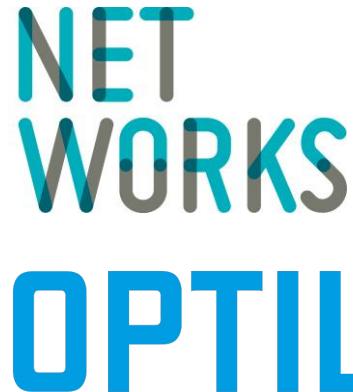


Parameterized Algorithms & Computational Experiments Challenge 2022

Directed Feedback Vertex Set



www.pacechallenge.org



Outline

- goals, impact, and history of PACE [Holger]
- announcement of the PACE 2023 challenge [Max, Sebastian]
- **results of the PACE 2022 challenge [Christian]**
- **presentations by PACE 2022 winners [Rafel, Sylwester]**

Goals

Investigate the applicability of algorithmic ideas from parameterized algorithmics

1. Provide **bridge** between algorithm theory and algorithm engineering practice
2. Inspire new **theoretical** developments
3. Investigate the **competitiveness** of analytical and design framework
4. Produce universally accessible **libraries** of implementations & benchmark inputs
5. Encourage **dissemination** of the findings in scientific papers

Steering Committee

Steering Committee

- (since 2016) [Holger Dell](#) (Goethe University Frankfurt and IT University of Copenhagen)
- (since 2019) [Johannes Fichte](#) (Technische Universität Dresden)
- (since 2019) [Markus Hecher](#) (Technische Universität Wien)
- (since 2016) [Bart M. P. Jansen](#) (chair) (Eindhoven University of Technology)
- (since 2020) [Łukasz Kowalik](#) (University of Warsaw)
- (since 2021) [André Nichterlein](#) (Technical University of Berlin)
- (since 2020) [Marcin Pilipczuk](#) (University of Warsaw)
- (since 2020) [Manuel Sorge](#) (Technische Universität Wien)

Former members

- (2017-2021) [Édouard Bonnet](#) (LIP, ENS Lyon)
- (2016-2019) [Thore Husfeldt](#) (IT University of Copenhagen and Lund University)
- (2016-2020) [Petteri Kaski](#) (Aalto University)
- (2016-2020) [Christian Komusiewicz](#) (Philipps-Universität Marburg)
- (2016-2019) [Frances Rosamond](#) (University of Bergen)
- (2017-2020) [Florian Sikora](#) (LAMSADE, Université Paris Dauphine)

Impact of PACE

Motivation: Explaining success

- PACE 2017: Top 4 solvers on mi

Improved Analysis of Highest-Degree Branching
for Feedback Vertex Set

Yoichi Iwata*

National Institute of Informatics, Japan

yiwata@nii.ac.jp

Yusuke Kobayashi†

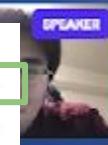
Kyoto University, Japan

yusuke@kurims.kyoto-u.ac.jp

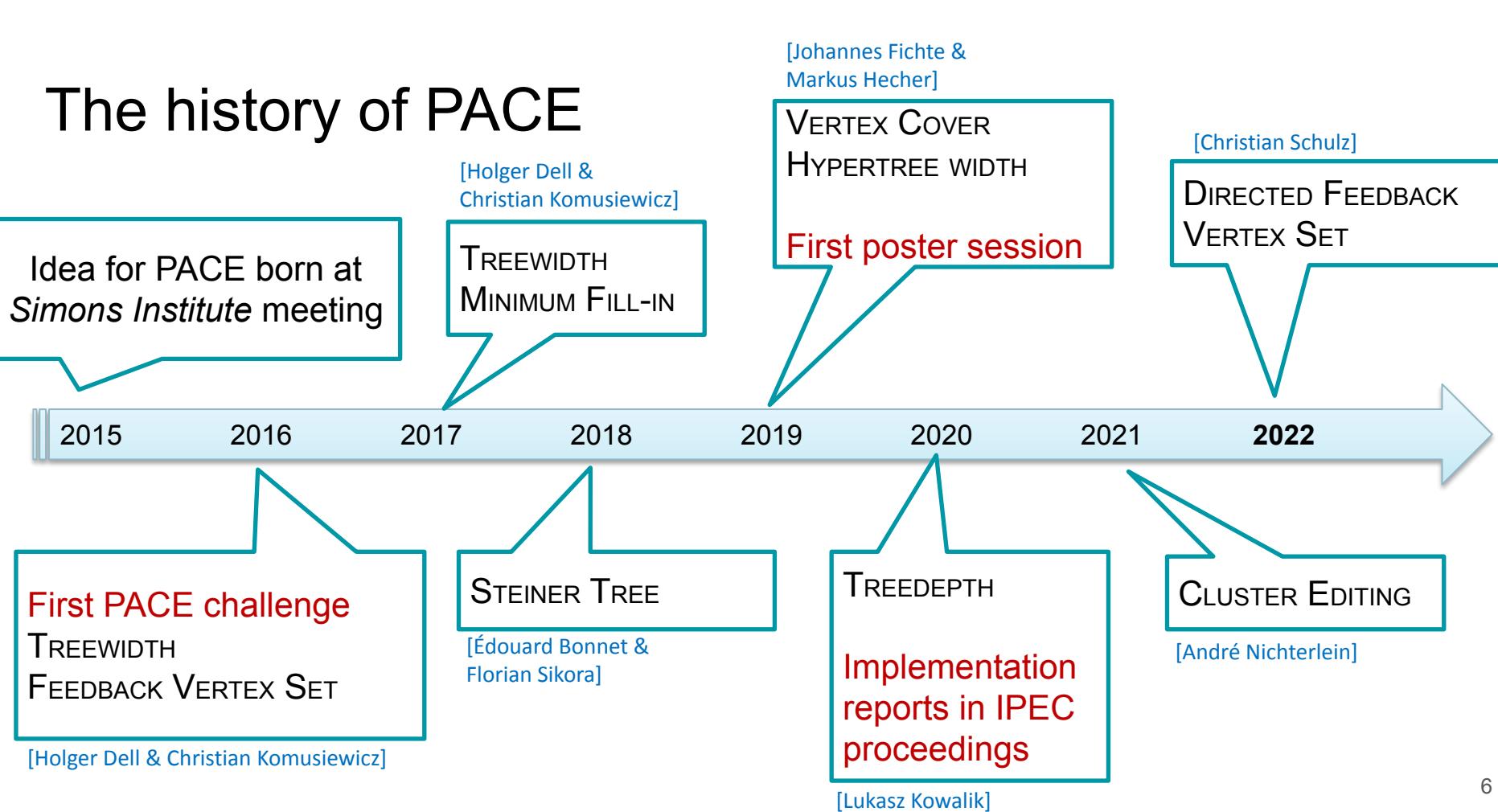
runs in $O^*(3^k)$ time. In this paper, we give a faster deterministic algorithm which runs in $O^*(3.460^k)$ time. As explained below, this study is strongly motivated by Parameterized Algorithms and Computational Experiments (PACE) challenge and its follow-up empirical evaluation by Kiljan and Pilipczuk [13]. Instead of designing a new theoretically fast algorithm, we analyze the theoretical worst-case running time of the empirically fast algorithm that has been developed through the PACE challenge and the empirical evaluation, and we show that this algorithm is not only empirically fast but also theoretically fast.

