

# Parameterized Algorithms & Computational Experiments Challenge 2022

Directed Feedback Vertex Set

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[www.pacechallenge.org](http://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](#) (LMSADE, Université Paris Dauphine)

# Impact of PACE

## Motivation: Explaining success

- PACE 2017: Top 4 solvers on mil

## 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.

## Story behind PACE 2016

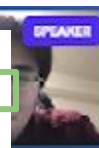
Developed a new algorithm to solve the LP!

⇒ Practical and theoretical improvements

CALP 2017)

ms (FOCS 2018)

2018 (AAAI 2019).



# The history of PACE

Idea for PACE born at  
*Simons Institute* meeting

[Holger Dell &  
Christian Komusiewicz]

TREEWIDTH  
MINIMUM FILL-IN

[Johannes Fichte &  
Markus Hecher]

VERTEX COVER  
HYPERTREE WIDTH

First poster session

[Christian Schulz]

DIRECTED FEEDBACK  
VERTEX SET

2015

2016

2017

2018

2019

2020

2021

2022

First PACE challenge

TREEWIDTH  
FEEDBACK VERTEX SET

[Holger Dell & Christian Komusiewicz]

STEINER TREE

[Édouard Bonnet &  
Florian Sikora]

TREEDEPTH

Implementation  
reports in IPEC  
proceedings

[Lukasz Kowalik]

CLUSTER EDITING

[André Nichterlein]

# PACE 2023: Twinwidth

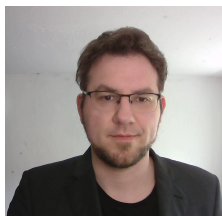
## Main goal of PACE: *Bridging the Gap Between FPT-Theory and Practice*

- 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)

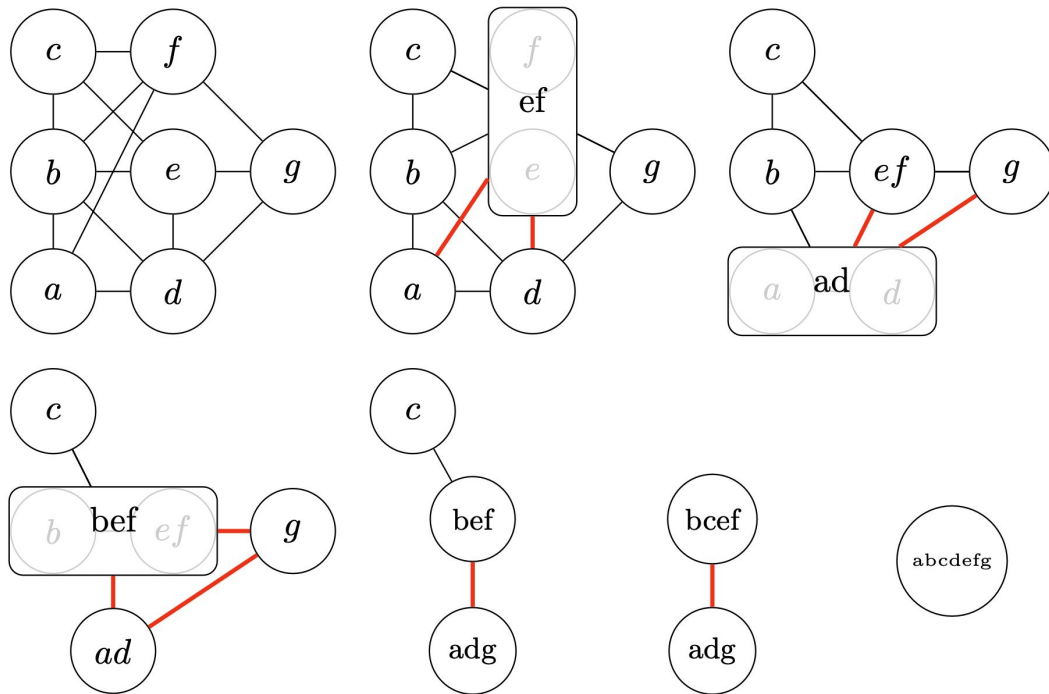


Sebastian Berndt (Lübeck)

