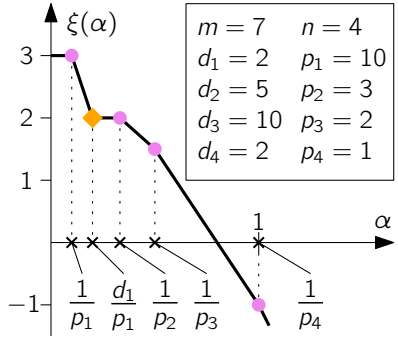

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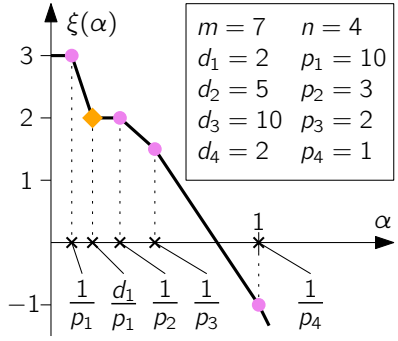

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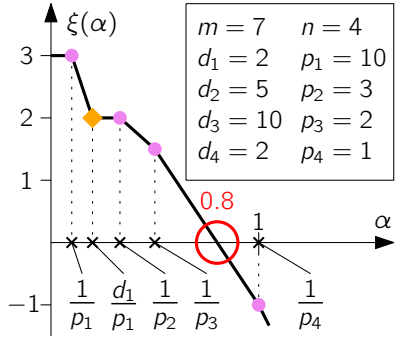

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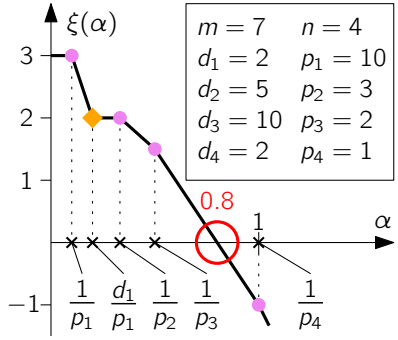

$v_1(\hat{\alpha}) = d_1 = 2$
$v_2(\hat{\alpha}) = 0.8 \cdot 3 = 2.4$
$v_3(\hat{\alpha}) = 0.8 \cdot 2 = 1.6$
$v_4(\hat{\alpha}) = 1$

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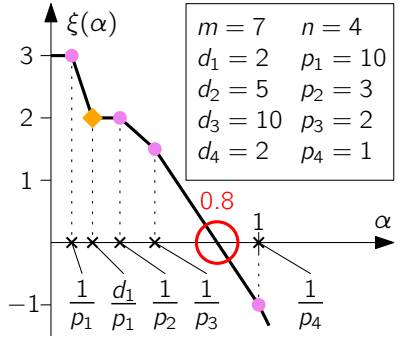
- Interpolate value $\hat{\alpha}$ where $\xi(\hat{\alpha}) = 0$
- Round the $v_j(\hat{\alpha})$ to appropriate integers



$v_1(\hat{\alpha}) = d_1 = 2$ $\quad v_1 = 2$
$v_2(\hat{\alpha}) = 0.8 \cdot 3 = 2.4$ $\quad v_2 = 3$
$v_3(\hat{\alpha}) = 0.8 \cdot 2 = 1.6$ $\quad v_3 = 1$
$v_4(\hat{\alpha}) = 1$ $\quad v_4 = 1$

Volume Assignment Algorithm

- Job volumes $v_j = v_j(\alpha) = \max(1, \min(d_j, \alpha p_j))$, $\alpha \geq 0$
- Excess resources $\xi(\alpha) = m - \sum_{j \in J} v_j(\alpha)$
- Evaluate ξ in parallel* at all $2n$ values where ξ' changes
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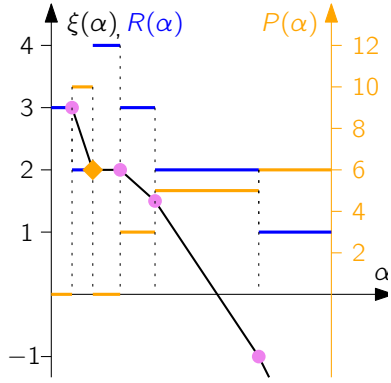
*__Parallel evaluation of ξ:__

- Compute ξ based on auxilliary terms R and P



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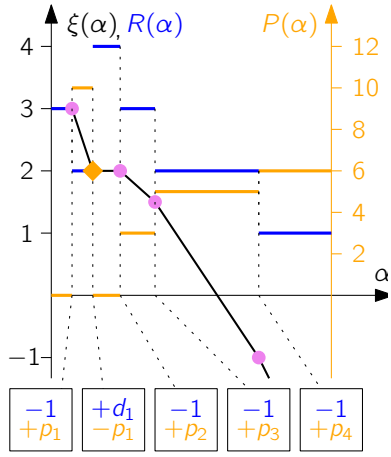

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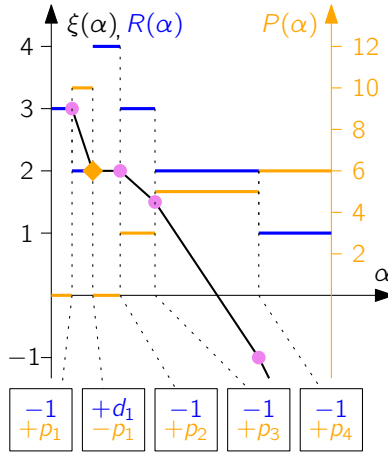
- Create, sort *events* which manipulate R and P
- Compute *all intermediate values* of R, P with prefix sum



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- Create, sort *events* which manipulate R and P
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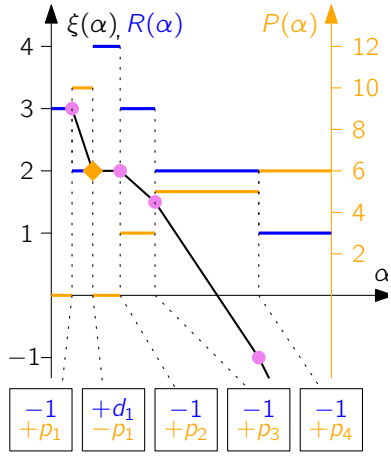
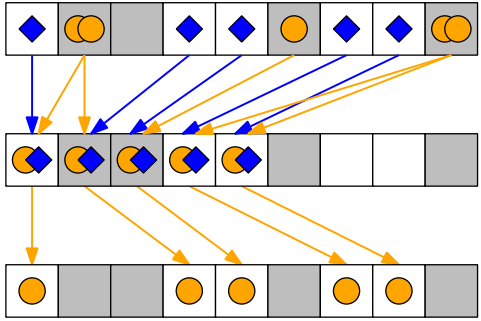
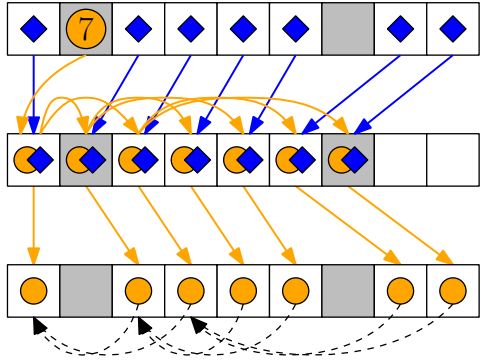
All-reductions, prefix sums, sorting $\mathcal{O}(m)$ elements:
Possible in $\mathcal{O}(\log m)$ time [Ajtai, Komlós, Szemerédi '83]



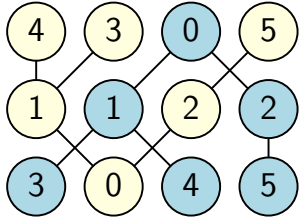
Zuordnung von Anfragen via Präfixsummen





Reusing Suspended Workers

Naïve scheduling



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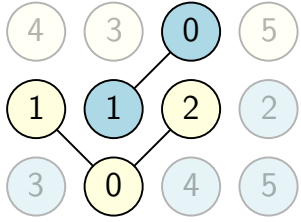

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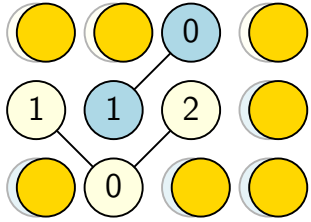

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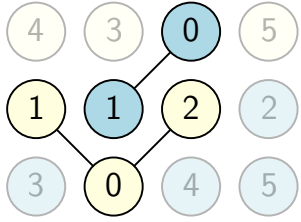

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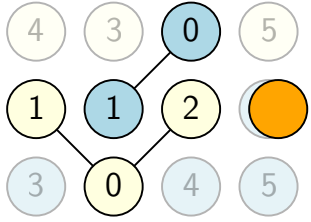

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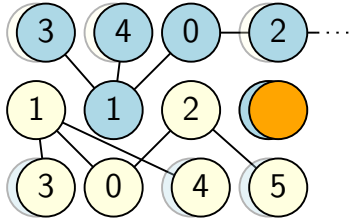

- Idle procs. can be seized by other jobs
- Jobs can re-grow differently after shrinking

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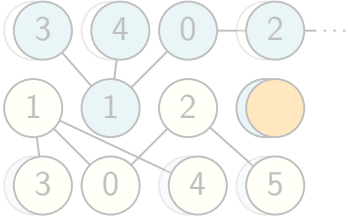
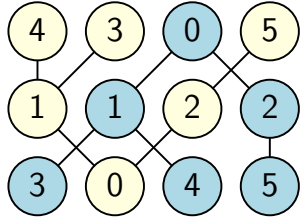


Improvements



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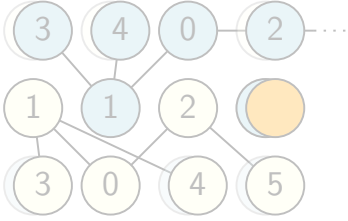

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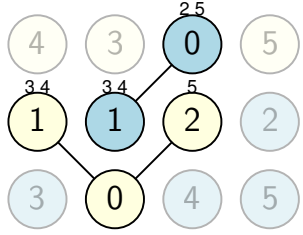

- Workers transitively remember past children

Reusing Suspended Workers

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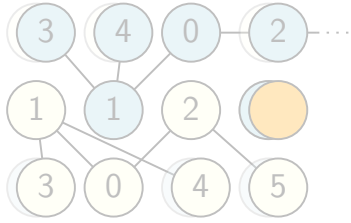

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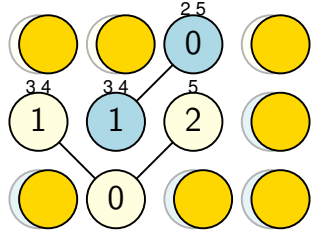

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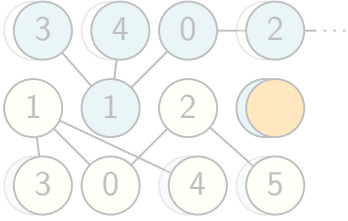

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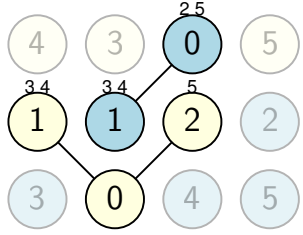

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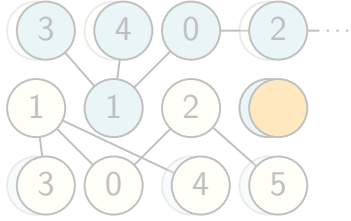

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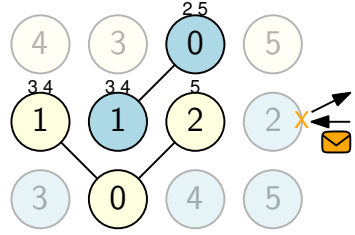

- Workers transitively remember past children
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Reusing Suspended Workers

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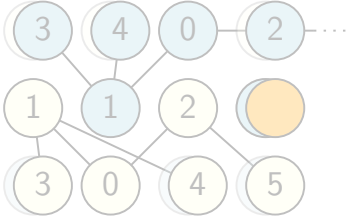

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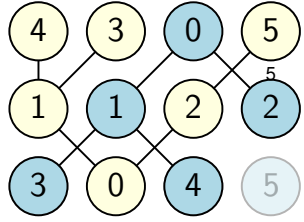

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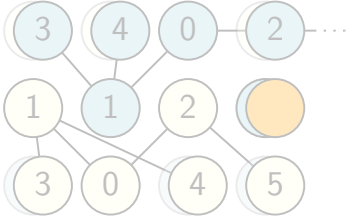

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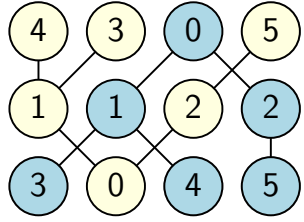

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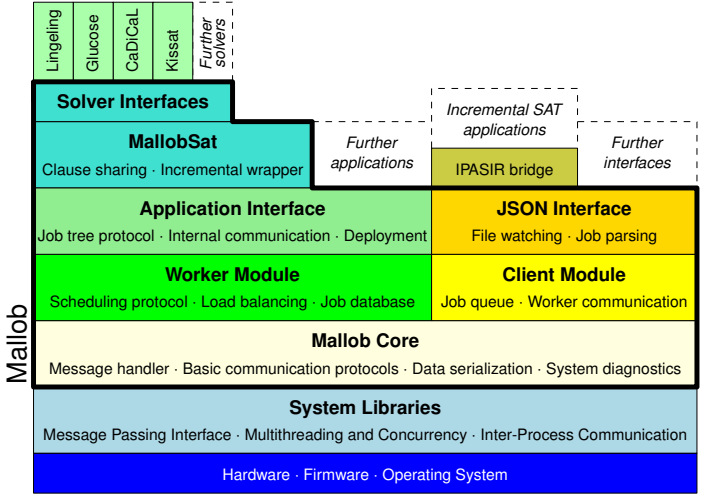
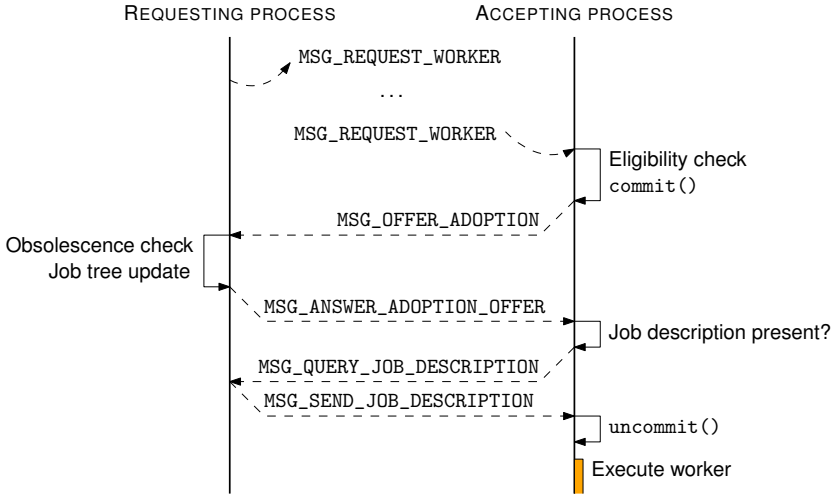
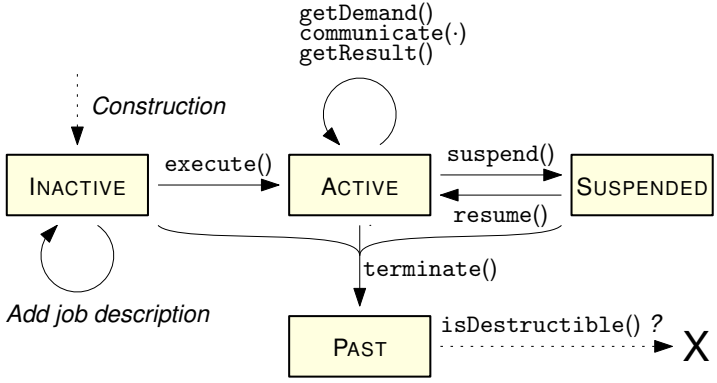
Mallob: Technology Stack



Mallob: Example Protocol

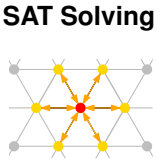


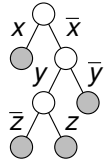
Mallob: Worker Life Cycle



Mallob: Anwendungsstudien

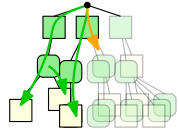
SAT Solving

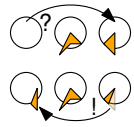




Malte Sönnichsen Maximilian Schick

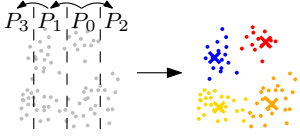
Hierarchisches Planen





Niko Wilhelm

k-means Clustering

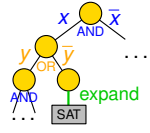


Michael Dörr

QBF Solving (WIP)