JALP 2017)
ms (FOCS 2018)

2018 (AAAI 2019).



The history of PACE



PACE 2023: Twinwidth

Main goal of PACE: *Bridging the Gap Between FPT-Theory and Practice*

- Previously: Pushing theory towards practice
- This time: Inspire theory from practice
- **Twinwidth:** Basically no algorithms known
 - But many interesting applications

Program Committee:



Max Bannach (Lübeck)

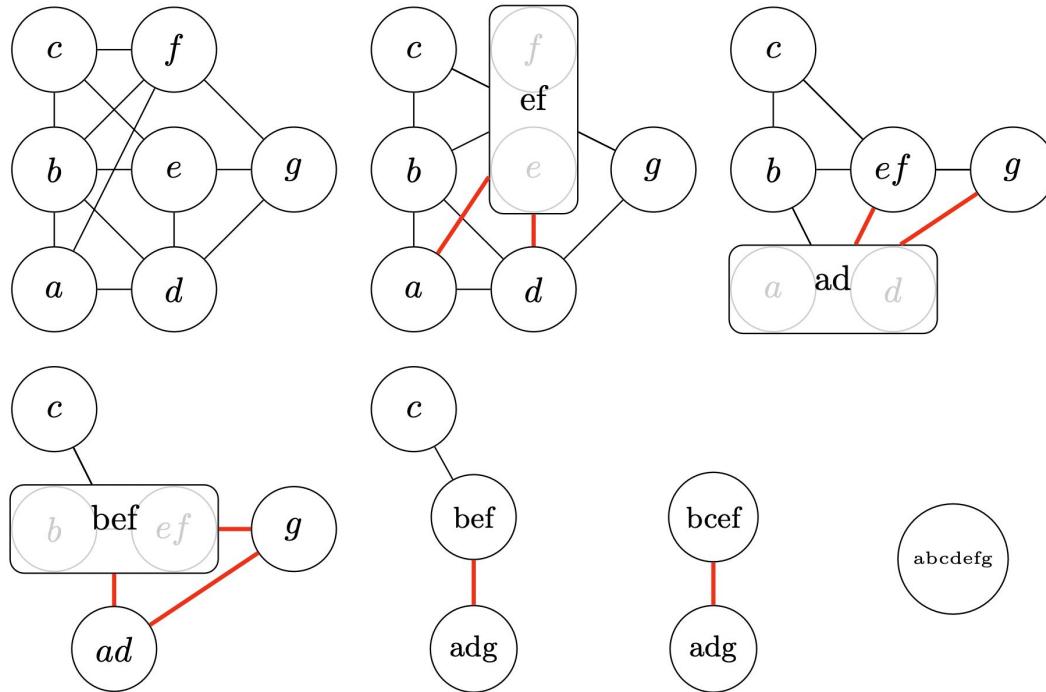


Sebastian Berndt (Lübeck)

PACE 2023: Twinwidth

High-Level idea:

- Find vertices with similar neighborhood (twins)
- Contract vertices
- Add red edges to neighborhood differences (errors)
- Continue until everything is contracted
- Twinwidth = minimal maximal red-degree of vertex