# 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

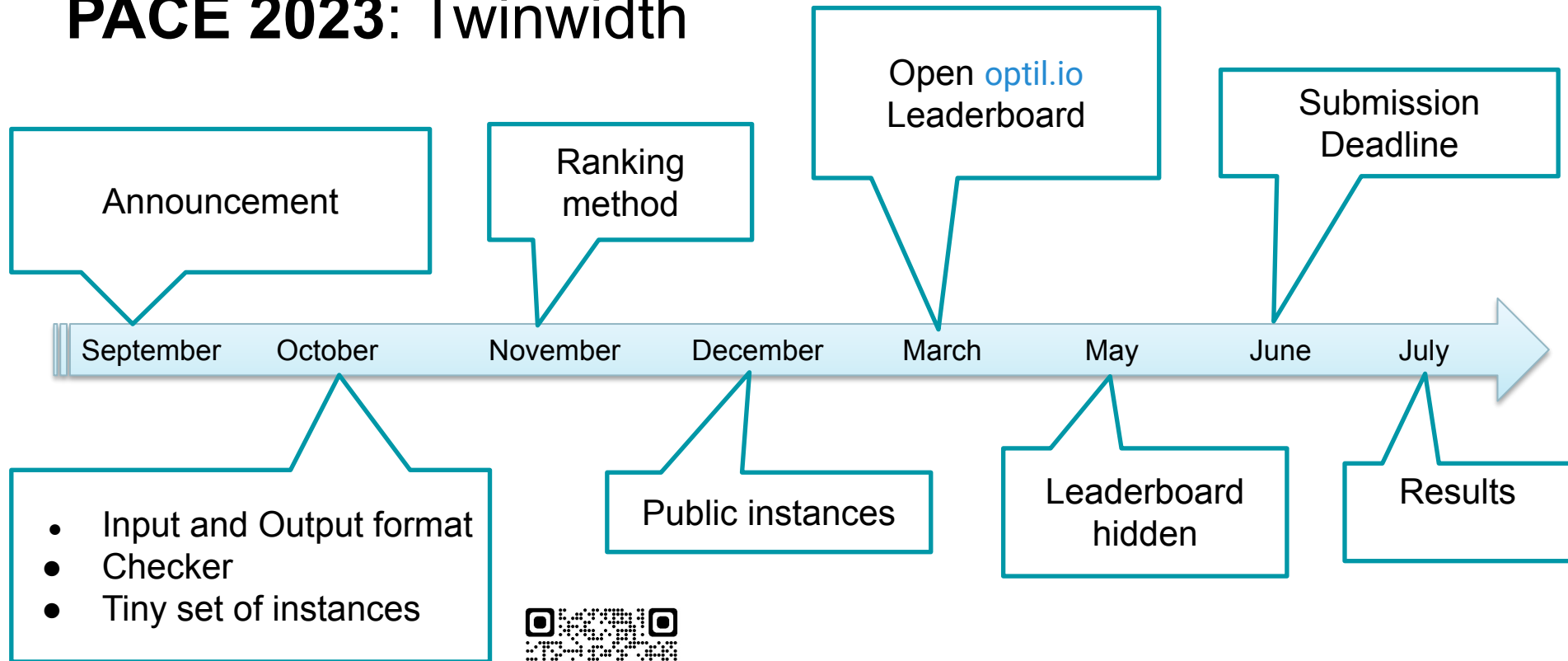
## Challenge tracks:

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



[pacechallenge.org/2023](https://pacechallenge.org/2023)





**Wanted: PACE PC for 2024!**

- run the challenge!

Contact the PACE SC.

# Parameterized Algorithms & Computational Experiments Challenge **2022**

Directed Feedback Vertex Set

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[www.pacechallenge.org](http://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

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# Participants

90 participants

26 teams

12 countries

3 continents

Programming Languages:

C++, Rust, Java

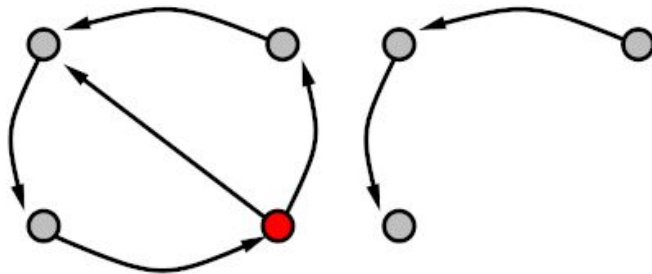


# Directed Feedback Vertex Set

**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  $k! 4^k n^{O(1)}$ .

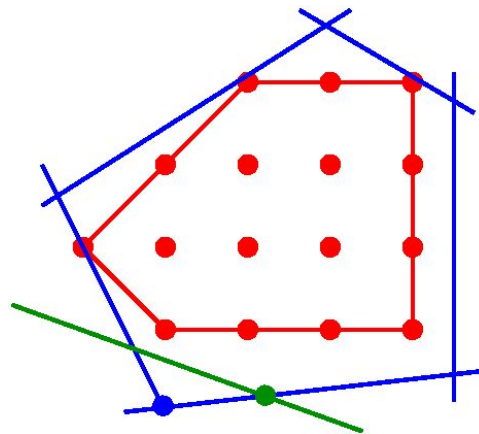
# Our Internal Solvers

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

$$\begin{array}{ll}\min & \sum_{v \in V} x_v \\ \text{s.t.} & \sum_i x_{v_i} \geq 1 \quad \forall \text{ cycles } C = \{v_1, v_2, \dots, v_k\} \text{ in } G\end{array}$$

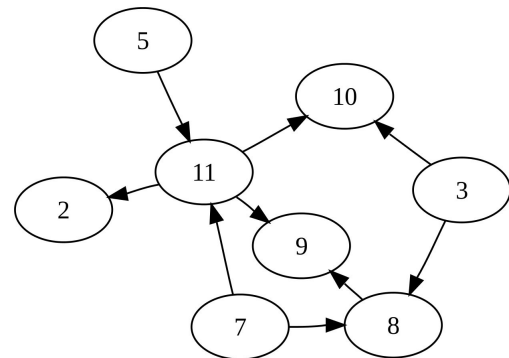




# Data Sets

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

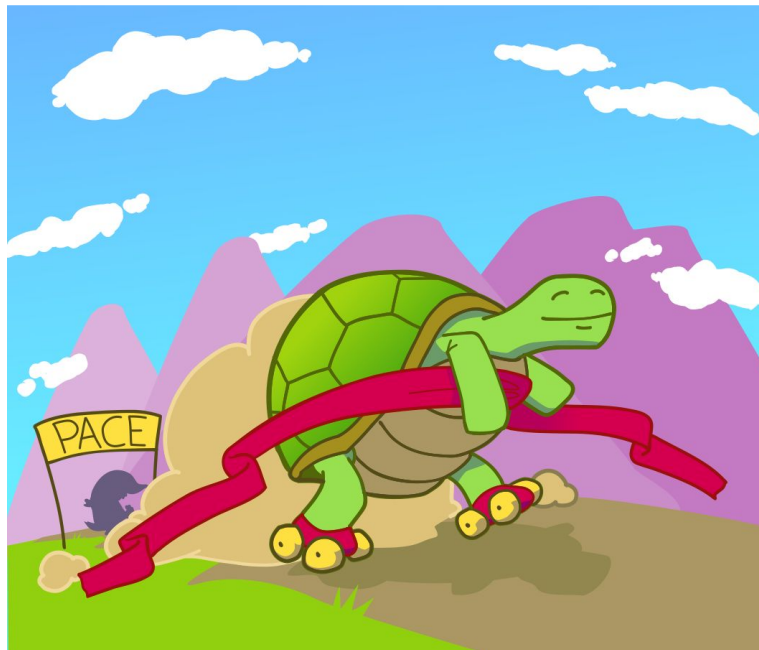
ILPs (with lazy constraints)