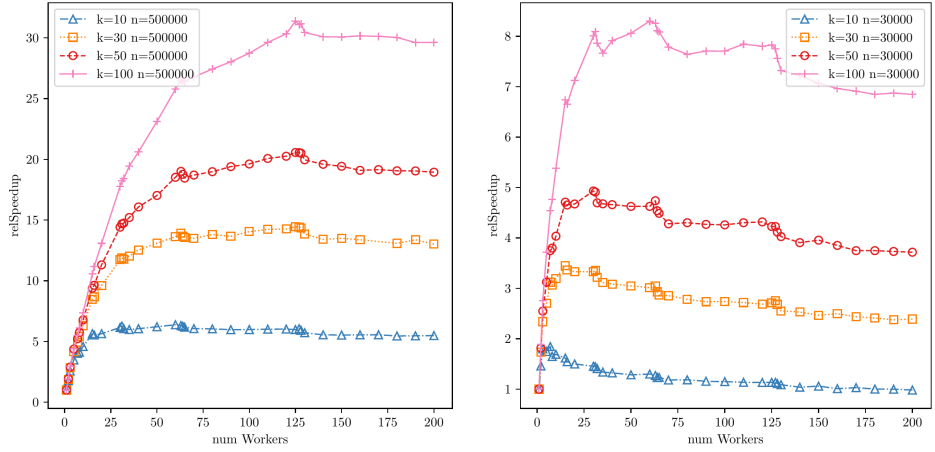
$\forall x \exists y \forall z$

$F(x, y, z)$



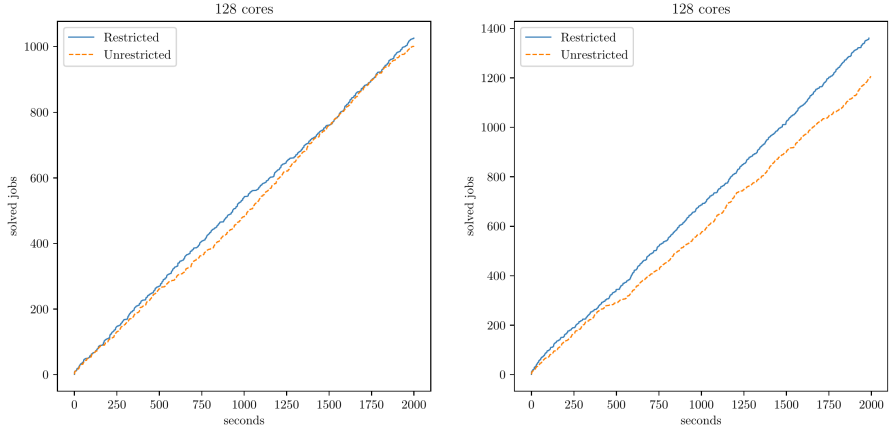
Kollab. Maximilian Heisinger

Mallob: Fallstudie *k*-means [Michael Dörr] (1/2)



(a) 54 dimensional *covertype* self speedup **(b)** 115 dimensional *benign_traffic* self speedup

Mallob: Fallstudie *k*-means [Michael Dörr] (2/2)



(a) Solved jobs per time with maximum 8 concurrent jobs

(b) Solved jobs per time with maximum 6 concurrent jobs and more smaller sized jobs

SuperMUC-NG

Allgemein

- 311 040 Rechenkerne
- 719 TB Arbeitsspeicher
- Spitzenleistung: 26,9 PetaFLOPS
- SUSE Linux Enterprise Server 12 SP3

6 336 “dünne” Rechenknoten auf 8 Islands

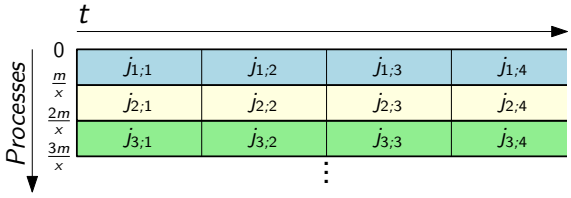
- 2× Intel Skylake Xeon Platinum 8174 @ 2.7 GHz
- 2×24 = 48 physische Kerne (= 96 Hardwarethreads)
- 96 GB Arbeitsspeicher (= 1 GB pro Hardwarethread)
- Interconnect: Intel OmniPath, Topologie: Fat tree

31st @ TOP500
(June 2023)

Leibniz Rechenzentrum
https://doku.lrz.de/supermuc-ng-10745965.html

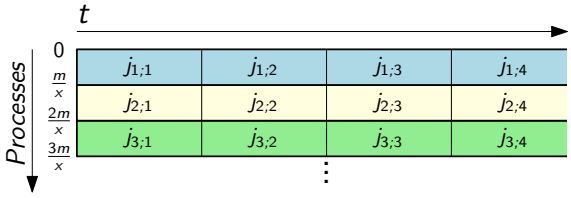
Efficiency for Uniform Jobs

Setup: 1536 processes $\times$ four cores
Scenario: x jobs in parallel with fixed CPU limit

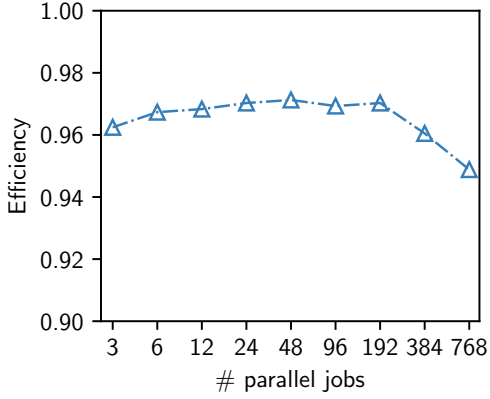


Efficiency for Uniform Jobs

Setup: 1536 processes × four cores
Scenario: x jobs in parallel with fixed CPU limit

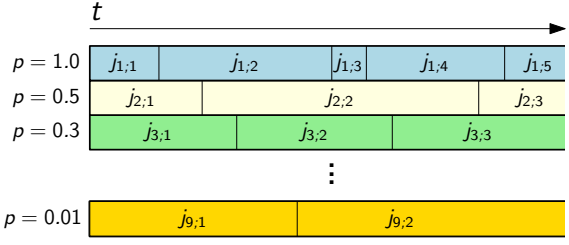


Efficiency: >96% for reasonable loads



Impact of Job Priorities

Setup: 384 processes $\times$ four cores
Scenario: 9 “clients” introducing jobs sequentially



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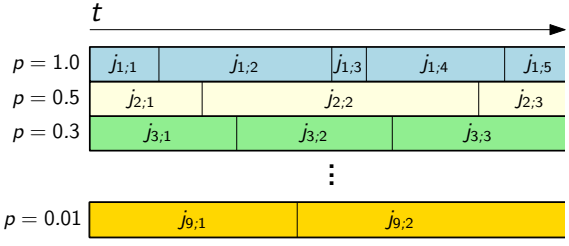

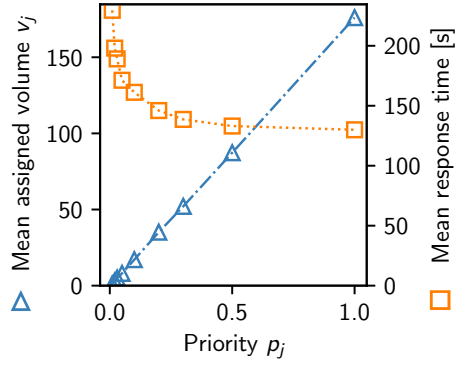

Scheduling: Experimente [Euro-Par'22]+

Durchschnittliche Latenzen

- $\approx$ 10 ms für Scheduling des 0. Arbeiters
- $\approx$ 1 ms für Berechnung fairer Volumen
- $\approx$ 6 ms für Verdoppelung der Arbeiter einer Aufgabe

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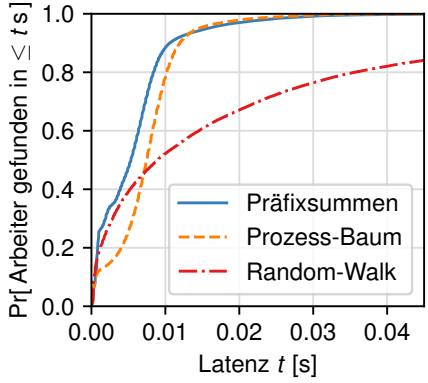

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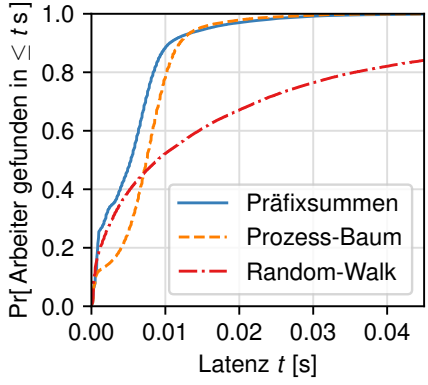
Stabilitäts-Metriken

Je Aufgabe werden 25% mehr Arbeiter angelegt als mindestens nötig.



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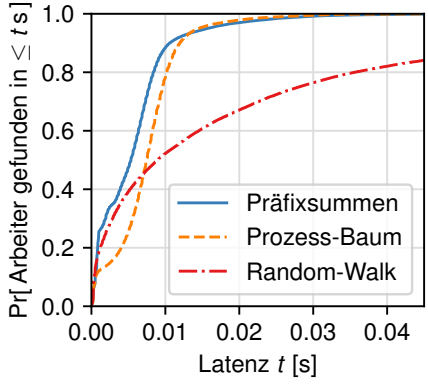
89% aller Arbeiter w_j^i werden nur ein mal initialisiert.



Realistic Arrival Rates: Worker Reuse

	Workers created / Workers required		
Worker reuse stategy	median	max.	total
None	1.43	33.0	2.14
Basic [SAT'21]	1.40	31.5	2.07
Latest [Euro-Par'22]	**1.25**	**24.5**	**1.80**

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$\Rightarrow$ Most workers ($\approx 90\%$) are initialized only once

Unser System MallobSat [SAT'21, ISC'20-23]

Karlsruher Institut für Technologie

Solver-Konfiguration

- Schnittstellen für performante Solver (KissAT, CaDiCaL, Lingeling, Glucose) [Biere et al. 2018, 2020; Audemard & Simon 2009]
- Minimale Randomisierungen $\Rightarrow$ effektive Arbeitsaufteilung per Klauselaustausch

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- Prozess-Baum für jegliche Kommunikation
- Beliebiges Hinzufügen, Entfernen von Solver-Prozessen

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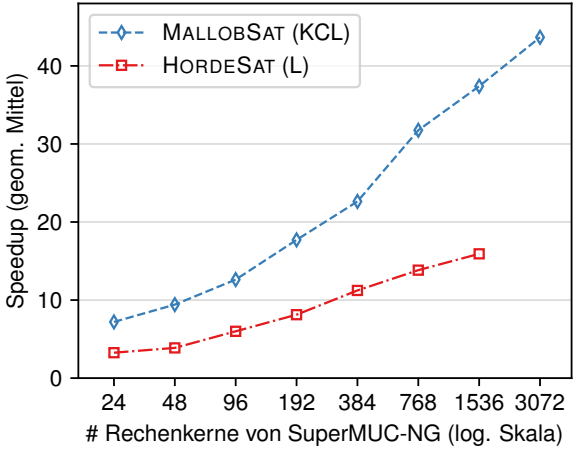
"*Mallob-mono is now, by a* wide *margin, the most powerful SAT solver on the planet.*"

—Byron Cook, Amazon Distinguished Scientist, 2021
https://www.amazon.science/blog/automated-reasonings-scientific-frontiers

Int. SAT Competition 2020–2023

MallobSat: Performance und Skalierung



400 Probleme aus SAT Comp. 2021 · Seq. Baseline KissatMAB-HyWalk · Seq. Zeitlimit 32 h (gelöst: 331) · Par. Zeitlimit 300 s

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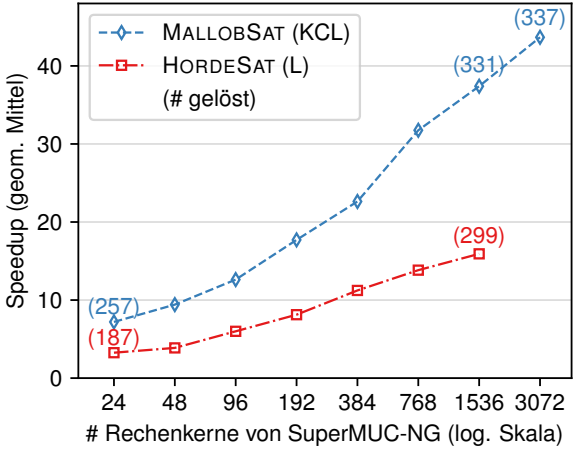

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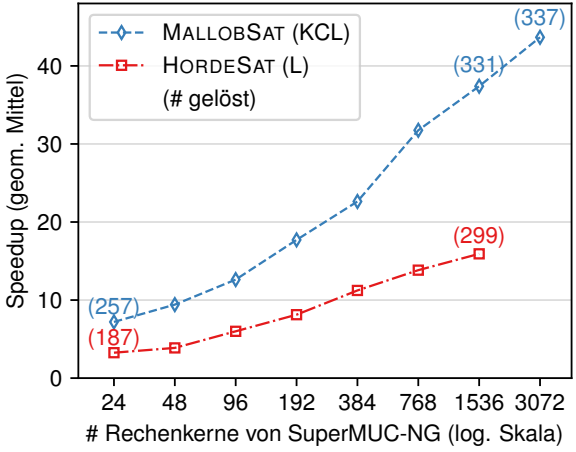

Seq. Laufzeit $\geq$ 1 h $\Rightarrow$ Speedup **419** auf 3072 Kernen

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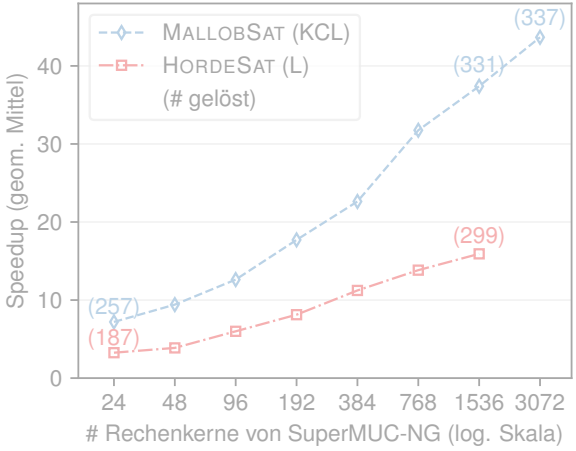

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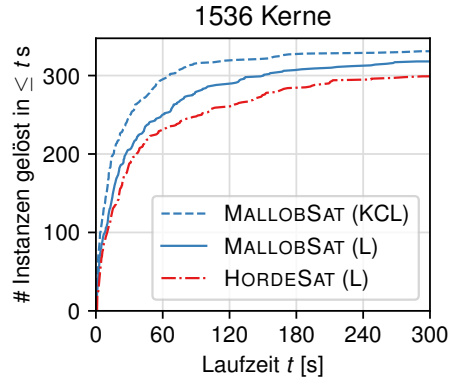

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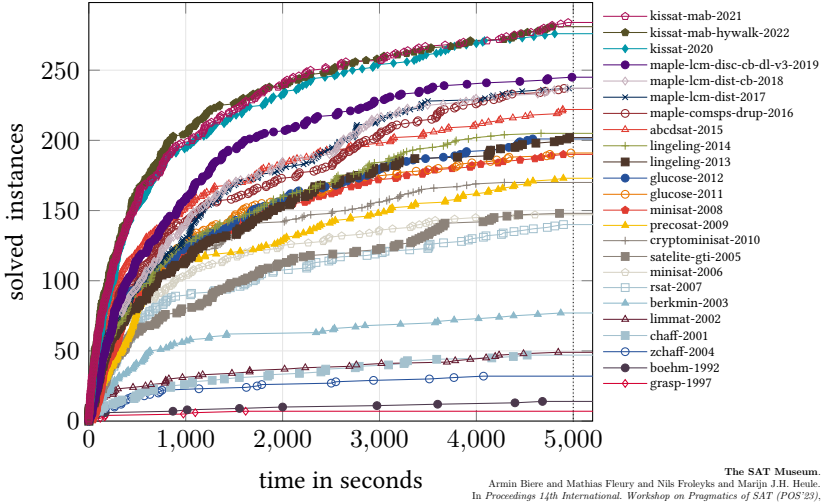
Benchmark-Instanzen: Anniversary'22

5355 Probleme,
138 Familien + 72 unbekannt

Schriftgröße $\propto$ # Probleme

via `wordclouds.com`,
GBD (`benchmark-database.de`)

SAT Competition All Time Winners on SAT Competition 2022 Benchmarks



https://cca.informatik.uni-freiburg.de/satmuseum

The SAT Museum.
Armin Biere and Mathias Fleury and Nils Froleyks and Marijn J.H. Heule.
In *Proceedings 14th International. Workshop on Pragmatics of SAT (POS'23)*,
vol. 3545, CEUR Workshop Proceedings, pages 72-87, CEUR-WS.org 2023.
[paper - bibtex - data - zenodo - ceur - workshop - proceedings]

SAT Solving und Machine Learning: Schnittstellen

- Algorithmenselektion
  Xu, Lin, et al. “SATzilla: portfolio-based algorithm selection for SAT.” JAIR 2008.
  Eggensperger, Katharina, Marius Lindauer, and Frank Hutter. “Neural networks for predicting algorithm runtime distributions.” IJCAI 2018.
- SAT Solving mit maschinellem Lernen
  Liang, Jia Hui, et al. “Learning rate based branching heuristic for SAT solvers.” SAT 2016.
  Guo, Wenxuan, et al. “Machine learning methods in solving the boolean satisfiability problem.” Machine Intelligence Research (2023).
- Neuronale Netze per SAT/SMT Solving verifizieren
  Huang, Xiaowei, et al. “Safety verification of deep neural networks.” CAV 2017.
  Ehlers, Ruediger. “Formal verification of piece-wise linear feed-forward neural networks.” ATVA 2017.
- Analysieren und Verstehen des Verhaltens von SAT Solvern und Instanzen
  Soos, Mate, Raghav Kulkarni, and Kuldeep S. Meel. “CrystalBall: gazing in the black box of SAT solving.” SAT 2019.
  Fuchs, Tobias, Jakob Bach, and Markus Iser. “Active Learning for SAT Solver Benchmarking.” TACAS 2023.