Taken from Bonnet, Kim, Thomassé, Watrigant

PACE 2023: Twinwidth

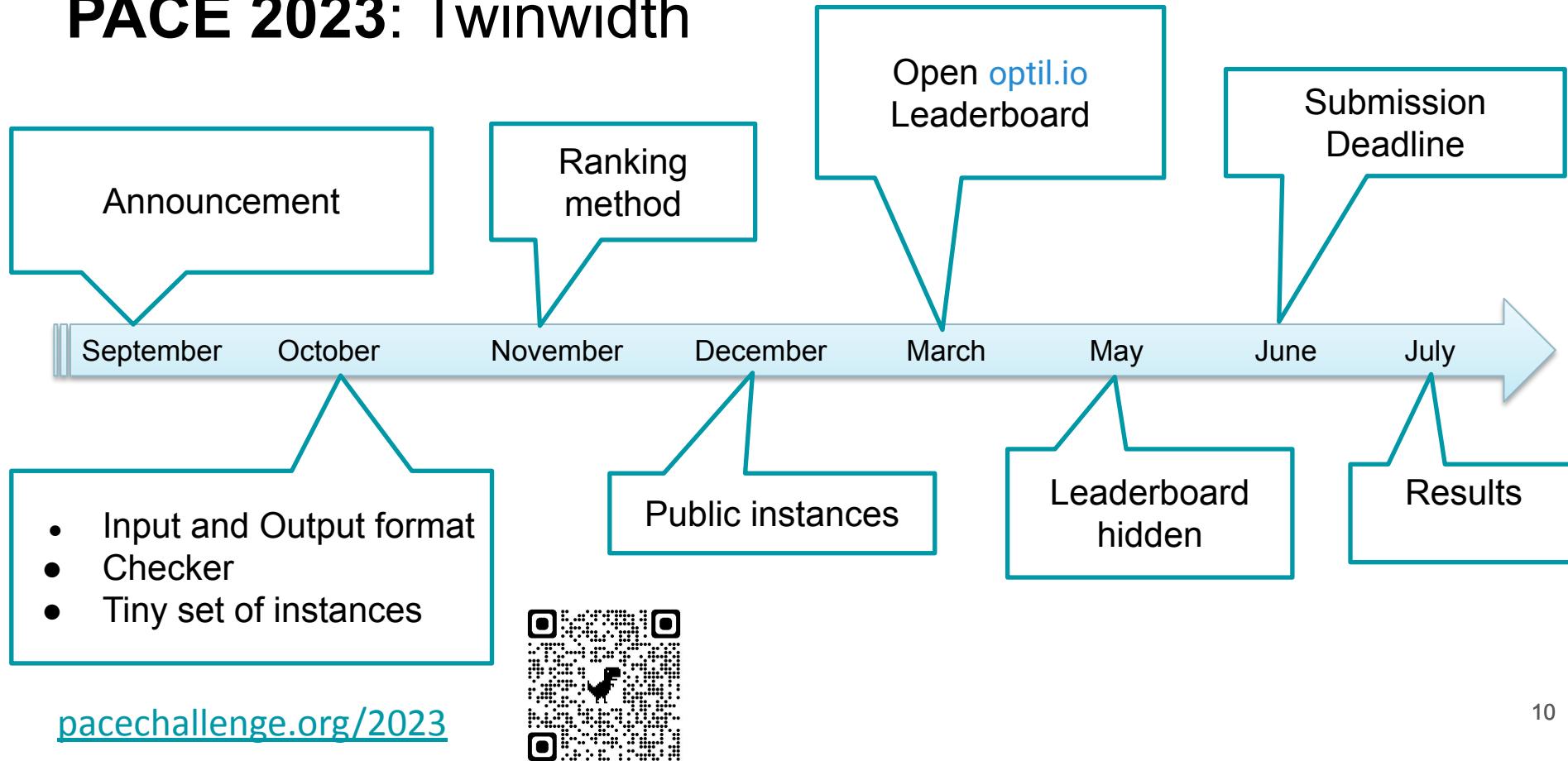
Challenge tracks:

1. Exact algorithms
2. Heuristic algorithms

New this year:

- Testset contains some instances of predefined graph classes
 - to be announced: e.g., planar graphs, twinwidth = 2, ...
- Extra theory award for solver with most interesting theoretical guarantees

PACE 2023: Twinwidth





Wanted: PACE PC for 2024!

- run the challenge!

Contact the PACE SC.

Parameterized Algorithms & Computational Experiments Challenge 2022

Directed Feedback Vertex Set



www.pacechallenge.org



PACE 2022 – Organisation

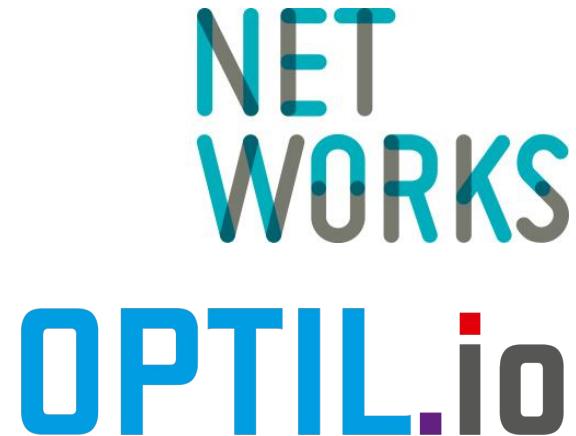
Program Committee:

- [Christian Schulz](#) (chair) (Universität Heidelberg)
- [Ernestine Großmann](#) (Universität Heidelberg)
- [Tobias Heuer](#) (Karlsruher Institut für Technologie)
- [Darren Strash](#) (Hamilton College)

Thanks to sponsors:

Networks for sponsoring the prizes

Optil.io (especially Artur Laskowski and Jan Badura) for their online judge system



Participants

90 participants

26 teams

12 countries

3 continents

Programming Languages:

C++, Rust, Java

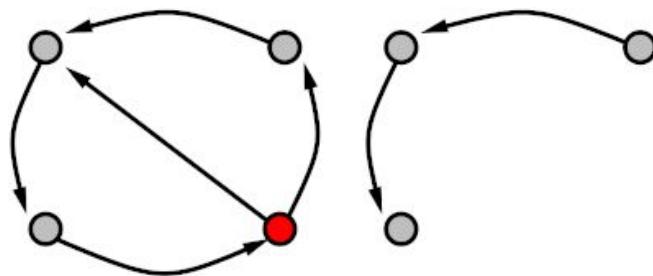


Directed Feedback Vertex Set

Input: A directed graph $G=(V,E)$.

Output: Find a minimum subset $X \subseteq V$ such that,

when all vertices of X and their adjacent edges are deleted from G , the remainder is acyclic.



Parameterized complexity of DFVS was open for a long time, until solved by Jianer Chen, Yang Liu, Songjian Lu, Barry O'Sullivan, Igor Razgon (STOC 2008); it can be solved in time $k! 4^k n^{O(1)}$.

Our Internal Solvers

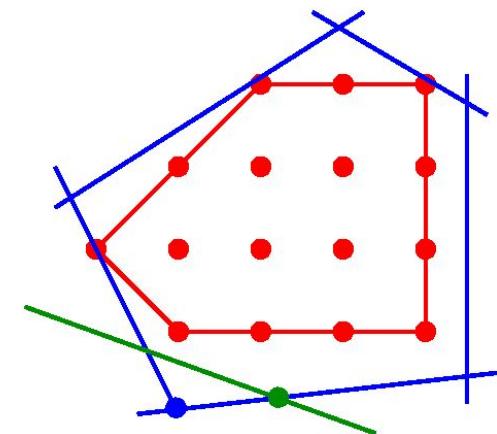
Simple data reduction rules (exact, heuristic on reduced instances)