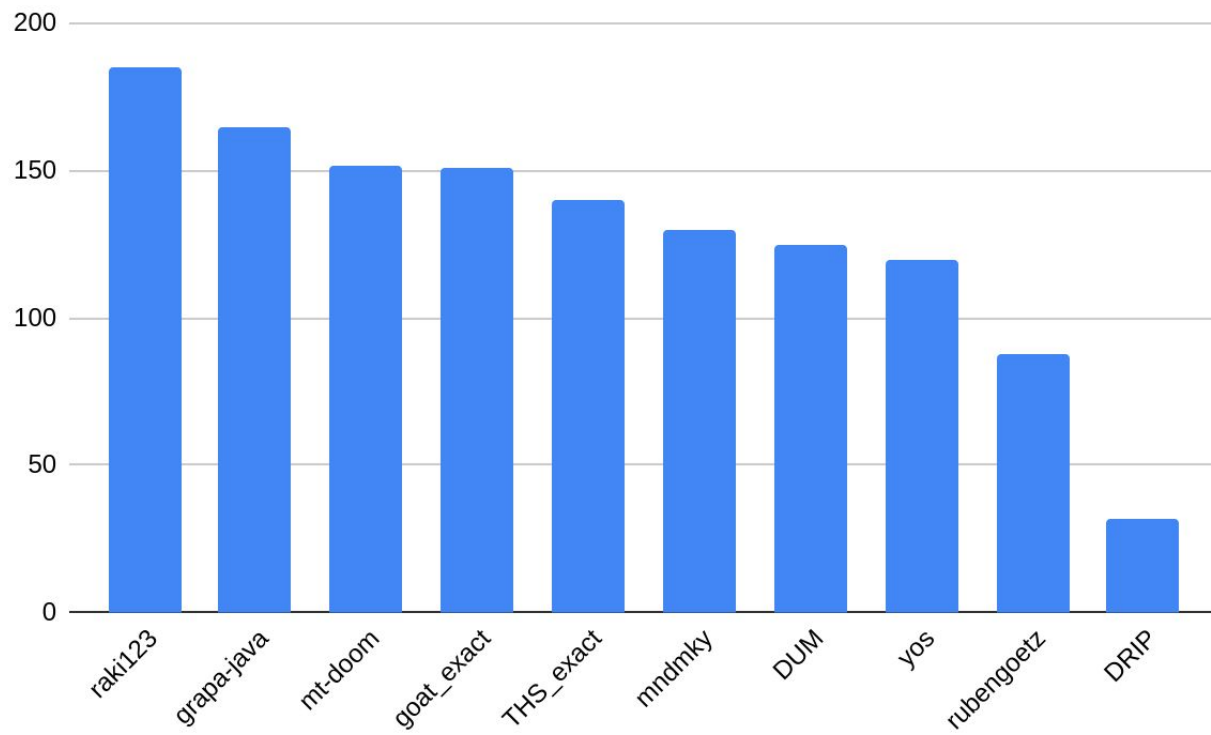
SAT Solvers (with lazy constraints)

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**

**300 €**

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





# 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 Meintrup, 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**

**100 €**

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



# 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 Suchy**

Czech Technical University in Prague, Faculty of Information Technology

as the

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

**200 €**

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



# 7th Parameterized Algorithms and Computational Experiments Challenge PACE

Uniting FPT and Practice

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

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**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**

**250 €**

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



# 7th Parameterized Algorithms and Computational Experiments Challenge PACE

Uniting FPT and Practice

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

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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





# 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

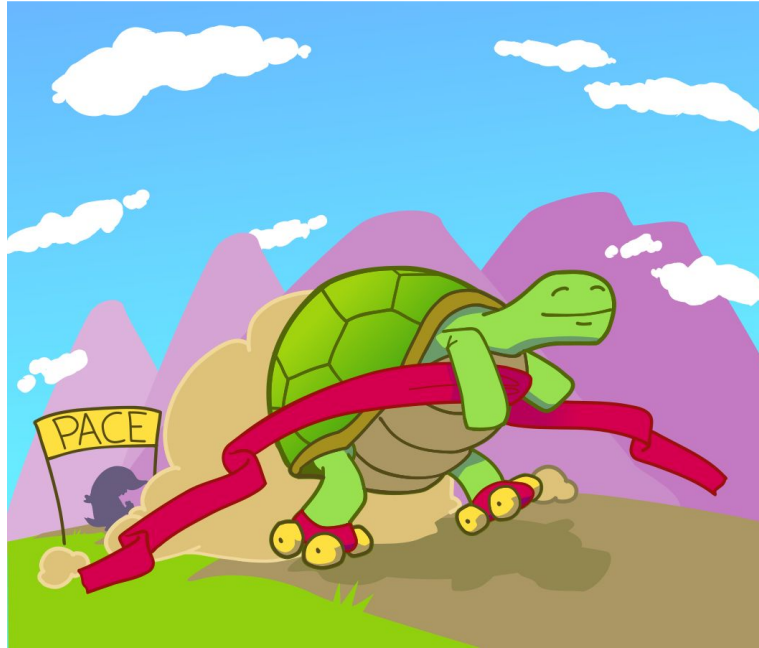
All techniques used data reductions!