SAT Solving: Anwendungsbeispiele

Karlsruher Institut für Technologie

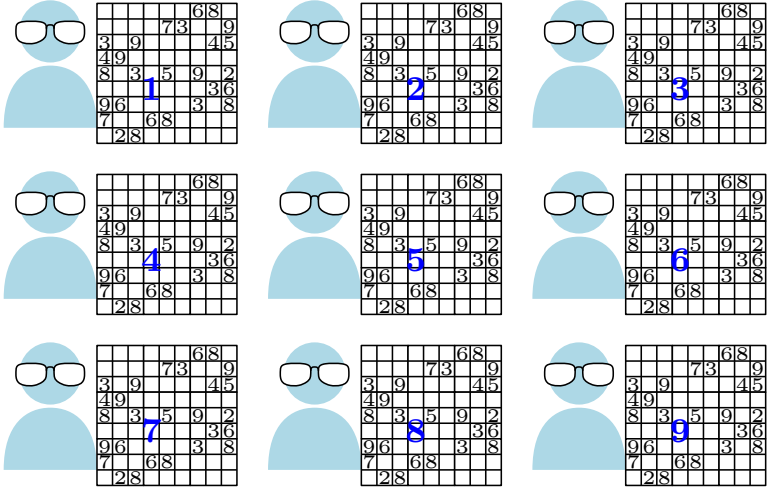
Synthese/Entwurf/Analyse von eingebetteten Systemen

- Design-Space-Exploration via SAT-Decoding
  Lukasiewycz, Martin et al. “Sat-decoding in evolutionary algorithms for discrete constrained optimization problems.” IEEE Congress on Evolutionary Computation, 2007.
- Rekonstruktion von verschleierten Schaltkreisen
  Yu, Cunxi, et al. “Incremental SAT-based reverse engineering of camouflaged logic circuits.” IEEE Tr. Computer-Aided Design of Integrated Circuits and Systems, 2017.
- Testen von Hardware-Neural-Networks
  Gebregiorgis, Anteneh, and Mehdi B. Tahoori. “Testing of neuromorphic circuits: Structural vs functional.” ITC 2019.

Kryptographie

- Urbild-Angriffe auf Hashfunktionen, Schwachstellen in Blockziffern
  Lafitte, Frédéric et al. “Applications of SAT solvers in cryptanalysis: finding weak keys and preimages.” JSAT, 2014.
- Analyse, Kontrolle, Verifikation von kryptographischen Bausteinen, z.B. Streamziffern
  Soos, Mate et al. “Extending SAT solvers to cryptographic problems.” SAT, 2009.

Paralleles Logisches Schließen



Explizite Suchraum-Unterteilung

- Partitioniere Suchraum entlang einiger Entscheidungen
  $\Rightarrow$ Unabhängige Teilprobleme

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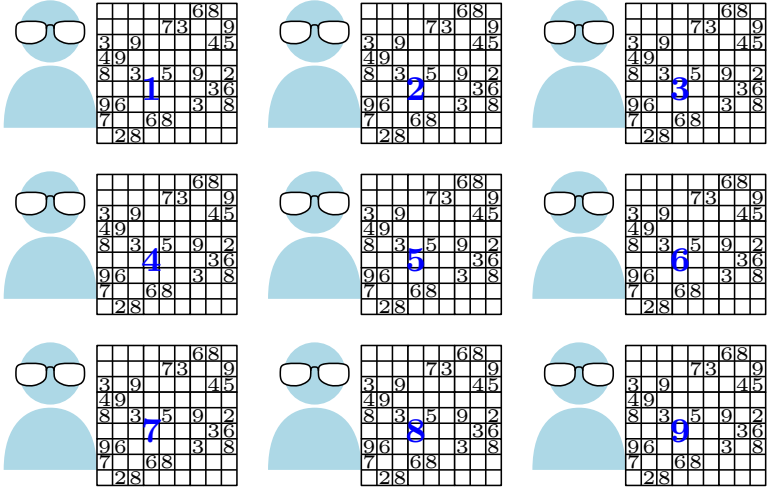

Explizite Suchraum-Unterteilung

- Partitioniere Suchraum entlang einiger Entscheidungen
  $\Rightarrow$ Unabhängige Teilprobleme
- Schwierige Lastverteilung!

Beispiele aus SAT Solving:

- PSATO, PaSAT, MiraXT
- Treengeling
- Paracooba

Verteiltes SAT Solving: Stand der Technik

Bester Ansatz: Portfolio verschiedener Solver

- Seq. Algorithmen produzieren Konflikt-Klauseln
- Solver tauschen Klauseln aus

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HordeSat [Balyo et al. 2015]

- Orchestriert Hunderte von sequentiellen Solvern
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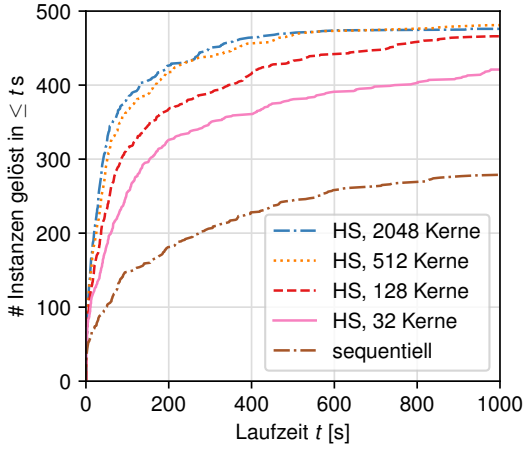
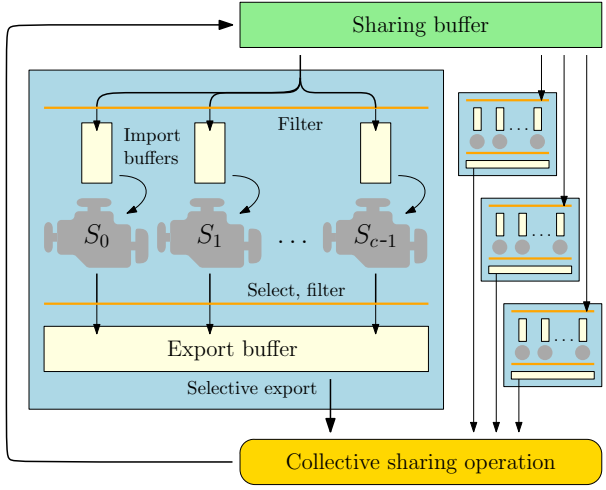
- Experimente mit bis zu 2048 Kernen
  - Median Speedup auf 2048 Kernen: 13
    — Effizienz: 0.6%!



Daten von Balyo et al. (2015)

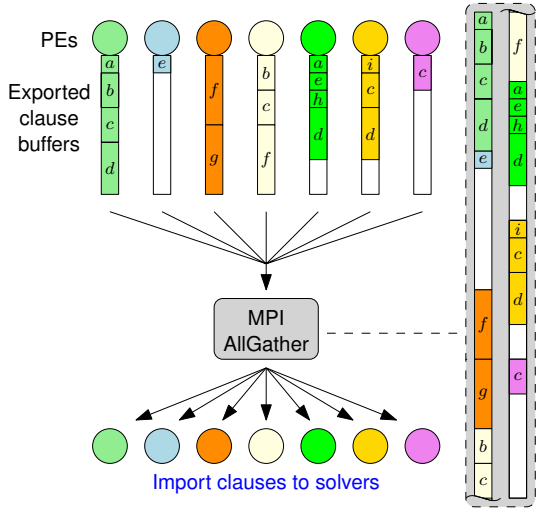
Solver Architecture à la HordeSat



Clause Exchange in HordeSat

Periodic collective operation **AllGather**

- Locally best clauses are shared with everyone
- Duplicate clauses
- "Holes" in buffer carrying no information
- Buffer grows proportionally with # proc.
  ⇒ Bottleneck w.r.t communication *and* local work



MallobSat: Overview

Compact clause sharing

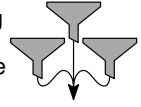
Hierarchical merging + duplicate detection

Sublinear buffer scaling

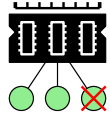
Handling LBD values

Distributed clause filtering

Exact filtering of clauses shared before / from self



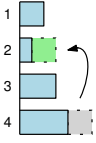
Memory Awareness



Reduction of solver threads

Negotiated memory panic

Adaptive buffering



Keep best clauses at expense of worse clauses

For export + import

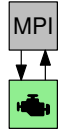
Diversification

Glucose, Lingeling, CaDiCaL, Kissat

Input permutation

Clause sharing!

Controlling



Subprocess for solvers

Seamless preemption and termination

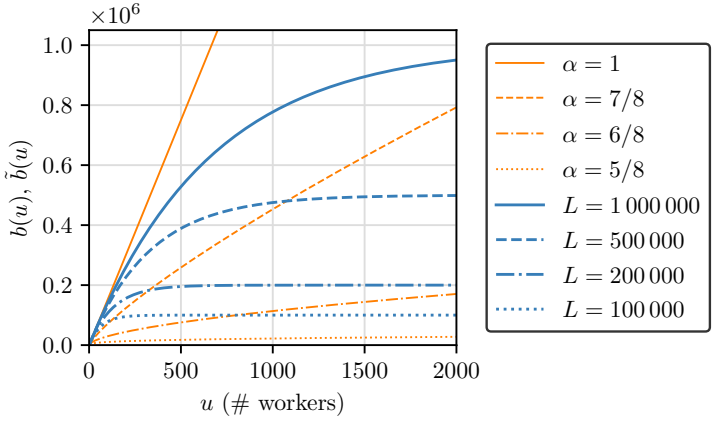
Fault tolerance

MallobSat: Buffer-Limitierungen

Max. Buffergröße nach u aggregierten Buffern der Größe $\leq \beta$:

$$b_\alpha(u) = u \cdot \alpha^{\log_2(u)} \cdot \beta$$

$$\tilde{b}_L(u) = L - (L - \beta) \cdot e^{\frac{\beta}{\beta - L}(u-1)}$$



$\beta = 1500$

MallobSat: Handling LBD Values

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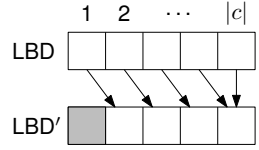
Our current approach: Increment each LBD before import

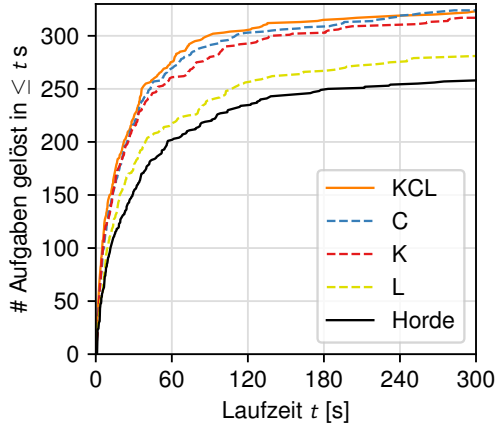
- Maintains LBD-based prioritization of clauses
- Solver keeps full control over its LBD-2-clauses
- "Regional clauses are the best!"



	Median RAM	PAR-2
Orig. LBD	108.8 GiB	75.7
Reset LBD	95.6 GiB	74.3
LBD++	97.3 GiB	72.9

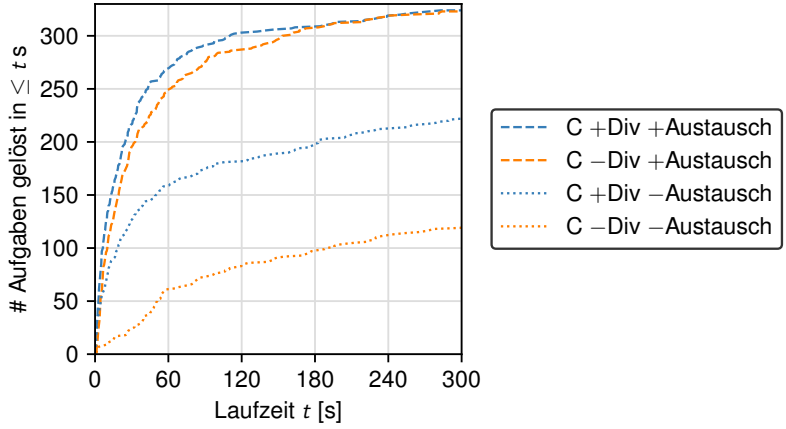
768 cores × 349 instances × 300 s

MallobSat: Solver-Auswahl und Diversifikation



768 Kerne (16 Maschinen) von SuperMUC-NG • 349 “lösbare” Probleme aus Int. SAT Competition 2022

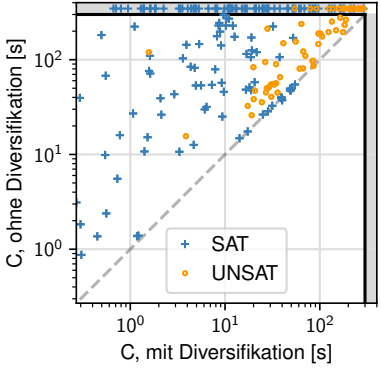
MallobSat: Diversifikation vs. Klauselaustausch



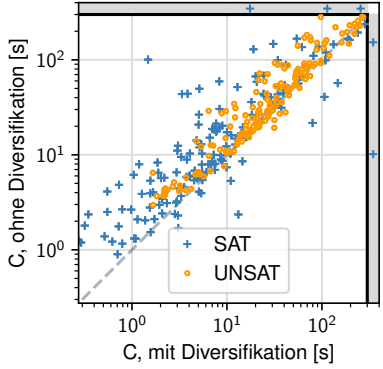
768 Kerne (16 Maschinen) von SuperMUC-NG • 349 “lösbare” Probleme aus Int. SAT Competition 2022

MallobSat: (k)ein Portfolio-Solver? (1/2)

Einfluss von Diversifikation
ohne Klauselaustausch



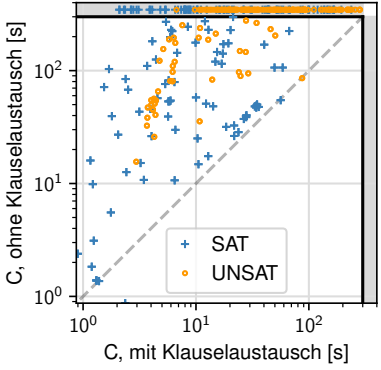
Einfluss von Diversifikation
mit Klauselaustausch



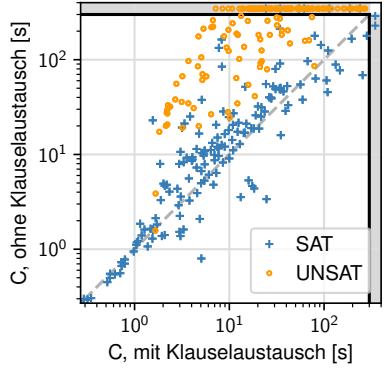
768 Kerne (16 Maschinen) von SuperMUC-NG • 349 “lösbare” Probleme aus Int. SAT Competition 2022

MallobSat: (k)ein Portfolio-Solver? (2/2)

Einfluss von Klauselaustausch
ohne Diversifikation

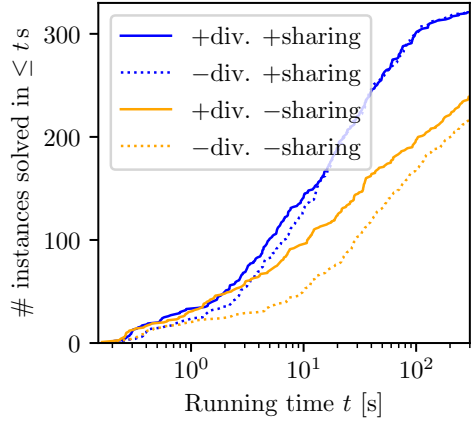


Einfluss von Klauselaustausch
mit Diversifikation



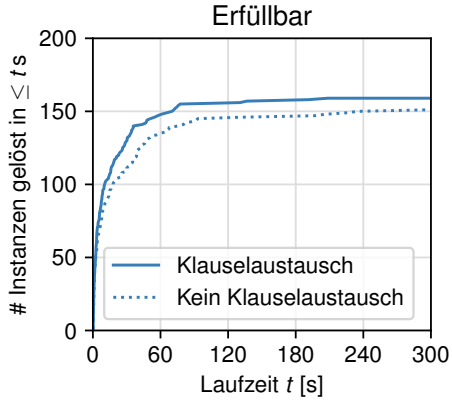
768 Kerne (16 Maschinen) von SuperMUC-NG • 349 “lösbare” Probleme aus Int. SAT Competition 2022

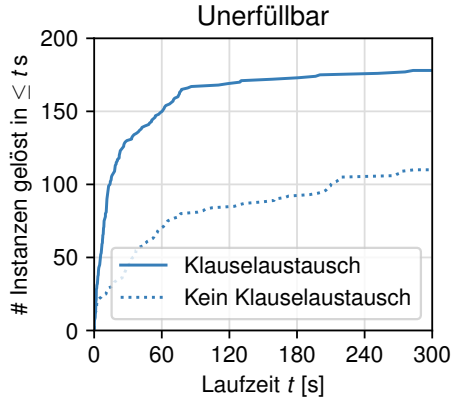
MallobSat: Diversification vs. Sharing



768 cores (16 machines) of SuperMUC-NG • 349 “solvable” problems from Int. SAT Competition 2022

MallobSat: Einfluss von Klauselaustausch



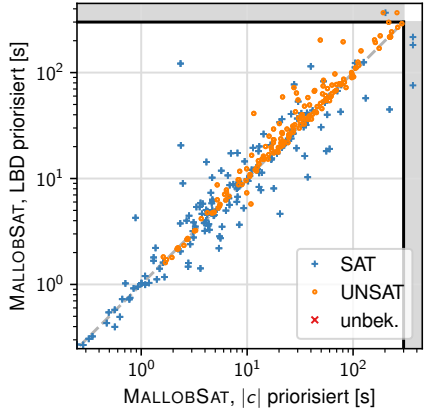


3072 Kerne (128 Maschinen) von SuperMUC-NG • 400 Probleme aus Int. SAT Competition 2021

MallobSat: Einfluss von LBD-Werten

Klausel-Qualität per LBD primär?