Heuristics based on random walks and max. acyclic subgraphs

ILP (with adding constraints lazily), using Gurobi

$$\min \sum_{v \in V} x_v$$

$$\text{s.t. } \sum_i x_{v_i} \geq 1 \quad \forall \text{ cycles } C = \{v_1, v_2, \dots, v_k\} \text{ in } G$$



Data Sets

Generated instances using **KaGen** (<https://github.com/sebalamm/KaGen>):

- Erdős-Rényi Graphs
- Random Geometric Graphs
- Random Hyperbolic Graphs
- Random Delaunay Graphs
- Barabási-Albert Graph Model (+ randomly inserted backward edges in topological ordering)

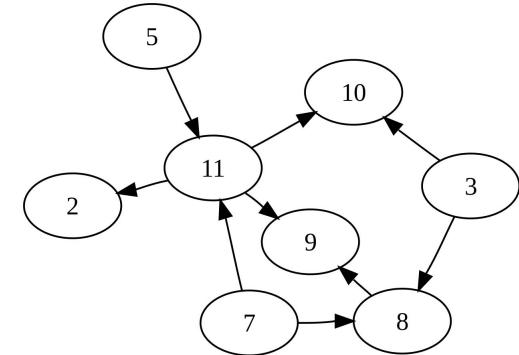
Removed random amounts of edges from bidirected graphs.

Also used real-world instances from the **SNAP** repository.

Generated hard instances for heuristic solvers (instances where random walks will fail).

Ran our solver (4-hour time limit)

→ included easy, middle, hard, and very hard instances (sometimes only bound known to us).



Tracks

Two Tracks (exact, heuristic).

Input for both tracks: directed graph $G=(V,E)$

Exact: 30 min, result has to be an optimal solution, ranking: number instances solved

Heuristic: 10 min, results should be good solution, ranking: size of FVS

Prizes:

- Best 5 submissions per track
- Tax may have to be paid if a single participant wins more than 450 Euros

Exact Track – Employed Techniques

Branch & Bound

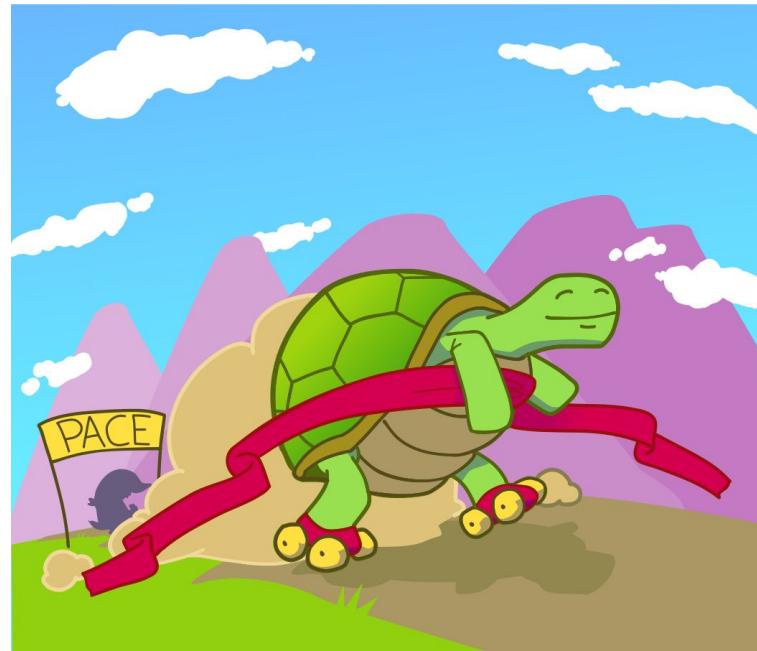
ILPs (with lazy constraints)

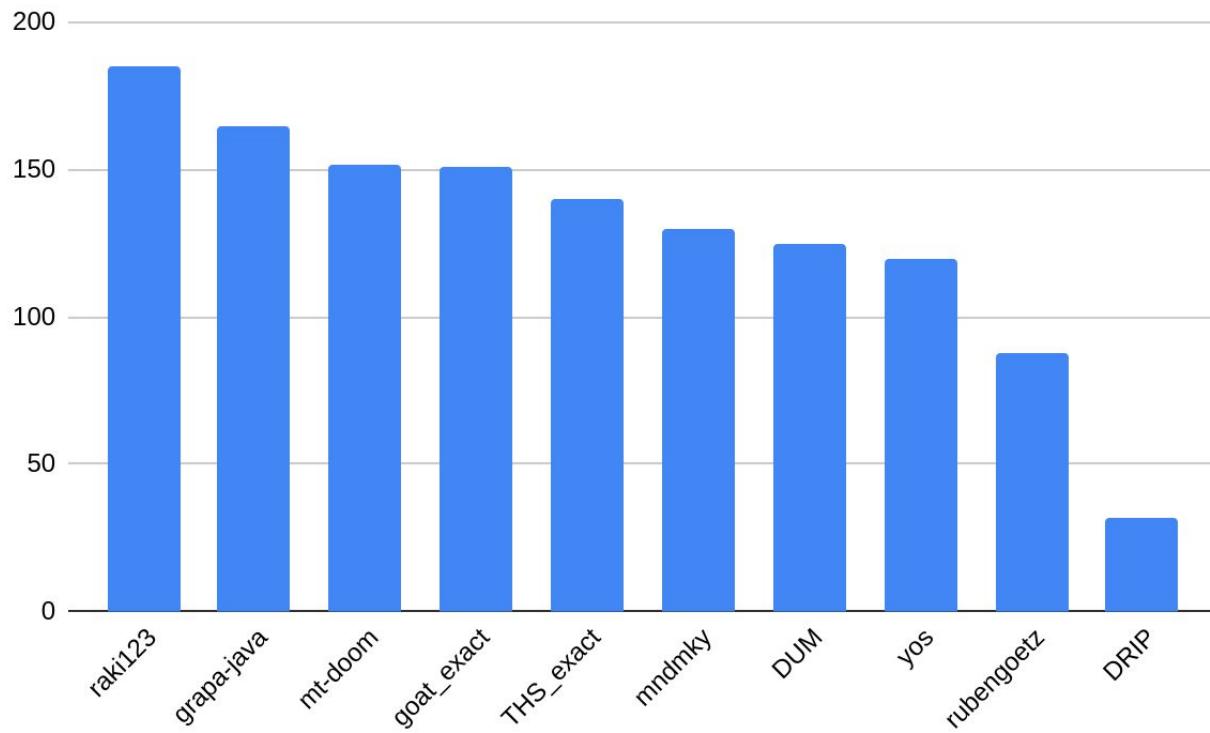
SAT Solvers (with lazy constraints)