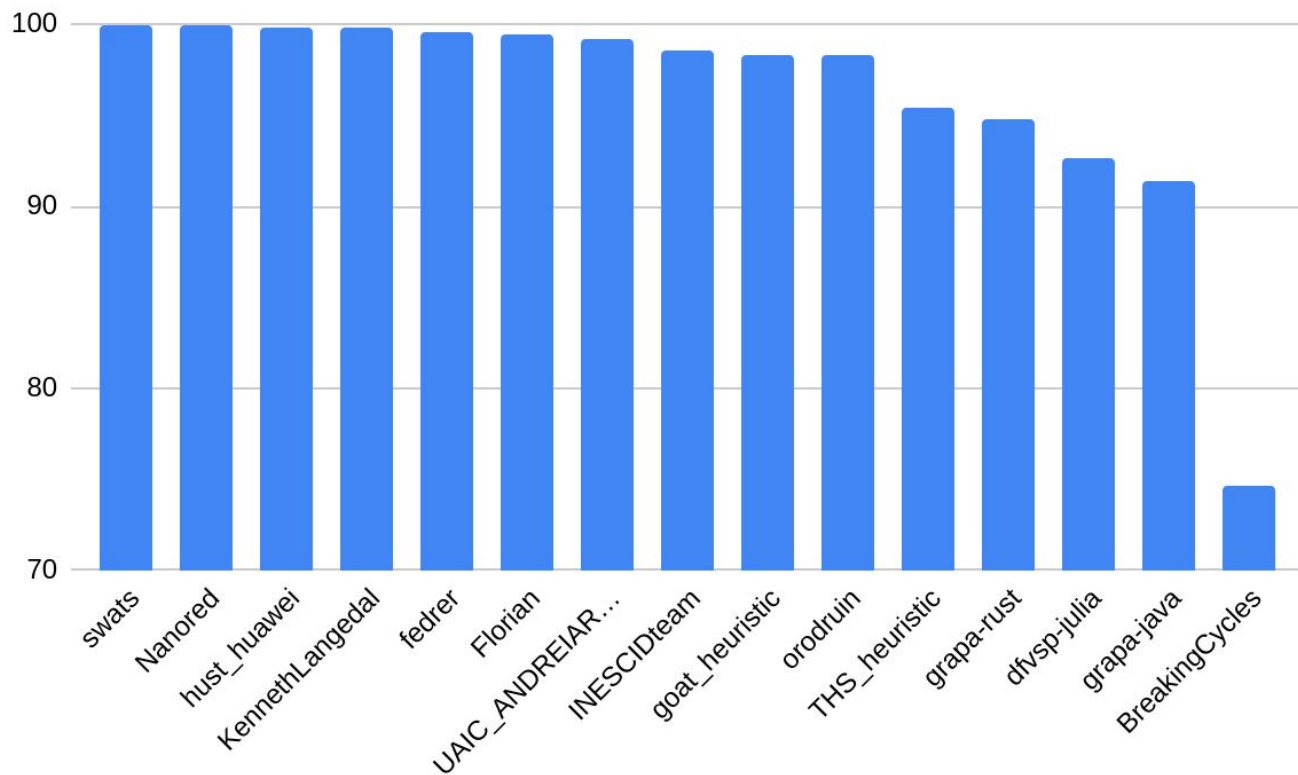
Vertex Cover Heuristic Solvers

Combinations of Multiple Local Search Heuristics

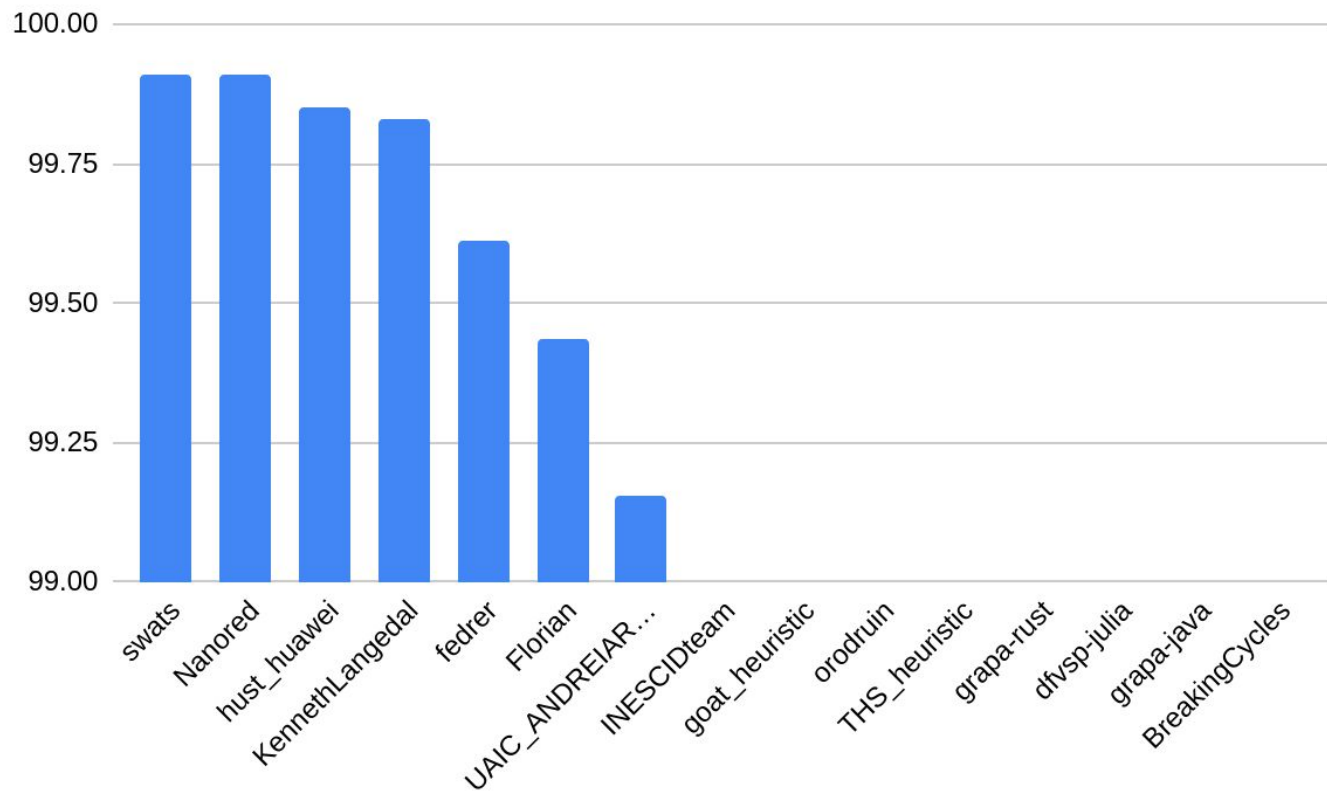
Sometimes via Topological Orderings

# Heuristic Track – Results





Geo mean of 100\*best solution/solution size over all instances



Zooooooming 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**

**300 €**

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



# 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**

**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

**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**

**100 €**

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



# 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

**200 €**

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



# 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**

**250 €**

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