- Leicht schlechtere Performance
- Auch für LBD ≤ 8, $|c| \leq 20$ priorisiert



768 Kerne (16 Maschinen) von SuperMUC-NG • 349 “lösbare” Probleme aus Int. SAT Competition 2022

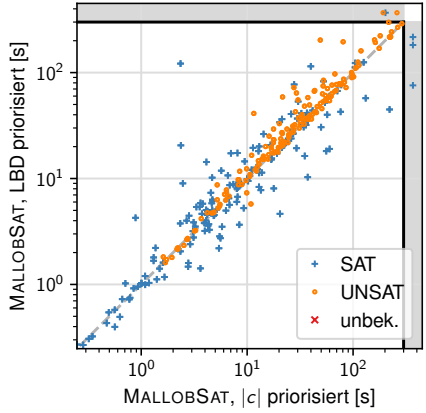
MallobSat: Einfluss von LBD-Werten

Klausel-Qualität per LBD primär?

- Leicht schlechtere Performance
- Auch für LBD ≤ 8, $|c| \leq 20$ priorisiert

Auswürfeln oder Reset aller LBDs vor Import

- Leicht schlechtere Performance
- Führt zu veränderter LBD-Verteilung in Solvern!



768 Kerne (16 Maschinen) von SuperMUC-NG • 349 “lösbare” Probleme aus Int. SAT Competition 2022

MallobSat: Einfluss von LBD-Werten

Klausel-Qualität per LBD primär?

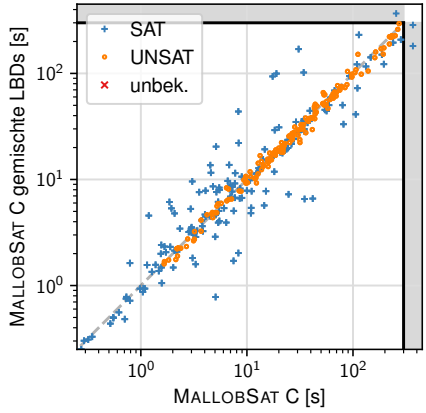
- Leicht schlechtere Performance
- Auch für LBD ≤ 8, $|c| \leq 20$ priorisiert

Auswürfeln oder Reset aller LBDs vor Import

- Leicht schlechtere Performance
- Führt zu veränderter LBD-Verteilung in Solvern!

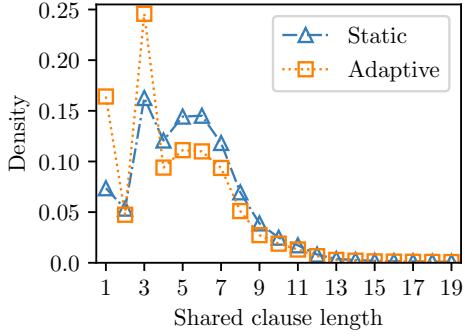
Durchmischung von LBDs geteilter Klauseln (rechts)

- LBDs innerhalb jeder Klausellänge permutieren
- Gleiche Performance!



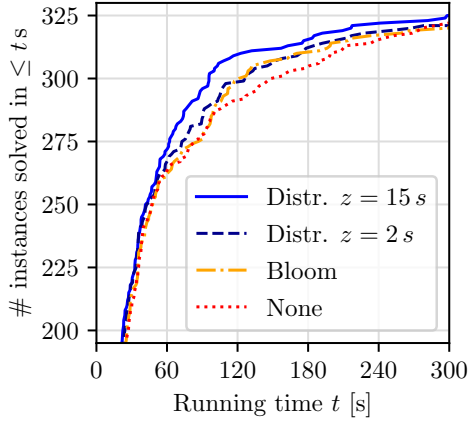
768 Kerne (16 Maschinen) von SuperMUC-NG • 349 “lösbare” Probleme aus Int. SAT Competition 2022

MallobSat: Clause Stores



768 cores (16 machines) of SuperMUC-NG • 349 “solvable” problems from Int. SAT Competition 2022

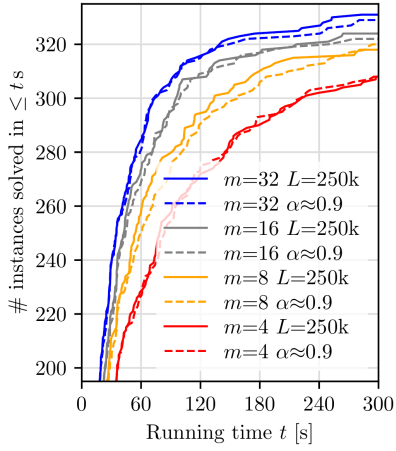
MallobSat: Clause Filtering



- ≥ 2× acceleration on some instances:
  Unsatisfiable model checking via CBMC
- Instances have multiple connected components
- Only 15-35% of clauses admitted by filter
  (total average 47%)
- Solvers might explore components in differing order
  ⇒ High overlaps but temporally shifted

768 cores (16 machines) of SuperMUC-NG • 349 “solvable” problems from Int. SAT Competition 2022

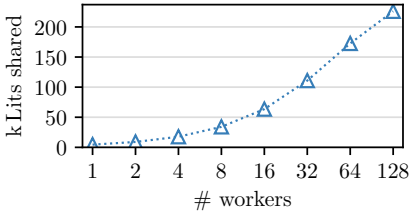
MallobSat: Sharing Buffer Scaling

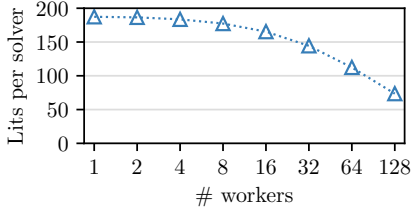


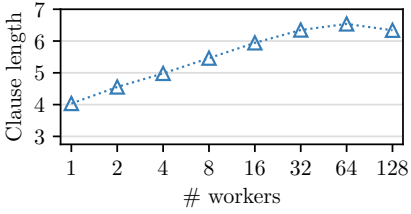
m	Variant	Lits/s	#	PAR	CSAR
32	L = 250k	345 274	331	127.4	27.5
32	$\alpha \approx 0.9$	345 274	329	130.2	28.5
16	L = 250k	221 835	324	139.2	29.6
16	$\alpha \approx 0.9$	190 728	322	141.7	30.5
8	L = 250k	127 031	318	151.7	36.0
8	$\alpha \approx 0.9$	105 132	320	153.2	39.3
4	L = 250k	68 126	308	173.6	45.6
4	$\alpha \approx 0.9$	57 718	308	173.7	45.3

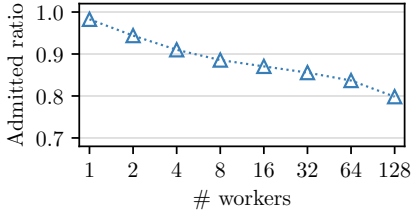
768 cores (16 machines) of SuperMUC-NG • 349 “solvable” problems from Int. SAT Competition 2022

MallobSat: Clause Sharing Insights





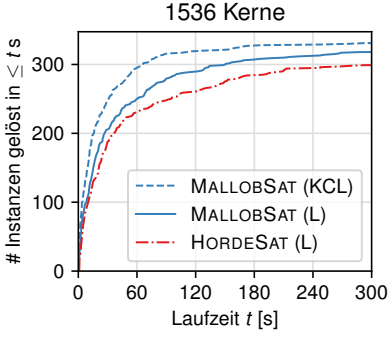




24 cores per worker

400 problems from
Int. SAT Competition 2021

MallobSat: Performance und Skalierung



	# gelöst		Speedup	
Kerne	H	M	H	M
24	**187**	**257**	3.3	7.2
48	217	279	3.9	9.4
96	244	305	6.0	12.6
192	270	312	8.1	17.7
384	287	321	11.2	22.6
768	297	328	13.8	31.8
1536	**299**	**331**	15.9	37.4
3072	–	**337**	–	**43.7**

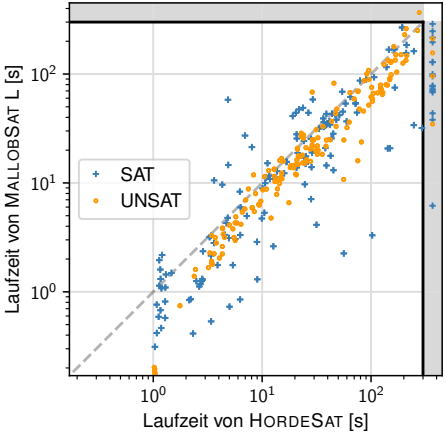
400 Probleme aus SAT Comp. 2021

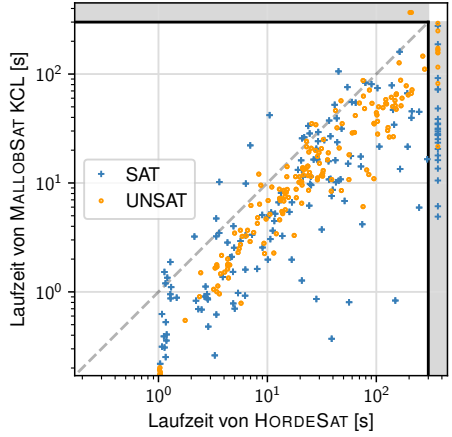
Seq. Baseline KissatMAB-HyWalk
Seq. Zeitlimit 32 h (gelöst: 331)
Par. Zeitlimit 300 s

Geom. Mittel der Speedups auf beiderseits gelösten Instanzen

MallobSat auf 3072 Kernen bei Problemen mit seq. Laufzeit $\geq$ 1 h: Speedup **419** (Effizienz $\approx$ **14%**)

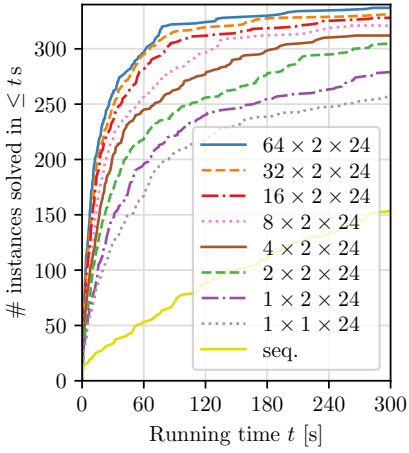
Direktvergleich: MallobSat vs. HordeSat

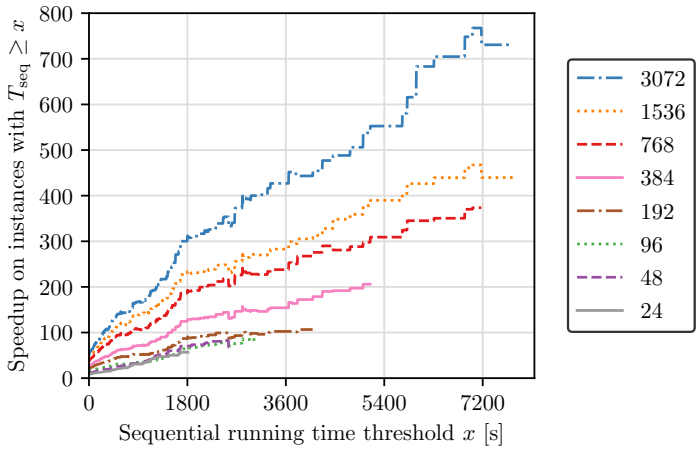




1536 Kerne (64 Maschinen) von SuperMUC-NG • 400 Probleme aus Int. SAT Competition 2021

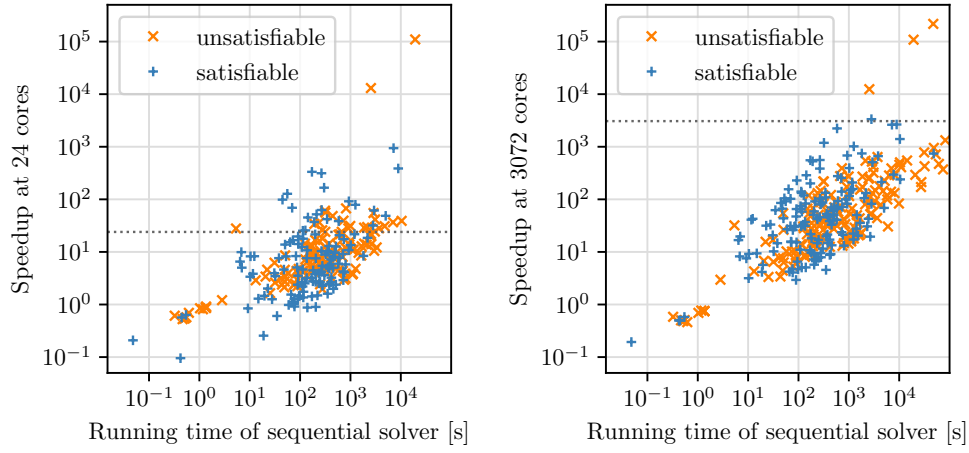
MallobSat: Strong + Weak Scaling





400 problems from Int. SAT Competition 2021

MallobSat: Per-Instance Speedups



400 problems from Int. SAT Competition 2021

MallobSat: Speedups je Familie

Ergebnis	Instanzfamilie	1. Autor	Speedups ▲
SAT	Hypertree Decomposition	Schidler	3, 5, 5, 5, 5, 7, 8, 9, 12, 13
SAT	Hamiltonkreis	Heule	4, 4, 7, 11, 17, 20, 21, 22, 24, 31, 33, 36, 42
SAT	Tree Decomposition	Ehlers	5, 7, 87
UNSAT	Zellularautomat	Chowdhury	5, 8, 8, 9, 9, 10, 22, 22, 66
			⋮
UNSAT	Relativiertes Pidgeon-Hole	Elffers	277, 542, 638
UNSAT	Bioinformatik	Bonet	292, 717
UNSAT	Balanciert zufällig	Spence	321, 388
SAT	Summe dreier Kubikzahlen	Riveros	384, 509, 1018, 3345
SAT	Schaltkreis-Multiplikation	Shunyang	17, 31, 32, 62, 105, 119, 213, 254, 393, 741, 746, 1401, 2650
UNSAT	Perfekte Matchings	Reeves	119, 413, 12 439, 108 593, 217 099

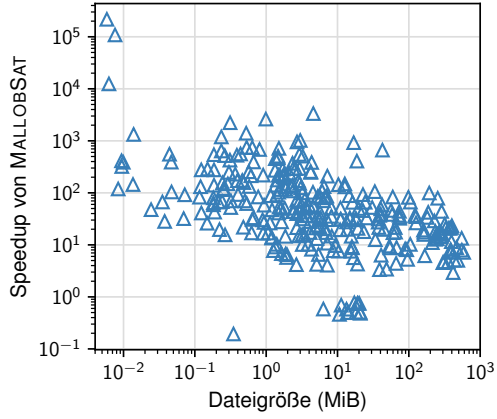
3072 Kerne (128 Maschinen) von SuperMUC-NG • 400 Probleme aus Int. SAT Competition 2021
Nur Instanzen mit seq. Laufzeit $\geq$ 60 s • Nur Familien mit $\geq$ 2 Instanzen

MallobSat: Konsistente Speedups

		Speedup auf x Kernen							
Instanz	**Seq. (s)**	24	48	92	192	384	768	1536	3072
ctl_4201_555_unsat.cnf	1873.9	14.4	20.1	32.8	49.0	75.3	105.7	138.7	171.2
edit_distance031_283.cnf	2465.9	20.3	36.3	59.8	85.9	122.7	184.2	230.8	247.1
edit_distance031_284.cnf	2561.6	22.0	34.3	59.4	87.7	130.4	185.7	230.3	256.8
mp1-bsat201-707.cnf	3087.9	41.4	67.7	125.3	165.5	234.1	260.7	287.5	321.3
mp1-bsat210-739.cnf	7011.8	36.6	60.3	109.1	150.8	253.0	294.4	324.3	387.5
mp1-klieber2017s-2000-022-eq.cnf	908.0	28.1	49.0	65.8	81.6	92.7	110.6	149.7	172.7
randomG-B-Mix-n16-d05.cnf	3053.2	24.4	41.1	63.5	106.5	163.4	238.5	332.6	413.3
rphp4_065_shuffled.cnf	671.5	24.1	42.3	66.0	94.0	129.0	179.4	231.5	276.8
rphp4_080_shuffled.cnf	2145.0	29.7	53.1	85.3	161.1	229.6	295.1	416.3	542.1
rphp4_090_shuffled.cnf	3709.9	28.2	51.3	91.7	138.9	261.7	379.4	503.2	638.1
satch2ways14u.cnf	1868.9	29.0	45.9	60.8	87.7	120.7	183.0	218.1	270.9
satch2ways15.cnf	10383.0	39.0	59.6	78.5	106.8	180.0	265.9	369.4	506.1
sp4-33-one-stri-tree-noid.cnf	727.5	39.4	55.6	95.6	133.4	198.0	266.6	320.0	390.0

Probleme aus Int. SAT Competition 2021 mit $> 5\%$ Beschleunigung pro Schritt, $> 5\%$ Effizienz auf 3072 Kernen

MallobSat: Speedups vs. Dateigröße

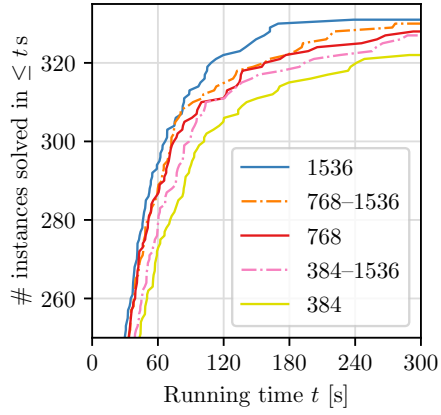


3072 Kerne (128 Maschinen) von SuperMUC-NG • 400 Probleme aus Int. SAT Competition 2021

MallobSat: Verformbarkeit

Verformbarkeits-Test

- 1536 Kerne insgesamt
- Benchmark-Stream: Übliche sequentielle Verarbeitung von SAT-Benchmarks (2021)
- Stör-Stream: ‖: 10 s “Stör-Aufgabe”, 10 s Pause :‖

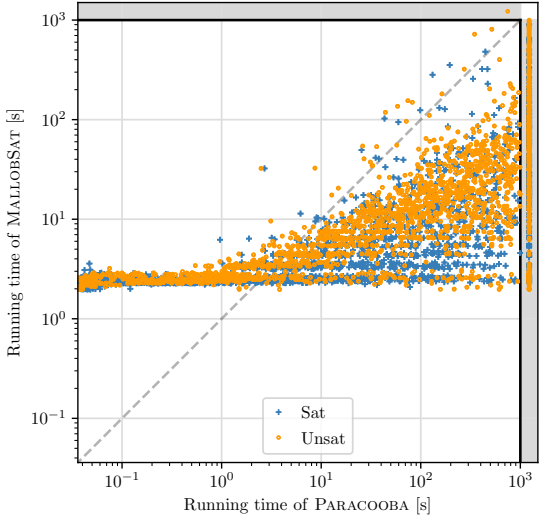


MallobSat: Wettbewerbe

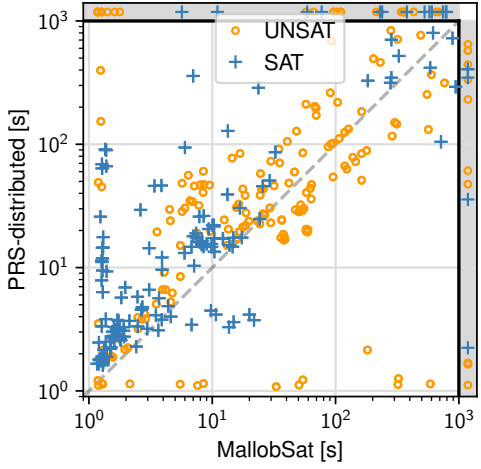
Exklusiv gelöste Instanzen

- 2 — 2020: 1. Platz Cloud Track
- 42 — 2021: 2. Platz Parallel Track
  3. Platz SAT, 2. Platz UNSAT
- 42 — 2021: 1. Platz Cloud Track
- 16 — 2022: 3. Platz Parallel Track
  2. Platz SAT, 1. Platz UNSAT
- 16 — 2022: 1. Platz Anniversary Parallel Track
  1. Platz UNSAT
- 16 — 2022: 1. Platz Cloud Track
- 266 — 2022: 1. Platz Anniversary Cloud Track
- 2022: 1. Platz FLoC Olympic Games: Cloud, Anniv. Cloud, Anniv. Parallel
- 4 — 2023: 1. Platz Cloud Track
- 2023: 2. Platz Parallel Track
  2. Platz SAT

MallobSat vs. Paracooba (ISC'22 Anniversary)



MallobSat vs. PRS-distributed (ISC'23)



Which Proof Format?