Vertex Cover Solvers

→ all have been combined with data reduction techniques

Exact Track – Results





Number of instances solved

Honorable Mentions

-	Alexander Meiburg	UC Santa Barbara	Timeroot	DQ (175)
-	Sylwester Swat	Poznań University Of Technology	swats	DQ (160)
-	Stefan Tanja	Eindhoven University of Technology	satanja	DQ (144)

Student Ranking

7th Parameterized Algorithms and Computational Experiments Challenge PACE

Uniting FPT and Practice

ALGO/IPEC 2022, September 5–9, Potsdam, Germany

This is to certify that the 2022 PACE Program Committee has selected

Sebastian Angrich, Ben Bals, Niko Hastrich, Theresa Hradilak, Otto Kissig, Jonas Schmidt, Leo Wendt, Katrin Casel, Sarel Cohen and Davis Issac
Hasso Plattner Institute

as the

Second Place Student Submissions Exact Track of the Feedback Vertex Set Challenge



Programme Committee:
Christian Schulz (chair)
Ernestine Großmann
Tobias Heuer
Darren Strash

300 €



NET
WORKS

7th Parameterized Algorithms and Computational Experiments Challenge PACE

Uniting FPT and Practice

ALGO/IPEC 2022, September 5–9, Potsdam, Germany

This is to certify that the 2022 PACE Program Committee has selected

**Enna Gerhard, Jona Dirks, Moritz Bergenthal, Jakob Gahde, Thorben Freese,
Mario Grobler and Sebastian Siebertz**

University of Bremen

as the

Best Student Submission Exact Track of the Feedback Vertex Set Challenge

400 €



Programme Committee:
Christian Schulz (chair)
Ernestine Großmann
Tobias Heuer
Darren Strash



General Ranking

7th Parameterized Algorithms and Computational Experiments Challenge PACE

Uniting FPT and Practice

ALGO/IPEC 2022, September 5–9, Potsdam, Germany

This is to certify that the 2022 PACE Program Committee has selected

**Henri Froese, Jonathan Guthermuth, Lars Huth, Marius Lotz, Johannes Meinstrup, Timo
Mertin, Manuel Penschuck and Hung Tran**

Goethe University Frankfurt and THM, University of Applied Sciences Mittelhessen

as the

Fifth Place Winner in the Exact Track of the Feedback Vertex Set Challenge



Programme Committee:
Christian Schulz (chair)
Ernestine Großmann
Tobias Heuer
Darren Strash

100 €



7th Parameterized Algorithms and Computational Experiments Challenge PACE

Uniting FPT and Practice

ALGO/IPEC 2022, September 5–9, Potsdam, Germany

This is to certify that the 2022 PACE Program Committee has selected

**Radovan Červený, Michal Dvořák, Xuan Thang Nguyen, Jan Pokorný, Lucie Procházková,
Jaroslav Urban, Václav Blažej, Dušan Knop, Šimon Schierreich and Ondrej Suchý**

Czech Technical University in Prague, Faculty of Information Technology

as the

Fourth Place Winner in the Exact Track of the Feedback Vertex Set Challenge



Programme Committee:
Christian Schulz (chair)
Ernestine Großmann
Tobias Heuer
Darren Strash

200 €



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WORKS

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ALGO/IPEC 2022, September 5–9, Potsdam, Germany

This is to certify that the 2022 PACE Program Committee has selected

Sebastian Angrich, Ben Bals, Niko Hastrich, Theresa Hradilak, Otto Kissig, Jonas Schmidt, Leo Wendt, Katrin Casel, Sarel Cohen and Davis Issac
Hasso Plattner Institute

as the

Third Place Winner in the Exact Track of the Feedback Vertex Set Challenge



Programme Committee:
Christian Schulz (chair)
Ernestine Großmann
Tobias Heuer
Darren Strash

250 €



NET
WORKS

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**Enna Gerhard, Jona Dirks, Moritz Bergenthal, Jakob Gahde, Thorben Freese,
Mario Grobler and Sebastian Siebertz**

University of Bremen

as the

Second Place Winner in the Exact Track of the Feedback Vertex Set Challenge

300 €



Programme Committee:
Christian Schulz (chair)
Ernestine Großmann
Tobias Heuer
Darren Strash



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7th Parameterized Algorithms and Computational Experiments Challenge PACE

Uniting FPT and Practice

ALGO/IPEC 2022, September 5–9, Potsdam, Germany

This is to certify that the 2022 PACE Program Committee has selected

Andre Schidler and Rafael Kiesel

TU Wien

as the

First Place Winner in the Exact Track of the Feedback Vertex Set Challenge

450 €

Programme Committee:
Christian Schulz (chair)
Ernestine Großmann
Tobias Heuer
Darren Strash



Short Presentation of Winning Solver

Heuristic Track – Employed Techniques

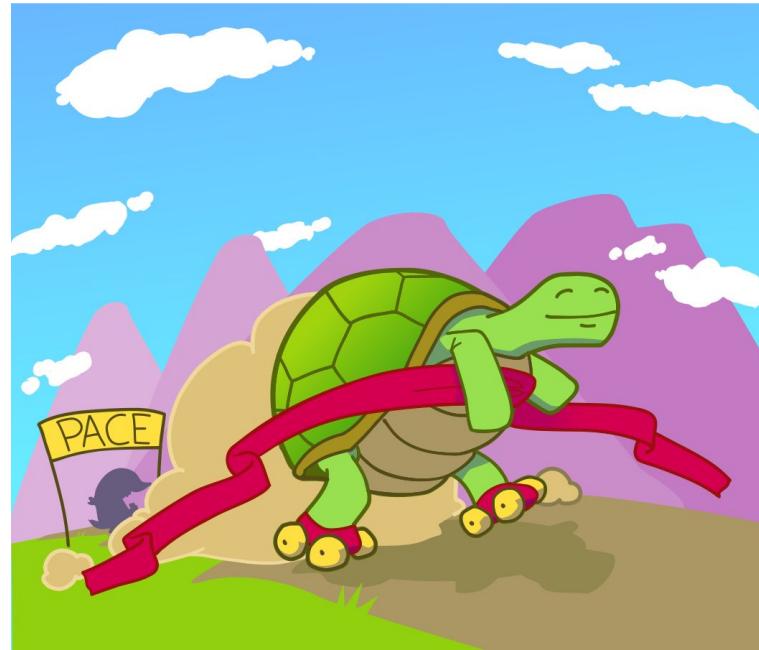
All techniques used data reductions!