# 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**

**300 €**

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



# 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

**450 €**

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



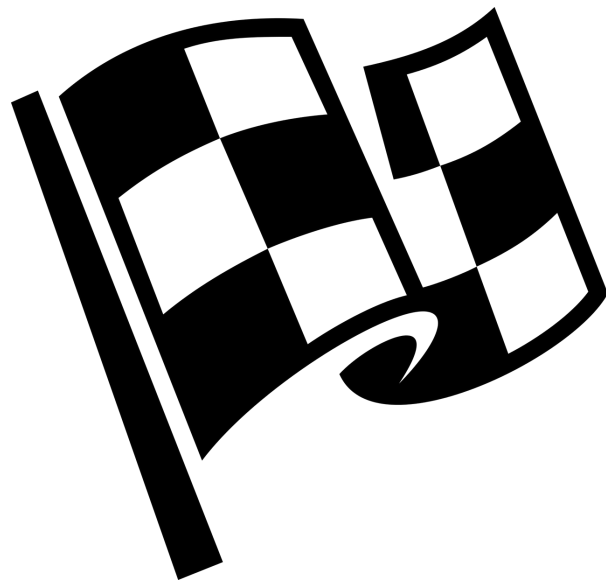
# Short Presentation of Winning Solver

# 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, Simon Schierreich and Ondrej Suchy; Czech Technical University in Prague, Faculty of Information Technology; goat\_exact; **151**

**5** Henri Froese, Jonathan Guthermuth, Lars Huth, Marius Lotz, Johannes Meintrup, 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 Suchy; 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 Meintrup, 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 Stichternath, 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**