DRAT proof format

add $\overline{x_3}$
add $x_1 x_2$
add $\overline{x_1}$
delete $\overline{x_3}$
add $x_3 \overline{x_4}$
add $x_1 x_3$
add $\square$

Which Proof Format?

DRAT proof format

add $\overline{x_3}$
add $x_1 x_2$
add $\overline{x_1}$
delete $\overline{x_3}$
add $x_3 \overline{x_4}$
add $x_1 x_3$
add $\square$

+ compact format
+ prevalent in solvers
- costly checking

Which Proof Format?

Karlsruher Institut für Technologie

DRAT proof format

add $\overline{x_3}$
add $x_1 x_2$
add $\overline{x_1}$
delete $\overline{x_3}$
add $x_3 \overline{x_4}$
add $x_1 x_3$
add $\square$

LRAT proof format

add $c_9 := \overline{x_3}$ via c_5, c_4
add $c_{10} := x_1 x_2$ via c_3, c_2
add $c_{11} := \overline{x_1}$ via c_6, c_9
delete c_9
add $c_{12} := x_3 \overline{x_4}$ via c_7, c_{11}
add $c_{13} := x_1 x_3$ via c_8, c_{12}
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\+ compact format
\+ prevalent in solvers
\- costly checking

Which Proof Format?

Karlsruher Institut für Technologie

DRAT proof format

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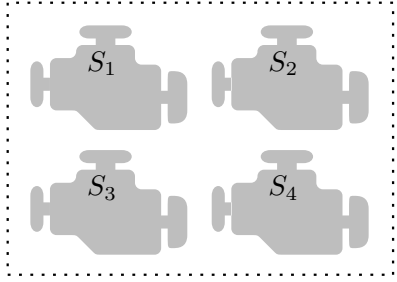

10 original clauses

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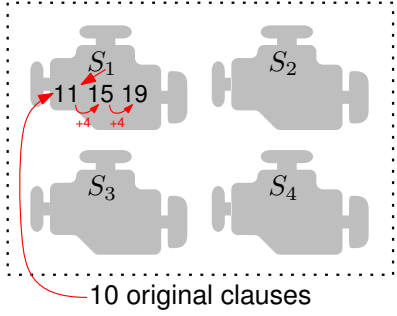

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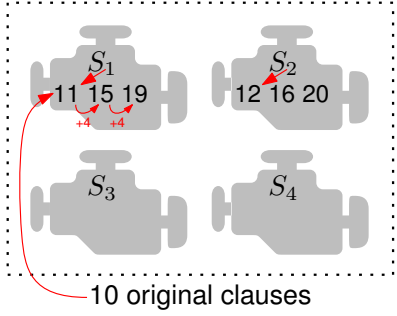

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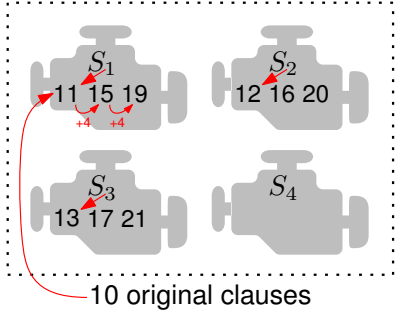

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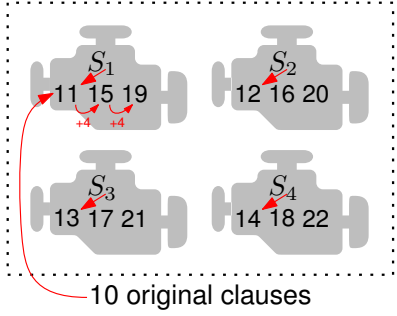

Distributed Approach

Parallel processing + distributed memory?

- Prune all partial proofs in parallel, **then** combine
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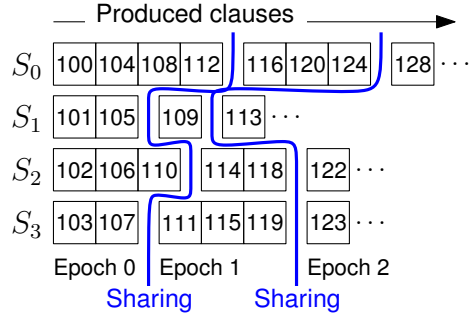

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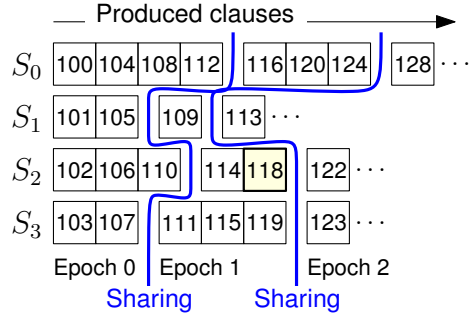

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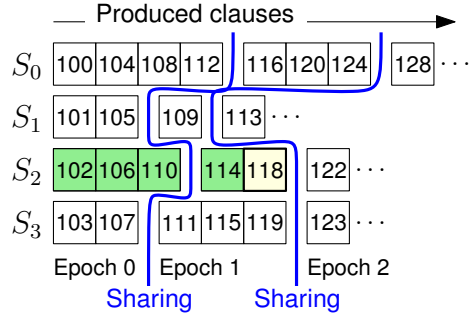

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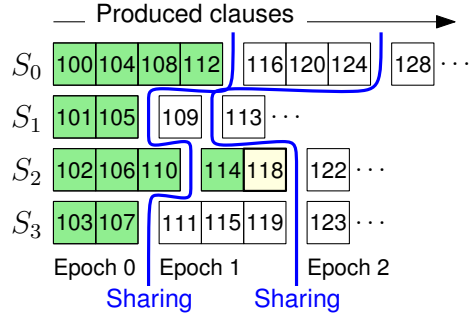

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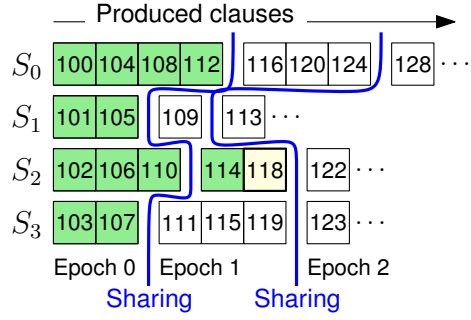

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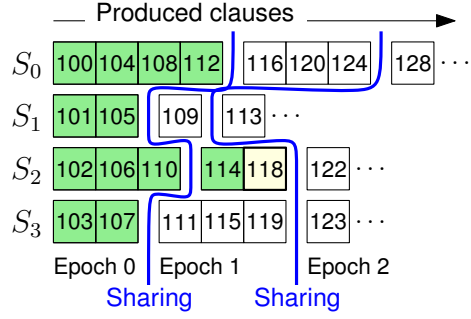

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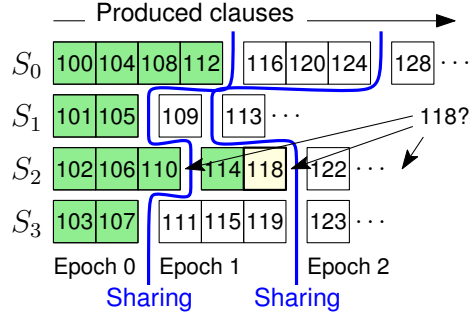

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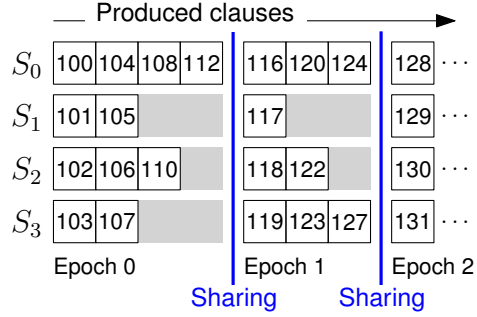

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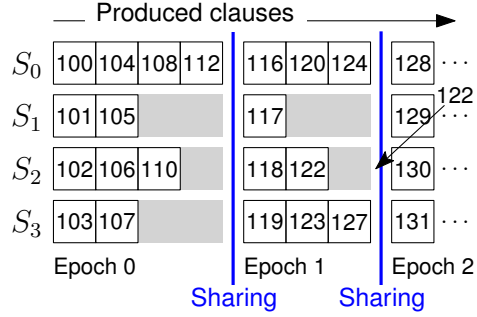
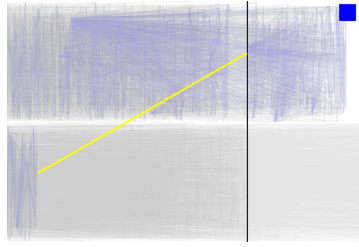


Rewind: Realization

Local Processing

- For each S_i: Frontier F_i of req. clause IDs *produced by* S_i; Backlog B_i of *remote* req. clause IDs
  - External-memory priority queues partitioned by epoch
- Epoch e: Process proof parts from ep. e
- Clause c with $id(c) \in F_i$: Insert each $d \in deps(c)$ into F_i or B_i



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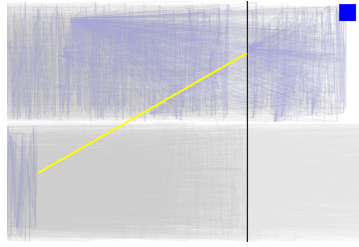


Redistribution of Clause IDs

- After processing epoch e: Extract IDs from ep. $e-1$ from all B_i
- All-reduction like Mallob's clause sharing, detecting duplicate IDs
- Strictly less communication than during solving

Kontext: Verteilte Graph-Algorithmen

***Single-source* Erreichbarkeit** *aller* Knoten t von Startknoten s in verteiltem gerichtetem Graphen G
n Knoten, m Kanten, Durchmesser D; p Prozessoren

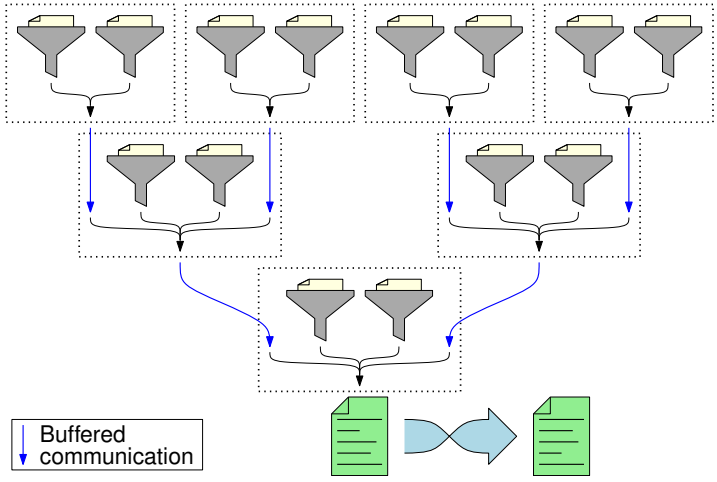
- Einfügen randomisierter Durchmesser-reduzierender Shortcuts
  Ghaffari, Mohsen, and Rajan Udwani. “Brief announcement: Distributed single-source reachability.” ACM Symp. on Principles of Distributed Computing, 2015.
- Stand der Technik (2019): $\tilde{\mathcal{O}}(m)$ Arbeit, $n^{1/2+o(1)}$ Tiefe w.h.p. in n
  Jambulapati, Arun et al. “Parallel reachability in almost linear work and square root depth.” FOCS 2019.

Unser Ansatz

- Grob $\mathcal{O}(m \log m + p \cdot \hat{e}K)$ Arbeit, $\mathcal{O}(D \log m + \hat{e} \cdot K \log p)$ Tiefe
  $\hat{e}$: # Klauselaustausch-Operationen; K: # Klauseln je Austausch
- Streaming-Algorithmus: Greift auf jede Kante ein einziges Mal, in fester Reihenfolge zu
- Externer Algorithmus: Benötigt prinzipiell nur $\mathcal{O}(K + \hat{e}p +$ *max. Ausgangsgrad* $+$ *ext. PQ*$)$ Speicher
- Gebündelte Kommunikation: $\hat{e} \cdot 2(p-1)$ Nachrichten der Länge $\mathcal{O}(K)$

Distributed Combination

- Hierarchically merge pruning output along tree of processors
- Root processor
  1. adds approximated “delete” lines
  2. writes stream into file
  3. reverses file



Experimental Setup (1/2)

Karlsruher Institut für Technologie

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- Base SAT solver: CaDiCaL [Biere 2018] modified to output LRAT, restricted portfolio
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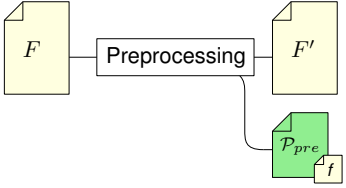

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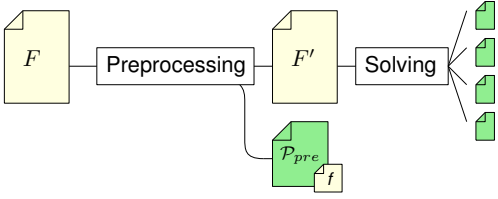

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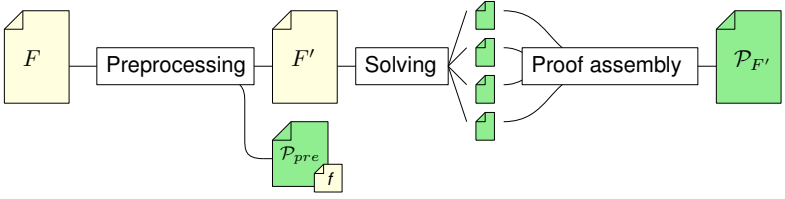

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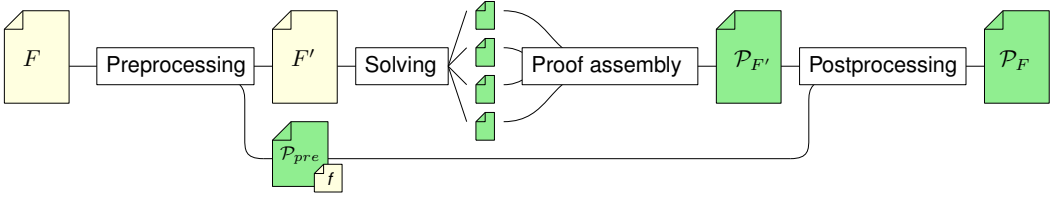

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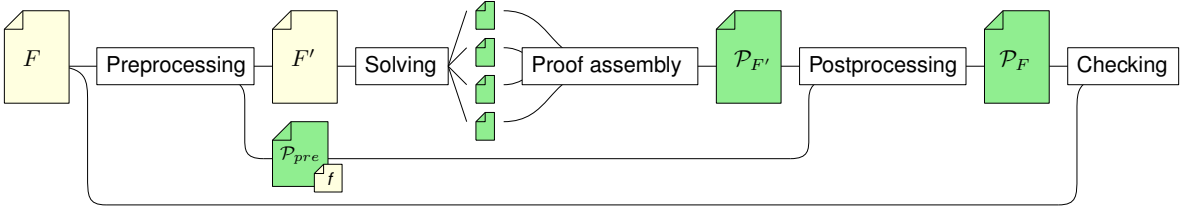

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Comparison to prior work

- Shared-memory clause-sharing portfolios: Heule, Manthey, Philipp @ POS'14
  - Synchronized, moderated logging into shared DRAT proof
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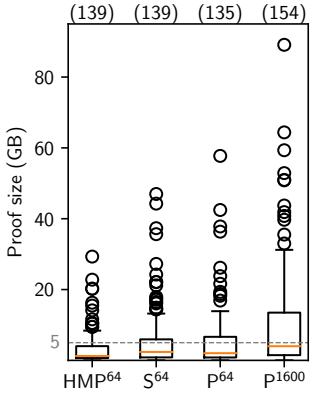
Resources

- 1600× setup: 100× `m6i.4xlarge` EC2 instances (16 hwthreads, 64 GB RAM)
- 64× setup: 1× `m6i.16xlarge` EC2 instance (64 hwthreads, 256 GB RAM)
- Sequential setup: One `m6i.4xlarge` EC2 instance

} ≤ 1000 s solving, ≤ 4000 s proof prod.