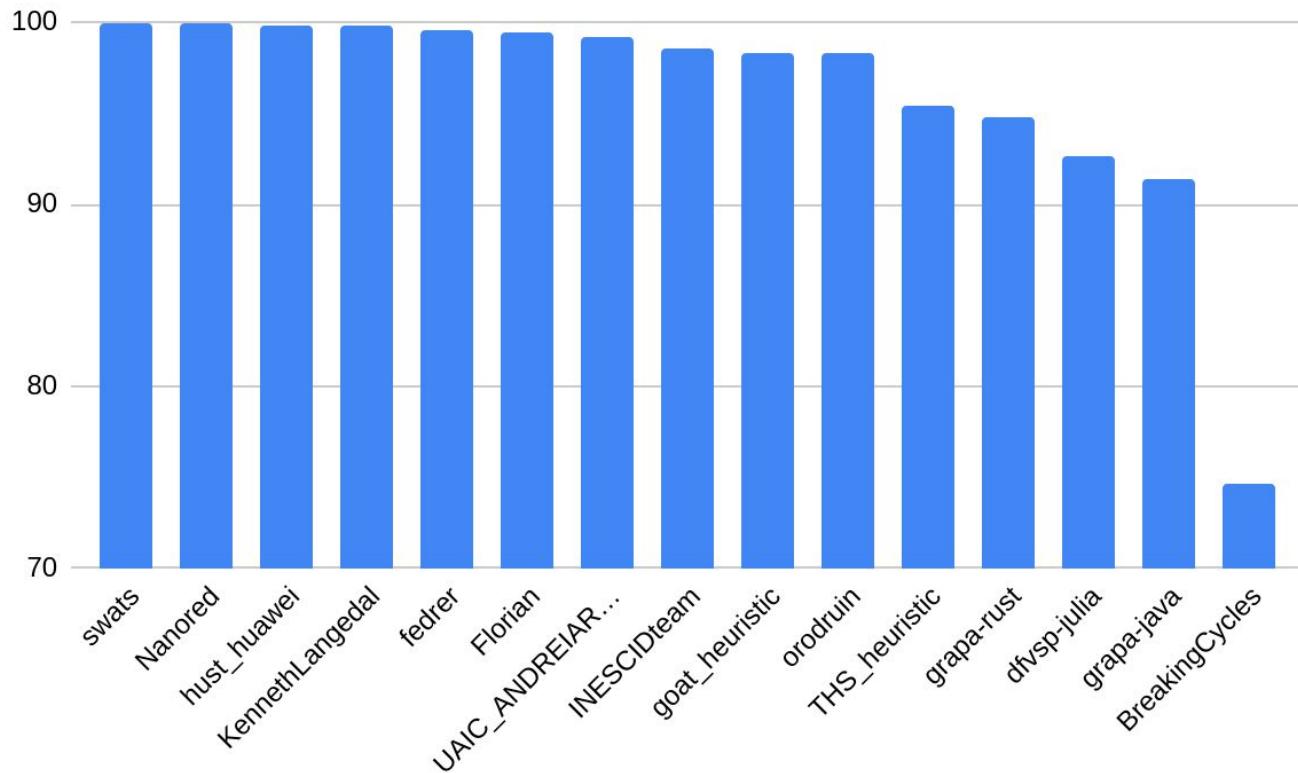
Vertex Cover Heuristic Solvers

Combinations of Multiple Local Search Heuristics

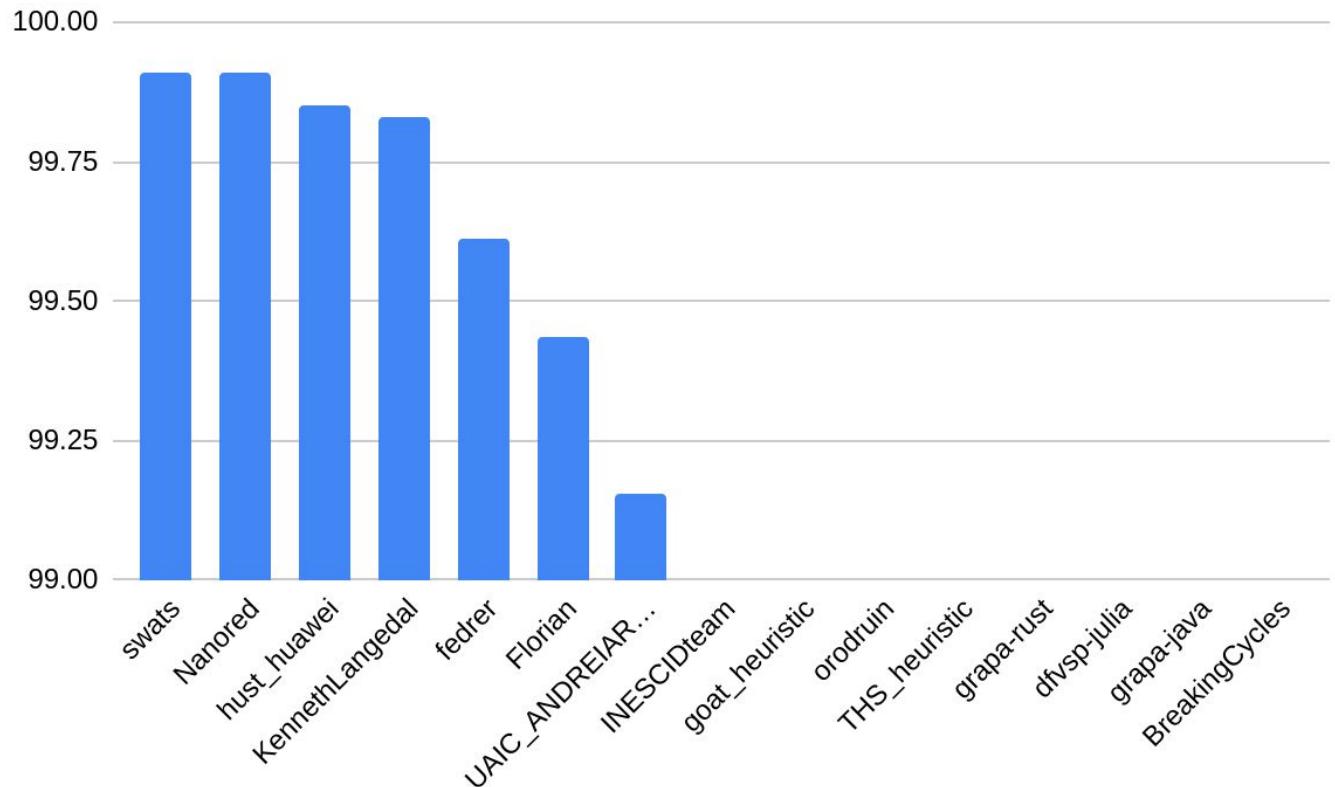
Sometimes via Topological Orderings

Heuristic Track – Results





Geo mean of $100 \times \text{best solution}/\text{solution size}$ over all instances



Zoooooming in!

Student Ranking

7th Parameterized Algorithms and Computational Experiments Challenge PACE

Uniting FPT and Practice

ALGO/IPEC 2022, September 5–9, Potsdam, Germany

This is to certify that the 2022 PACE Program Committee has selected

Andrei Arhire and Paul Diac

Alexandru Ioan Cuza University of Iași

as the

Second Best Student Submission Heuristic Track of the Feedback Vertex Set Challenge



Programme Committee:
Christian Schulz (chair)
Ernestine Großmann
Tobias Heuer
Darren Strash

300 €



7th Parameterized Algorithms and Computational Experiments Challenge PACE

Uniting FPT and Practice

ALGO/IPEC 2022, September 5–9, Potsdam, Germany

This is to certify that the 2022 PACE Program Committee has selected

Aman Jain, Sachin Agarwal, Nimish Agrawal, Soumyajit Karmakar and Srinibas Swain

IIIT, Guwahati

as the

Best Student Submission Heuristic Track of the Feedback Vertex Set Challenge



Programme Committee:
Christian Schulz (chair)
Ernestine Großmann
Tobias Heuer
Darren Strash

400 €



General Ranking

7th Parameterized Algorithms and Computational Experiments Challenge PACE

Uniting FPT and Practice

ALGO/IPEC 2022, September 5–9, Potsdam, Germany

This is to certify that the 2022 PACE Program Committee has selected

Aman Jain, Sachin Agarwal, Nimish Agrawal, Soumyajit Karmakar and Srinibas Swain

IIIT, Guwahati

as the

Fifth Place Winner in the Heuristic Track of the Feedback Vertex Set Challenge



Programme Committee:
Christian Schulz (chair)
Ernestine Großmann
Tobias Heuer
Darren Strash

100 €



7th Parameterized Algorithms and Computational Experiments Challenge PACE

Uniting FPT and Practice

ALGO/IPEC 2022, September 5–9, Potsdam, Germany

This is to certify that the 2022 PACE Program Committee has selected

Kenneth Langedal, Johannes Langguth and Fredrik Manne

University of Bergen and Simula Research Laboratory

as the

Fourth Place Winner in the Heuristic Track of the Feedback Vertex Set Challenge



Programme Committee:
Christian Schulz (chair)
Ernestine Großmann
Tobias Heuer
Darren Strash

200 €



NET
WORKS

7th Parameterized Algorithms and Computational Experiments Challenge PACE

Uniting FPT and Practice

ALGO/IPEC 2022, September 5–9, Potsdam, Germany

This is to certify that the 2022 PACE Program Committee has selected

**Yuming Du, Qingyun Zhang, Junzhou Xu, Shungen Zhang, Chao Liao, Zhihuai Chen, Zhibo Sun,
Zhouxing Su, Junwen Ding, Chen Wu, Pinyan Lu and Zhipeng Lv**

SMART, School of Computer Science and Technology, Huazhong University of Science
& Technology and Huawei TCS Lab Shanghai

as the

Third Place Winner in the Heuristic Track of the Feedback Vertex Set Challenge



Programme Committee:
Christian Schulz (chair)
Ernestine Großmann
Tobias Heuer
Darren Strash

250 €



NET
WORKS

7th Parameterized Algorithms and Computational Experiments Challenge PACE

Uniting FPT and Practice

ALGO/IPEC 2022, September 5–9, Potsdam, Germany

This is to certify that the 2022 PACE Program Committee has selected

**Gabriel Bathie, Gaétan Berthe, Yoann Coudert-Osmont, David Desobry,
Amadeus Reinald and Mathis Rocton**

École normale supérieure de Lyon and Université de Lorraine, CNRS, Inria, LORIA

as the

Second Place Winner in the Heuristic Track of the Feedback Vertex Set Challenge



Programme Committee:
Christian Schulz (chair)
Ernestine Großmann
Tobias Heuer
Darren Strash

300 €



7th Parameterized Algorithms and Computational Experiments Challenge PACE

Uniting FPT and Practice

ALGO/IPEC 2022, September 5–9, Potsdam, Germany

This is to certify that the 2022 PACE Program Committee has selected

Sylwester Swat
Poznań University Of Technology

as the

First Place Winner in the Heuristic Track of the Feedback Vertex Set Challenge



Programme Committee:
Christian Schulz (chair)
Ernestine Großmann
Tobias Heuer
Darren Strash