Evaluation: Proof Output

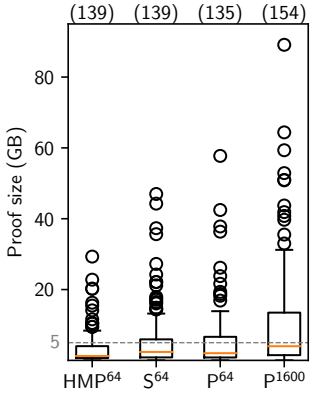
How large are the resulting proofs?



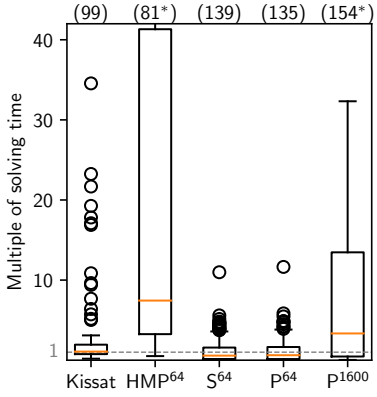
*Some data cut off

Evaluation: Proof Output

How large are the resulting proofs?

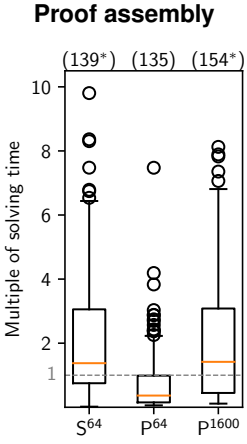


How fast can we check the proofs?



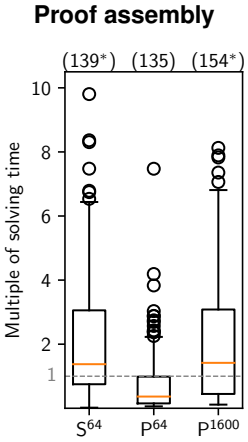
*Some data cut off

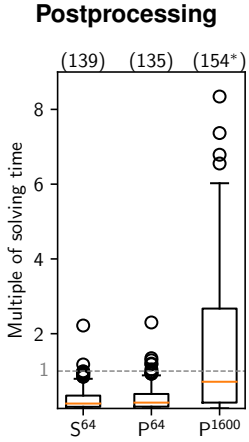
Evaluation: Overhead



*Some data cut off

Evaluation: Overhead

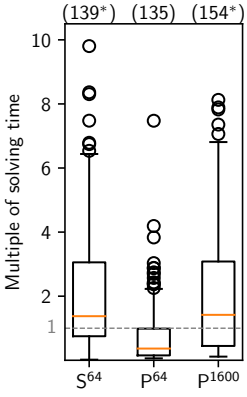




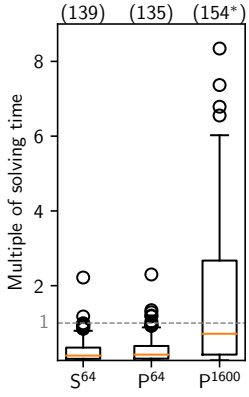
*Some data cut off

Evaluation: Overhead

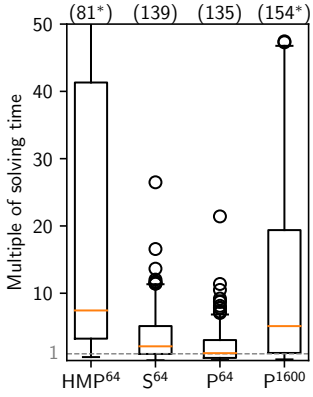
Proof assembly



Postprocessing



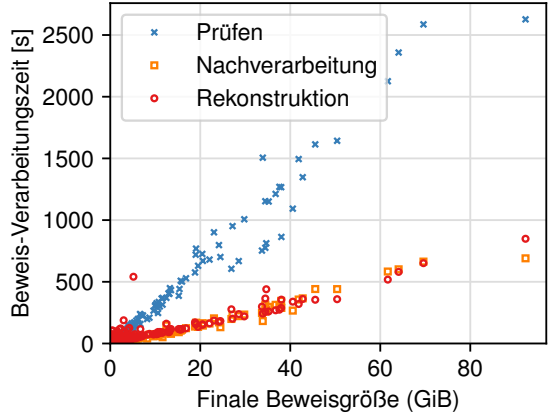
Total (HMP: checking only)



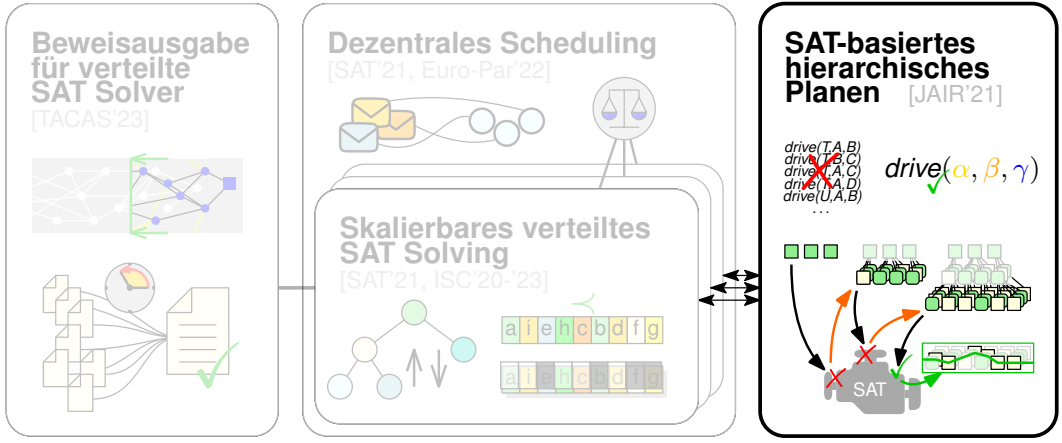
*Some data cut off

Beweise: Weitere Einblicke

- Durchsatz der Beweis-Rekonstruktion (median-Instanz): 114 MB/s
- Pruning-Faktor: durchschnittl. 28×, korreliert stark mit 1/Solving-Zeit
  - Je mehr Klauselaustausch-Operationen, desto verknüpfter wird der Beweis
- Größte Beweise (≥40 GB):
  - `mp1` Block-Puzzle
  - 2× `div` EPFL-Miter
  - 2× Sport-Turnierplanung
  - Sudoku-Problemgenerierung
  - Gruppentheorie (Hantzsche-Wendt)
  - Äquivalenz Pancake– vs. Selection-Sort
  - Kryptographie (MD5)



Übersicht


Beweisausgabe für verteilte SAT Solver
[TACAS'23]
Dezentrales Scheduling
[SAT'21, Euro-Par'22]
Skalierbares verteiltes SAT Solving
[SAT'21, ISC'20-'23]
SAT-basiertes hierarchisches Planen [JAIR'21]
drive(T,A,B)
drive(T,B,C)
drive(T,A,C)
drive(T,A,D)
drive(U,A,B)
drive(α, β, γ)
SAT

Hierarchisches Planen

$t_1(A, B)$ $t_2(C)$ $t_3(E, F, G)$

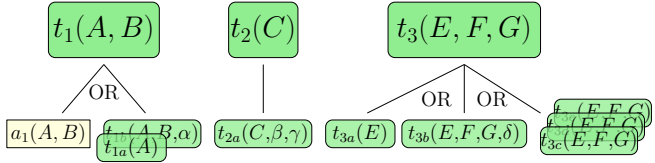
Problemstellung [Bercher et al. 2019]

- Erledige Sequenz von Aufgaben ...

Hierarchisches Planen

Problemstellung [Bercher et al. 2019]

- Erledige Sequenz von Aufgaben ...
- durch Zerlegen jeder Aufgabe ...



Hierarchisches Planen

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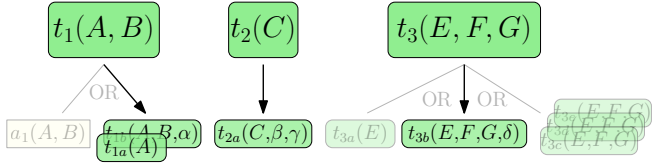

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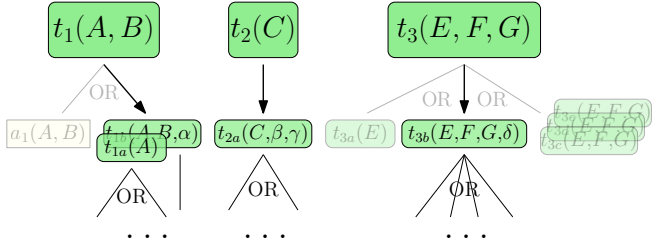

Hierarchisches Planen

Problemstellung [Bercher et al. 2019]

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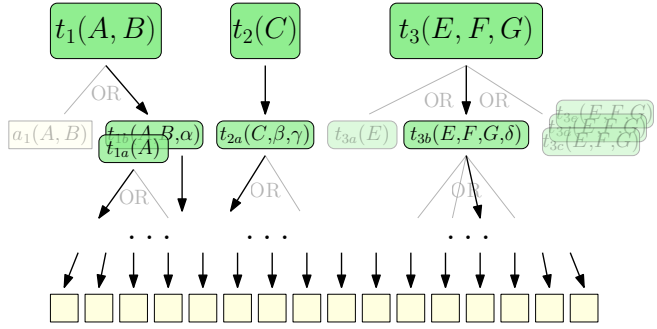
- durch Zerlegen jeder Aufgabe ...
- bis nur primitive Aufgaben verbleiben ...



Hierarchisches Planen

Problemstellung [Bercher et al. 2019]

- Erledige Sequenz von Aufgaben ...
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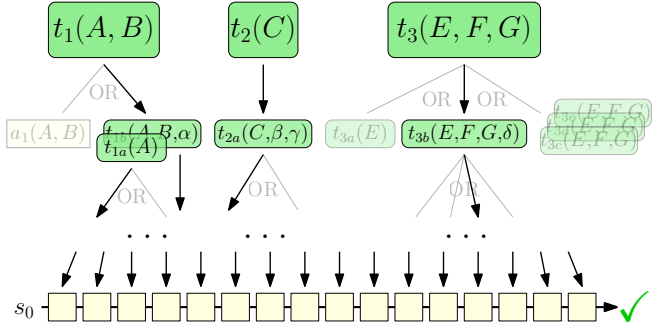
- bis nur primitive Aufgaben verbleiben ...
- die von Startzustand aus ausführbar sind.



Hierarchisches Planen

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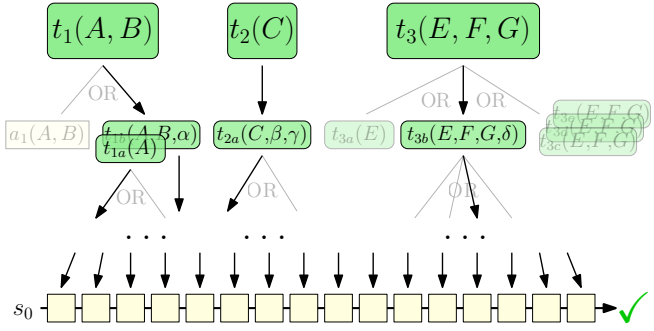
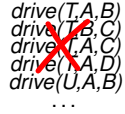


Vorherige SAT-basierte Ansätze [ICAPS'19; Behnke et al. 2018]

- Kodiere Hierarchie bis zu beschränkter Tiefe — erhöhe Tiefe bis Problem erfüllbar wird
- Teures Ausinstanziieren (Grounding) aller parametrisierten Objekte ⇒ kombinatorische Explosion

Unser Ansatz: Lilotane [JAIR'21]



$drive(\alpha, \beta, \gamma)$

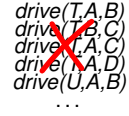
Zentrale Merkmale

- Kein Grounding: Parameter werden in Aussagenlogik kodiert

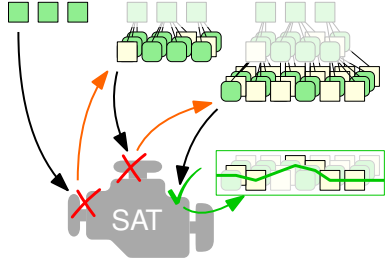
Unser Ansatz: Lilotane [JAIR'21]

Zentrale Merkmale

- Kein Grounding: Parameter werden in Aussagenlogik kodiert
- Inkrementelles SAT Solving: Wiederholte Interaktion mit einer einzigen Solver-Instanz [ICAPS'19]



$drive(\alpha, \beta, \gamma)$



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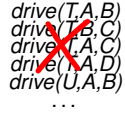

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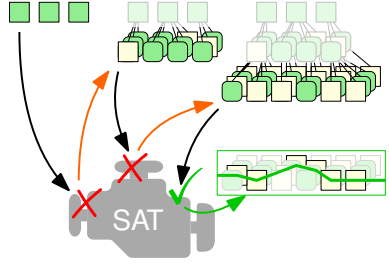
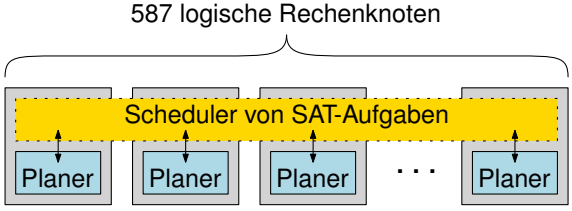


Vergleich mit vorherigem Stand der Technik

- Kleinere Formeln, oftmals um 1-2 Größenordnungen
- Effizientes Planen
  - 2. Platz in Int. Planning Competition 2020
  - 2× unabhängige Nutzung in IPC 2023

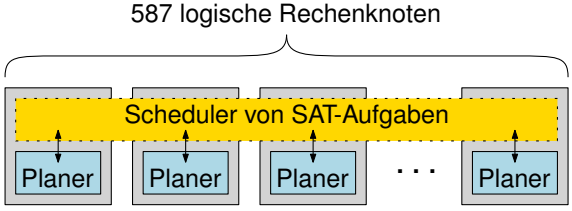
Planung × Verteiltes SAT Solving × Scheduling



SuperMUC-NG · 2346 Kerne insgesamt

1 Kern pro Planer-Instanz,
3 Kerne pro Mallob-Prozess

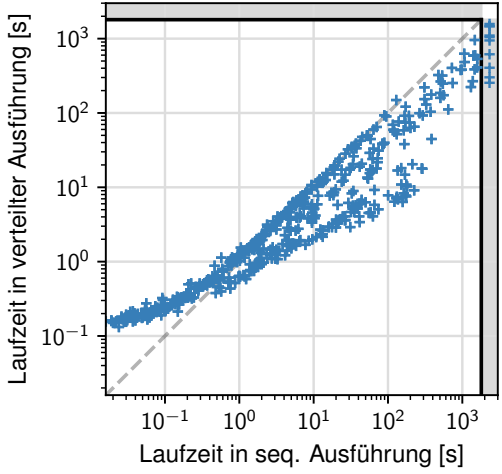
Planung × Verteiltes SAT Solving × Scheduling



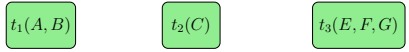
SuperMUC-NG · 2346 Kerne insgesamt

1 Kern pro Planer-Instanz,
3 Kerne pro Mallob-Prozess

Animation: `https://dominikschreiber.de/animallob`



Total-Order Hierarchical Task Network Planning



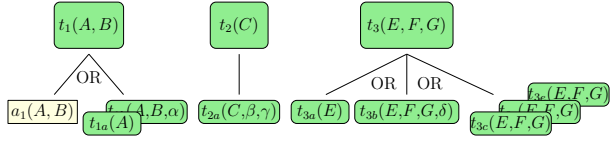
Objective

- Achieve a given set of tasks . . .

Total-Order Hierarchical Task Network Planning

Objective

- Achieve a given set of tasks . . .
- by recursively replacing each task with a specific set of subtasks . . .



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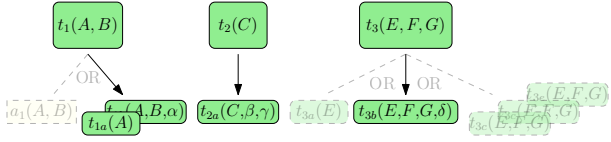

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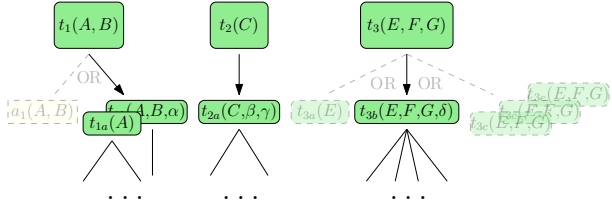

Total-Order Hierarchical Task Network Planning

Objective

- Achieve a given set of tasks . . .
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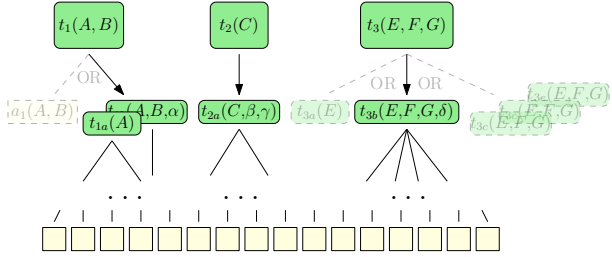
- until only “atomic” primitive tasks remain . . .