450 €



NET
WORKS

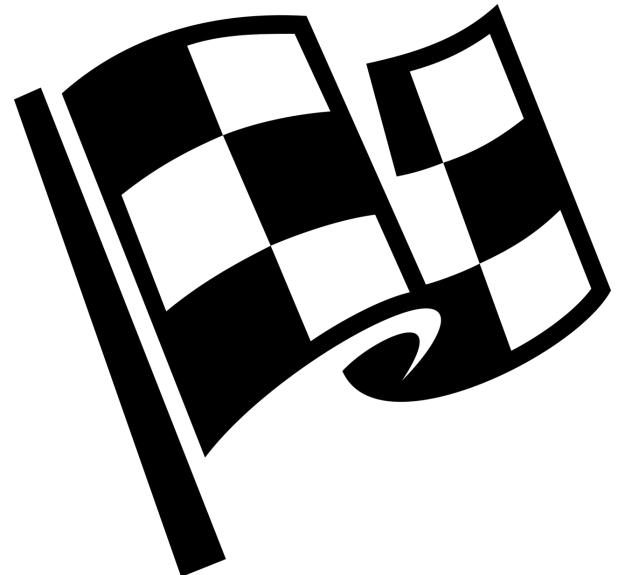
Short Presentation of Winning Solver

Conclusion

Students prizes: Announce them for next iterations?

Exact & heuristic track: works well!

Next: please join the poster session!



BACKUP

1 Andre Schidler and Rafael Kiesel, TU Wien, raki123, 185

2 Enna Gerhard, Jona Dirks, Moritz Bergenthal, Jakob Gahde, Thorben Freese, Mario Grobler and Sebastian Siebertz; University of Bremen; grapa-java, 165

3 Sebastian Angrich, Ben Bals, Niko Hastrich, Theresa Hradilak, Otto Kissig, Jonas Schmidt, Leo Wendt, Katrin Casel, Sarel Cohen and Davis Issac; Hasso Plattner Institute; mt-doom; 152

4 Radovan Červený, Michal Dvořák, Xuan Thang Nguyen, Jan Pokorný, Lucie Procházková, Jaroslav Urban, Václav Blažej, Dušan Knop, Šimon Schierreich and Ondrej Suchy; Czech Technical University in Prague, Faculty of Information Technology; goat_exact; 151

5 Henri Froese, Jonathan Gutherthum, Lars Huth, Marius Lotz, Johannes Meinstrup, Timo Mertin, Manuel Penschuck and Hung Tran; Goethe University Frankfurt and THM, University of Applied Sciences Mittelhessen; THS_exact; 140

6 Timon Behr; University of Konstanz; mndmky; 130

7 Henri Dickel, Matija Miskovic and Lennart Uhrmacher;
Philipps-Universität Marburg; DUM; 125

8 Yosuke Mizutani; University of Utah; yos; 120

9 Ruben Götz; Karlsruher Institut für Technologie; rubengoetz; 88

10 Aman Jain, Sachin Agarwal, Nimish Agrawal, Soumyajit Karmakar and Srinibas Swain;
IIIT, Guwahati; DRIP; 32

1 Sylwester Swat; Poznań University Of Technology; swats; 99.91178342

2 Gabriel Bathie, Gaétan Berthe, Yoann Coudert-Osmont, David Desobry, Amadeus Reinald and Mathis Rocton; École normale supérieure de Lyon and Université de Lorraine, CNRS, Inria, LORIA; Nanored; 99.91075832

3 Yuming Du, Qingyun Zhang, Junzhou Xu, Shungen Zhang, Chao Liao, Zhihuai Chen, Zhibo Sun, Zhouxing Su, Junwen Ding, Chen Wu, Pinyan Lu and Zhipeng Lv; SMART, School of Computer Science and Technology, Huazhong University of Science & Technology and Huawei TCS Lab Shanghai; hust_huawei; 99.85213384

4 Kenneth Langedal, Johannes Langguth and Fredrik Manne; University of Bergen and Simula Research Laboratory; KennethLangedal; 99.83192281

5 Aman Jain, Sachin Agarwal, Nimish Agrawal, Soumyajit Karmakar and Srinibas Swain; IIIT, Guwahati; fedrer; 99.6106619

6 Florian Sikora; LAMSADE; Florian; 99.43488493

7 Andrei Arhire and Paul Diac; Alexandru Ioan Cuza University of Iași; UAIC_ANDREIARHIRE; 99.15607445

8 Daniel Castro, Luis Russo, Aleksandar Ilic, Paolo Romano and Ana Correia; INESC-ID & IST; INESCIDteam; 98.61916057

9 Radovan Červený, Michal Dvořák, Xuan Thang Nguyen, Jan Pokorný, Lucie Procházková, Jaroslav Urban, Václav Blažej, Dušan Knop, Šimon Schierreich and Ondrej Suchý; Czech Technical University in Prague, Faculty of Information Technology; goat_heuristic; **98.27759269**

10 Sebastian Angrich, Ben Bals, Niko Hastrich, Theresa Hradilak, Otto Kißig, Jonas Schmidt, Leo Wendt, Katrin Casel, Sarel Cohen and Davis Issac; Hasso Plattner Institute, Potsdam, Germany and Digital Engineering Faculty, University of Potsdam, Potsdam, Germany; orodruin; **98.24494653**

11 Jonathan Guthermuth, Lars Huth, Marius Lotz, Johannes Meinstrup, Timo Mertin, Manuel Penschuck, Lukas Schwarz and Hung Tran; Goethe University Frankfurt and THM, University of Applied Sciences Mittelhessen; THS_heuristic; **95.35703548**

12 Ozan Can Heydt, Leon Stichernath, Kenneth Dietrich and Philipp Haker; Universität Bremen; grapa-rust; **94.74375391**

13 Maria Bresich, Günther Raidl and Johannes Varga; TU Wien; dfvsp-julia; **92.64443062**

14 Enna Gerhard, Jona Dirks, Moritz Bergenthal, Jakob Gahde, Thorben Frese, Mario Grobler and Sebastian Siebertz; Universität Bremen; grapa-java; **91.36931307**

15 Mert Biyikli; Heidelberg University; BreakingCycles; **74.61280732**