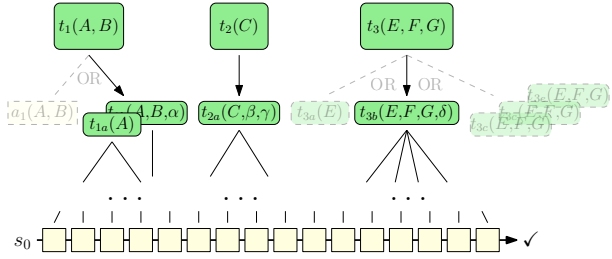


Total-Order Hierarchical Task Network Planning

Karlsruher Institut für Technologie

Objective

- Achieve a given set of tasks . . .
- by recursively replacing each task with a specific set of subtasks . . .
- until only “atomic” primitive tasks remain . . .
- which form a plan, a sequence of executable actions from the given initial state



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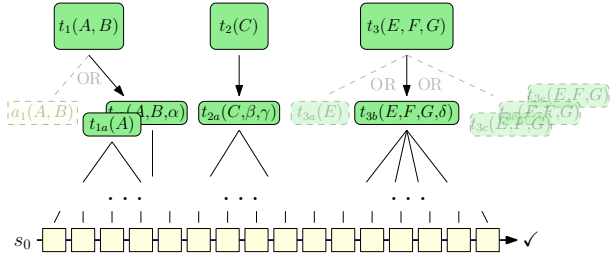

Structures

- Fact: Boolean feature of world state

Total-Order Hierarchical Task Network Planning

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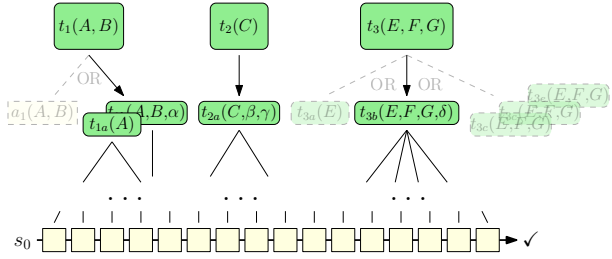

Structures

- Fact: Boolean feature of world state
- Task: Footprint of sth. to achieve

Total-Order Hierarchical Task Network Planning

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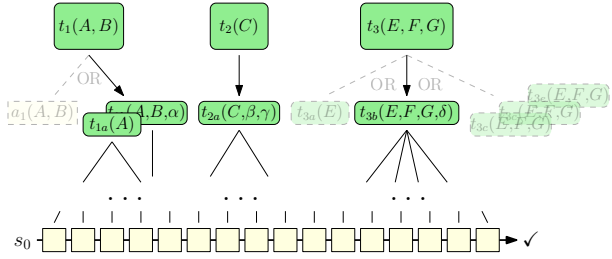

Structures

- Fact: Boolean feature of world state
- Task: Footprint of sth. to achieve
- Method: Recipe to achieve certain compound task ⇒ preconditions, subtasks

Total-Order Hierarchical Task Network Planning

Objective

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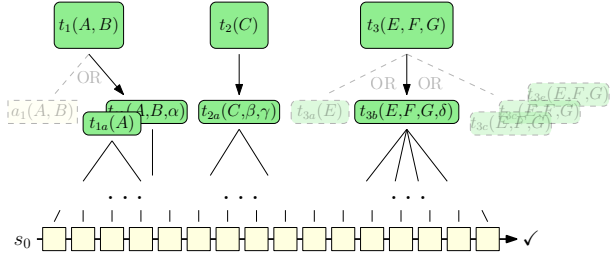

Structures

- Fact: Boolean feature of world state
- Task: Footprint of sth. to achieve
- Method: Recipe to achieve certain compound task ⇒ preconditions, subtasks
- Operator: Recipe to execute primitive task ⇒ preconditions, effects

Total-Order Hierarchical Task Network Planning

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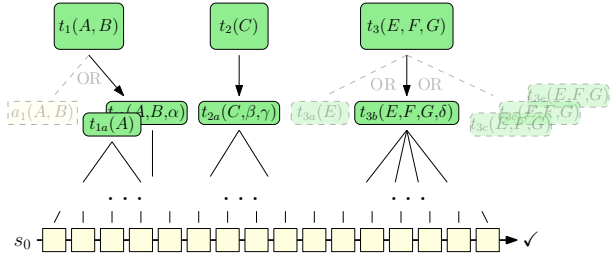

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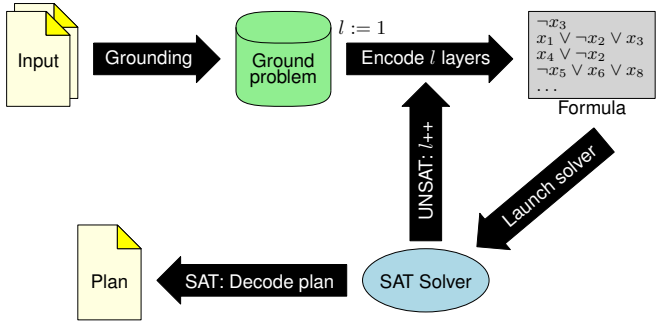
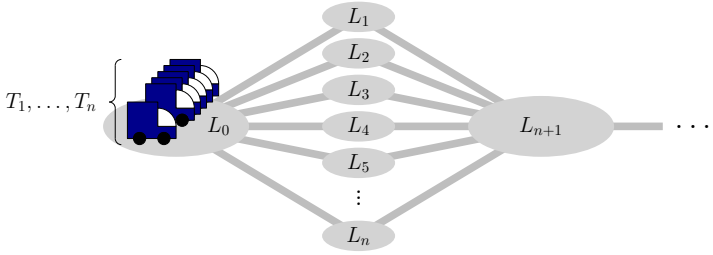
- Operator: Recipe to execute primitive task ⇒ preconditions, effects
- Action (Reduction): *ground* operator (method) – no free variables

SAT-based TOHTN Planning



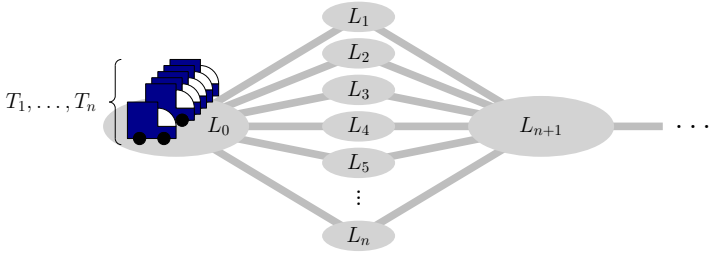
Behnke et al. (AAAI'18) with separate formulae & solver instances,
Schreiber et al. (ICAPS'19) with incremental SAT solving

The Problem with Grounding



$drive(T_1,L_0,L_1)$	$drive(T_1,L_0,L_2)$	$drive(T_1,L_0,L_3)$	$\cdots$	$drive(T_n,L_0,L_n)$
$drive(T_2,L_0,L_1)$	$drive(T_2,L_0,L_2)$	$drive(T_2,L_0,L_3)$		
$drive(T_3,L_0,L_1)$	$drive(T_3,L_0,L_2)$			
$drive(T_4,L_0,L_1)$				$\vdots$
$drive(T_5,L_0,L_1)$		$\ddots$		
$\vdots$				
$drive(T_n,L_0,L_1)$		$\cdots$		$drive(T_n,L_0,L_n)$

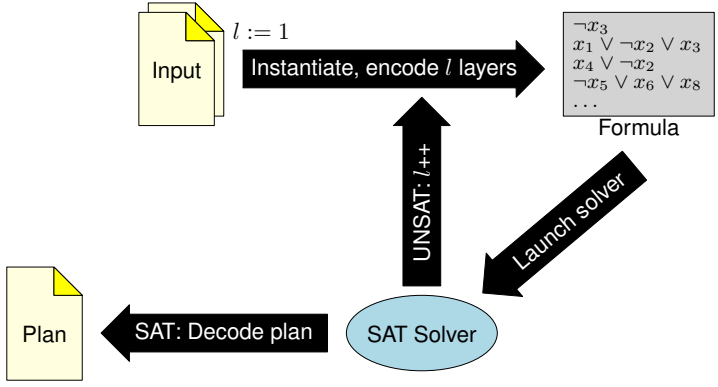
The Problem with Grounding



$$
\begin{array}{llll}
drive(T_1,L_0,L_1) & drive(T_1,L_0,L_2) & drive(T_1,L_0,L_3) & \cdots\ drive(T_n,L_0,L_n) \\
drive(T_2,L_0,L_1) & drive(T_2,L_0,L_2) & drive(T_2,L_0,L_3) & \\
drive(T_3,L_0,L_1) & drive(T_3,L_0,L_2) & & \\
drive(T_4,L_0,L_1) & & \ddots & \vdots \\
drive(T_5,L_0,L_1) & & & \\
\vdots & & & \\
drive(T_n,L_0,L_1) & & \cdots & drive(T_n,L_0,L_n)
\end{array}
$$

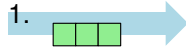
$\Rightarrow$ Combinatorial blowup!

Our Approach



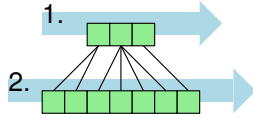
Instantiation

- Layer 0: Instantiate operations matching initial tasks



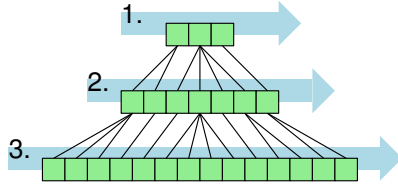
Instantiation

- Layer 0: Instantiate operations matching initial tasks
- Layer l: Instantiate possible children of op. at layer $l - 1$



Instantiation

- Layer 0: Instantiate operations matching initial tasks
- Layer l: Instantiate possible children of op. at layer $l-1$
- Keep variables, do not ground into separate operations
- Layer fully instantiated: Encode, attempt to solve



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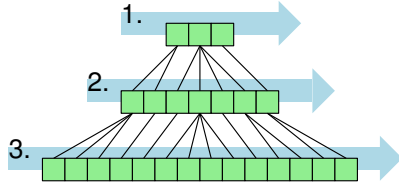
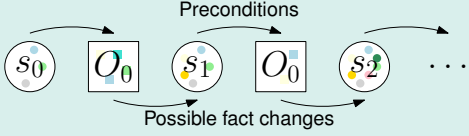


Reachability Analysis



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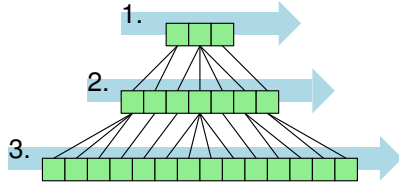

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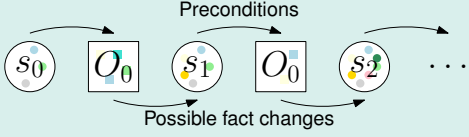

⇒ (Over-)approximate fact changes of instantiated operations, add to possible facts

⇒ Discard operations with impossible preconditions

SAT Encoding

	Tree-REX (ICAPS'19)	**Lilotane (ours)**
Operation variables (per position)	$drive(T_1, L_0, L_1)$, $drive(T_1, L_0, L_2)$, $drive(T_2, L_0, L_1)$, $drive(T_2, L_0, L_2)$, ...	$drive(\alpha, \beta, \gamma)$

SAT Encoding

	Tree-REX (ICAPS'19)	**Lilotane (ours)**
Operation variables (per position)	$drive(T_1, L_0, L_1)$, $drive(T_1, L_0, L_2)$, $drive(T_2, L_0, L_1)$, $drive(T_2, L_0, L_2)$, ...	$drive(\alpha, \beta, \gamma)$
Fact variables (per position)	$at(T_1, L_0)$, ..., $road(L_0, L_1)$, ...	$at(T_1, L_0)$, ..., $road(L_0, L_1)$, ... $at(\alpha, \beta)$, $at(\alpha, \gamma)$, $road(\beta, \gamma)$

SAT Encoding

	Tree-REX (ICAPS'19)	**Lilotane (ours)**
Operation variables (per position)	$drive(T_1, L_0, L_1)$, $drive(T_1, L_0, L_2)$, $drive(T_2, L_0, L_1)$, $drive(T_2, L_0, L_2)$, ...	$drive(\alpha, \beta, \gamma)$
Fact variables (per position)	$at(T_1, L_0)$, ..., $road(L_0, L_1)$, ...	$at(T_1, L_0)$, ..., $road(L_0, L_1)$, ... $at(\alpha, \beta)$, $at(\alpha, \gamma)$, $road(\beta, \gamma)$
Substitution variables (global)	—	$[\alpha/T_1]$, $[\alpha/T_2]$, ... $[\beta/L_0]$, $[\beta/L_1]$, ...

SAT Encoding

	Tree-REX (ICAPS'19)	**Lilotane (ours)**
Operation variables (per position)	$drive(T_1, L_0, L_1)$, $drive(T_1, L_0, L_2)$, $drive(T_2, L_0, L_1)$, $drive(T_2, L_0, L_2)$, …	$drive(\alpha, \beta, \gamma)$
Fact variables (per position)	$at(T_1, L_0)$, …, $road(L_0, L_1)$, …	$at(T_1, L_0)$, …, $road(L_0, L_1)$, … $at(\alpha, \beta)$, $at(\alpha, \gamma)$, $road(\beta, \gamma)$
Substitution variables (global)	—	$[\alpha/T_1]$, $[\alpha/T_2]$, … $[\beta/L_0]$, $[\beta/L_1]$, …
Selected clause schemes	$drive(T_1, L_0, L_1) \Rightarrow at(T_1, L_0)$	$drive(\alpha, \beta, \gamma) \Rightarrow at(\alpha, \beta)$ *exactly-one*$([\alpha/T_1], [\alpha/T_2], \ldots, [\alpha/T_n])$ $[\alpha/T_1] \wedge [\beta/L_0] \Rightarrow (at(\alpha, \beta) \Leftrightarrow at(T_1, L_0))$

Our Encoding

Boolean variables

- f_x^l: "At the l-th layer, fact f holds before the x-th operation" — f may contain variables (*pseudo-constants*)
- o_x^l: "At the l-th layer, the x-th operation is o" — o may contain pseudo-constants
- $prim_x^l$: "At the l-th layer, the x-th operation is primitive"
- $[\alpha/c]$: "Pseudo-constant α is substituted with constant c"

Sparse Encoding

- Only encode variables which are not trivially true or trivially false
- Reachability analysis from top to bottom, left to right: Filter impossible operations, facts
- Retroactively prune subtrees which turned out to be impossible

Our Encoding

Clauses (1/2)

- Initial state s_0: $\forall f \in s_0 : f_0^0$, $\forall f \notin s_0 : \neg f_0^0$

Our Encoding

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- Preconditions and effects: $o_x^l \Rightarrow \bigwedge_{f \in pre(o)} f_x^l \wedge \bigwedge_{f \in eff(o)} f_{x+1}^l$

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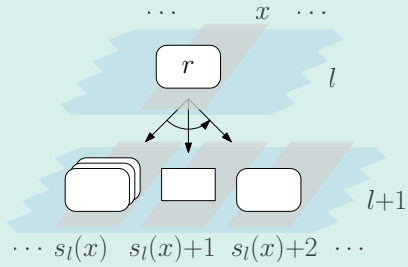
- Propagation of facts, actions: $f_x^l \Leftrightarrow f_{s_l(x)}^{l+1}$, $o_x^l \Rightarrow o_{s_l(x)}^{l+1}$



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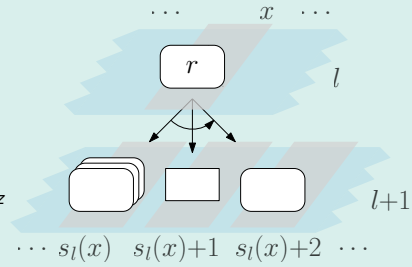
- Propagation of facts, actions: $f_x^l \Leftrightarrow f_{s_l(x)}^{l+1}$, $o_x^l \Rightarrow o_{s_l(x)}^{l+1}$
- Expansion of a reduction: $\forall z : o_x^l \Rightarrow \bigvee_{o' \in children(o,z)} (o')_{s_l(x)+z}^{l+1}$



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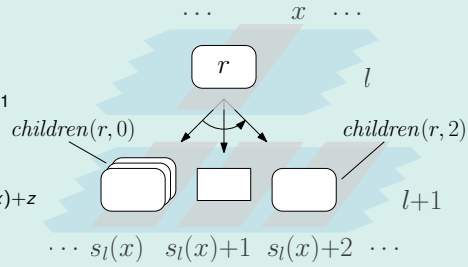

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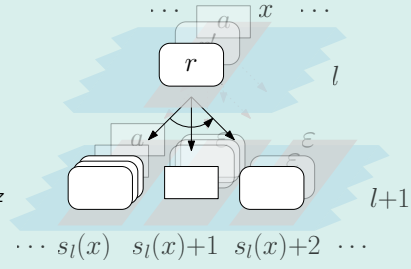

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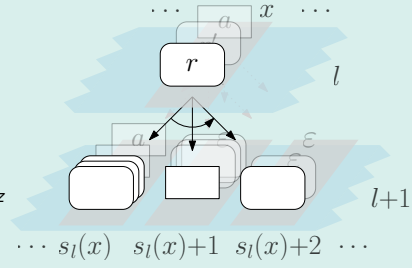
- Expansion of a reduction: $\forall z : o_x^l \Rightarrow \bigvee_{o' \in children(o,z)} (o')_{s_l(x)+z}^{l+1}$
- Assume fully expanded network at deepest layer l':
  $prim_0^{l'}, prim_1^{l'}, prim_2^{l'}, \ldots$



Our Encoding

Clauses (2/2)

- Domain of pseudo-constant α in o: $o^l_x \Rightarrow \bigvee_{c \in dom(\alpha)} [\alpha/c]$
  + at-most-one constraints over $\{[\alpha/c] \mid c \in dom(\alpha)\}$
- Link between pseudo-atom f and actual atom $f' := f[\alpha_1/c_1][\alpha_2/c_2]$:
  $([\alpha_1/c_1] \wedge [\alpha_2/c_2]) \Rightarrow (f^l_x \Leftrightarrow (f')^l_x)$
- Frame axioms: $(f^l_x \wedge \neg f^l_{x+1}) \Rightarrow (\neg prim^l_x \vee \bigvee_{o \in supp(\neg f)} o^l_x \vee \bigvee_{o \in isupp(\neg f)} o^l_x)$
  + If $o \in isupp(\neg f)$ is active, then active substitutions must unify an effect of o with f.

Further Challenges

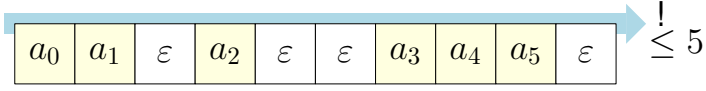
- Special handling of actions whose effects may become contradictory
- Enforce restrictions on a pseudo-constant's domain imposed by argument types
- Make "more general" operations subsume "less general" operations

Anytime Plan Improvement

a_0	a_1	ε	a_2	ε	ε	a_3	a_4	a_5	ε

- Maximize number of ε-actions (no-ops): Successively forbid current plan length (ICAPS'19)
- Leads to shortest possible plan at current layer (not globally optimal!)

Anytime Plan Improvement



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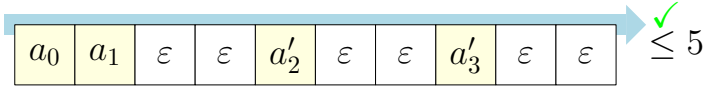

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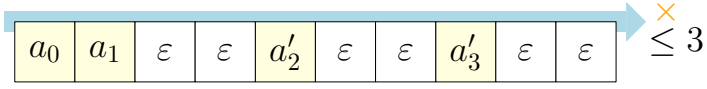
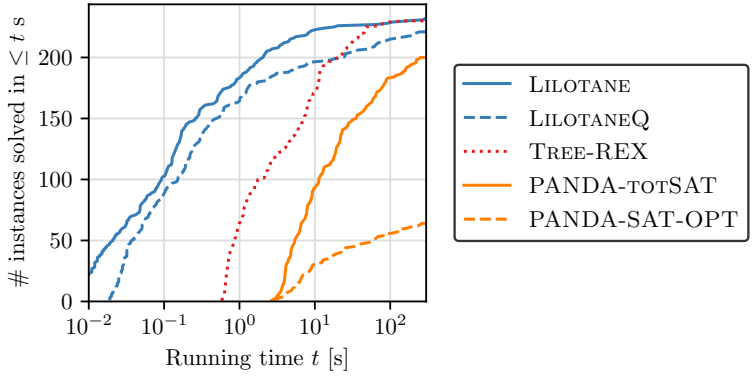
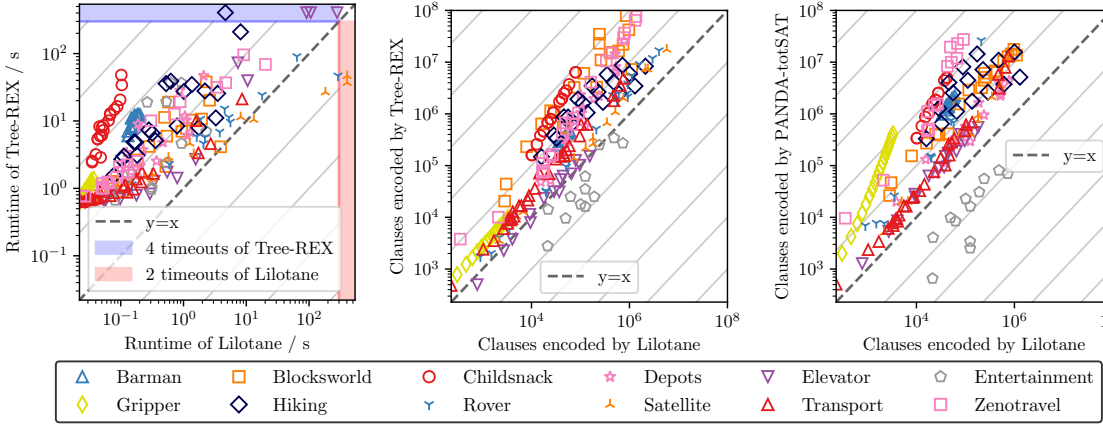


- Maximize number of ε-actions (no-ops): Successively forbid current plan length (ICAPS'19)
- Leads to shortest possible plan at current layer (not globally optimal!)
- Improved encoding exploiting incremental SAT
- Anytime procedure: Cancellable at any time, outputs best plan found

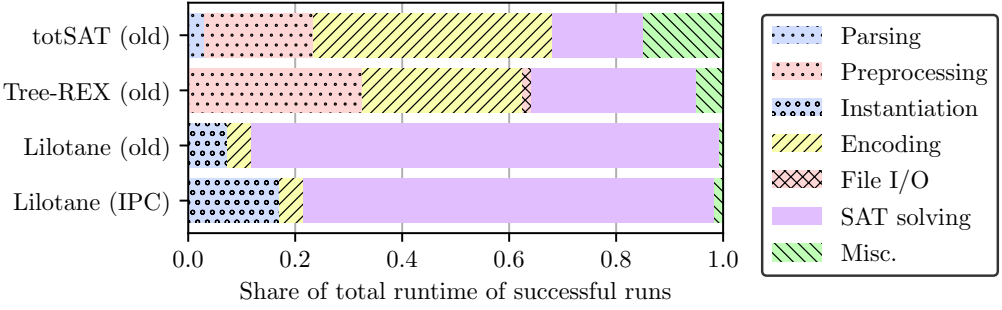
Comparing SAT-based Planners (1/2)



Comparing SAT-based Planners (2/2)

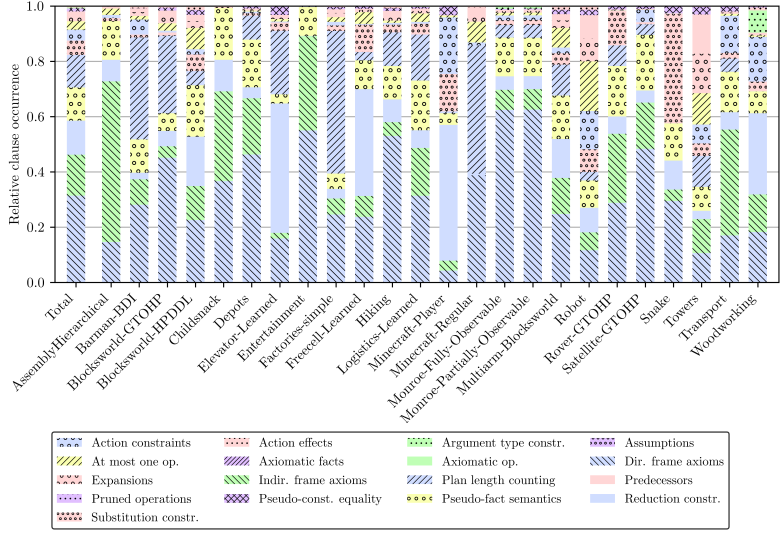


Tree-REX, totSAT, Lilotane: Share of Runtimes

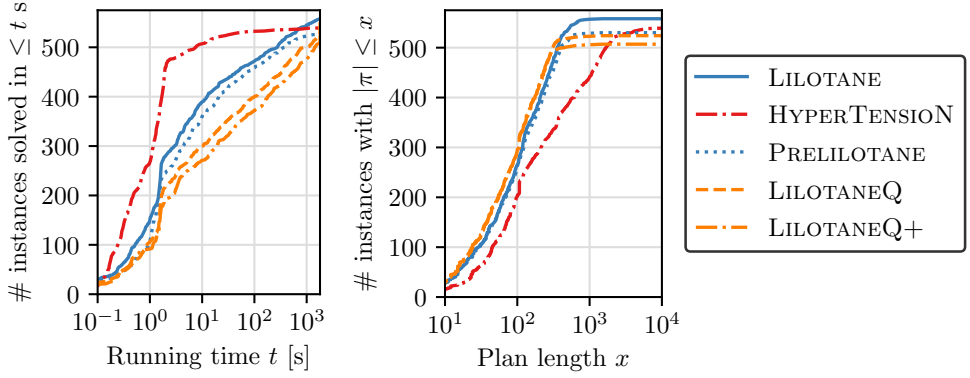


(old): pre-IPC benchmark set (Behnke ’18; Schreiber ’19) **(IPC)**: large IPC benchmark set

Lilotane: Clause Categories

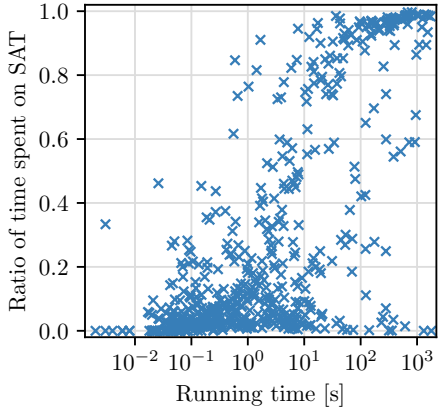


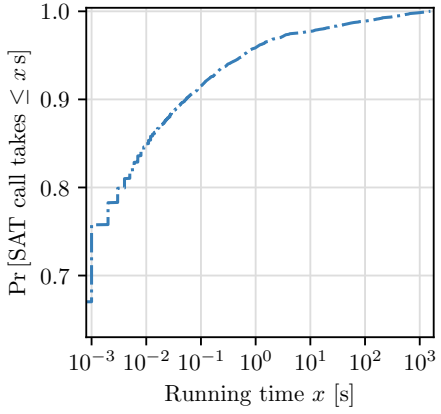
Evaluation on IPC Benchmarks



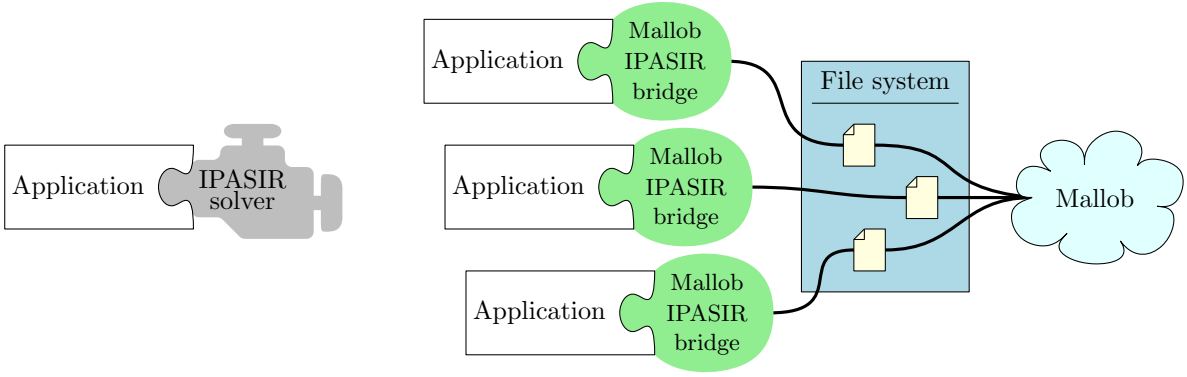
IPC'20: 82 problems across 7 domains solved exclusively by Lilotane (winner: 74 problems)

MALLOTANE: Requirement Analysis





MALLOTANE: Technology



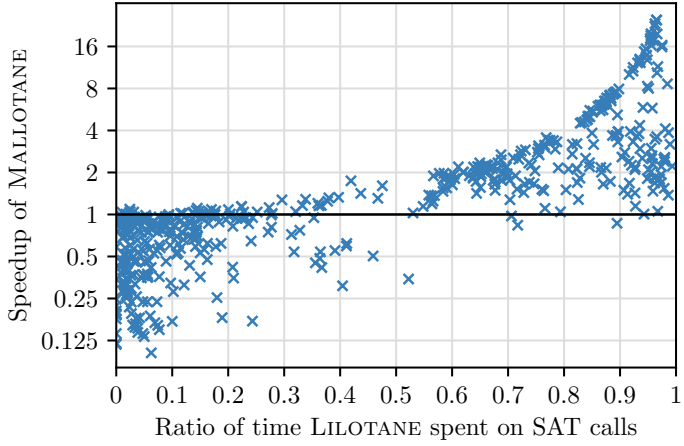
MALLOTANE: Speedups

Domain	#	min.	med.	geom.	max.	total
Assembly	5	0.15	1.11	0.772	3.19	**2.821**
Barman	18	0.18	0.84	0.808	4.12	**2.069**
BlocksworldG	22	0.12	0.81	0.639	1.14	**0.946**
BlocksworldH	1	0.91	0.91	0.910	**0.91**	**0.914**
Childsnack	26	0.19	0.46	0.460	1.09	**0.930**
Depots	22	0.32	0.77	0.734	1.33	1.196
Elevator	146	0.14	**3.40**	**3.103**	24.82	**9.054**
Entertainment	2	0.93	0.99	0.960	**0.99**	**0.938**
Factories	4	0.16	1.75	0.839	2.06	1.835
Freecell	12	1.01	**2.28**	**2.429**	5.17	**3.228**
Hiking	23	0.29	0.82	0.815	2.06	1.455
Logistics	50	0.54	**2.02**	1.948	3.86	**2.171**
MinecraftP	4	0.78	**2.16**	1.717	2.67	**2.294**
MinecraftR	32	0.37	0.96	0.895	1.09	**0.990**
MonroeFO	19	0.58	0.91	0.899	1.14	**0.949**
MonroePO	19	0.83	0.94	1.014	2.68	1.058
Multiarm	4	1.02	**2.20**	1.649	3.17	**2.869**
Robot	8	0.10	0.34	0.375	1.37	1.249
Rover	24	0.12	1.89	1.528	5.85	**3.477**
Satellite	15	0.16	1.04	0.849	1.42	1.125
Snake	20	0.14	0.74	0.586	1.11	1.027
Towers	6	0.20	0.84	0.581	**0.89**	**0.864**
Transport	32	0.13	0.54	0.645	8.63	**3.207**
Woodworking	22	0.14	0.65	0.547	1.01	**0.824**

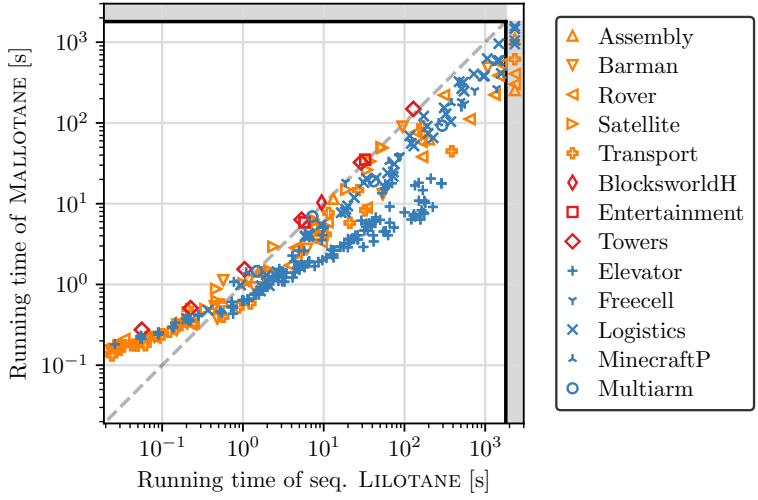
Med./geom./total speedups ≥ 2

Max./total speedups < 1

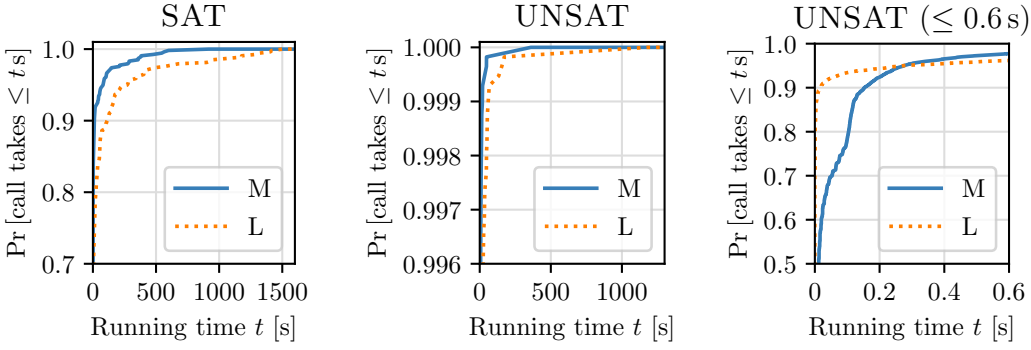
MALLOTANE: Speedups vs. SAT Ratio



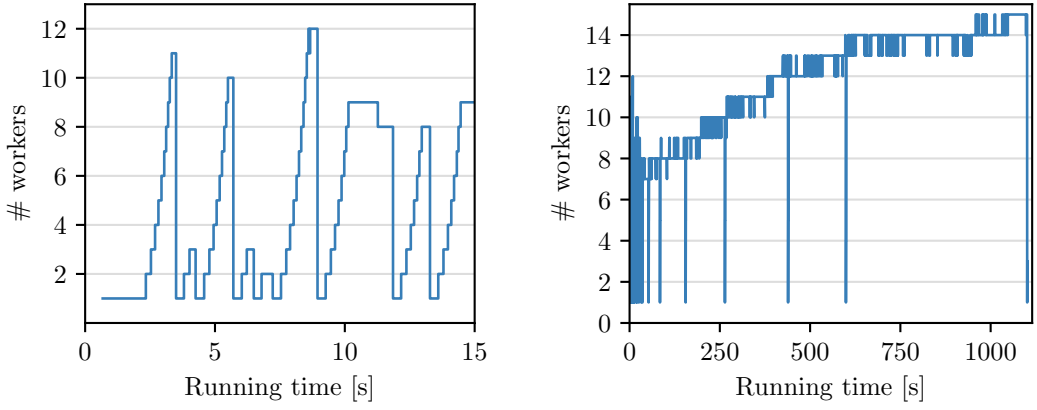
MALLOTANE: Speedups by Domain



MALLOTANE: Duration of SAT Calls



MALLOTANE: Job Volume over Time



Problem from *Assembly* domain · Demand of a job increment doubles each 0.5 s