3rd Parameterized Algorithms & Computational Experiments Challenge

Where it came from, how it went, who won, and what’s next
History of PACE

PACE was conceived in Fall 2015, borne from the feeling that:

“parameterized algorithmics should have a greater impact on practice”

Inspired by success of SAT-solving competitions

2015-2016: First iteration
• Track A: TREEWIDTH
• Track B: FEEDBACK VERTEX SET

2016-2017: Second iteration
• Track A: TREEWIDTH
• Track B: MINIMUM FILL-IN

2017-2018: Third iteration [STEINER TREE]
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 frameworks
4. produce universally accessible libraries of implementations & benchmark inputs
5. encourage dissemination of the findings in scientific papers
SAT-Encodings of Tree Decompositions

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Publications following the second PACE
Publications following the second PACE

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Benchmarking treewidth as a practical component of
tensor-network-based quantum simulation

Eugene F. Dumitrescu¹, †, Allison L. Fisher², Timothy D. Goodrich², *, Travis S.
Humble¹, †, Blair D. Sullivan², Andrew L. Wright²
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**An SMT Approach to Fractional Hypertree Width**

Johannes K. Fichte, Markus Hecher, Neha Lodha, and Stefan Szeider
Publications following the second PACE

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BENCHMARKING TREETWIDTH AS A PRACTICAL COMPO
TENSOR-NETWORK-BASED QUANTUM SIMULATION

Eugene F. Dumitrescu¹, †, Allison L. Fisher², Timothy D. Humble¹, †, Blair D. Sullivan², Andrew L. Wright²

Computation and Growth of Road Network Dimensions
Johannes Blum(✉) and Sabine Storandt
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Benchmarking treewidth as a practical constraint for tensor-network-based quantum simulations

Computing Tree Width: From Theory to Practice and Back

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Experimental Evaluation of Parameterized Algorithms for Feedback Vertex Set
Krzysztof Kiljan† Marcin Pilipczuk†
Publications following the second PACE

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Weighted Model Counting on the GPU by Exploiting Small Treewidth

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Directed Algorithms for Feedback

Krzysztof Kiljan and Marcin Pilipczuk
People behind PACE

Program committee chairs for 2017-2018:

Édouard Bonnet  ENS de Lyon
Florian Sikkora  Université Paris-Dauphine

Steering committee

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Petteri Kaski  Aalto University
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data experts

Systemberatung
Softwareentwicklung
Informationsverarbeitung
HOW IT WENT & WHO WON
The 3rd Parameterized Algorithms and Computational Experiments Challenge: Steiner Tree

Name: Édouard Bonnet and Florian Sikora (ENS de Lyon and Université Paris-Dauphine)
Date: August 22nd 2018, Helsinki
Challenge Problem: Steiner Tree

with edge weights

terminal
Challenge Problem: Steiner Tree

with edge weights

find the lightest tree spanning the terminals
Why Steiner Tree?

* Real-life applications: design of VLSI, optical and wireless communication systems, transport networks.

* Among Karp's 21 NP-complete problems: one of the most fundamental graph problems

* Established benchmark and strong programs: 11th DIMACS implementation challenge
Why Steiner Tree?

* Real-life applications: design of VLSI, optical and wireless communication systems, transport networks.

* Among Karp's 21 NP-complete problems: one of the most fundamental graph problems

* Established benchmark and strong programs: 11th DIMACS implementation challenge

* and, of course, fixed-parameter algorithms
Choice of the tracks

n: number of vertices
m: number of edges
t: number of terminals

Algorithms:
* Dreyfus-Wagner, Erickson-Monma-Veinott \(3^t n + 2^t(n \log n + m)\)

Tracks:
* Track A, few terminals
Choice of the tracks

n: number of vertices
m: number of edges
t: number of terminals
w: treewidth

Algorithms:
* Dreyfus-Wagner, Erickson-Monma-Veinott \(3^t n + 2^t(n \log n + m)\)
* DP \(O^*(w^w)\), improved to \(2^{O(w)} n\) by the rank-based approach

Tracks:
* Track A, few terminals
* Track B, low treewidth
Choice of the tracks

n: number of vertices
m: number of edges
t: number of terminals
w: treewidth

Algorithms:
* Dreyfus-Wagner, Erickson-Monma-Veinott $3^t n + 2^t (n \log n + m)$
* DP $O^*(w^w)$, improved to $2^{O(w)} n$ by the rank-based approach
* constant approximations, fixed-parameter approximations

Tracks:
* Track A, few terminals
* Track B, low treewidth
* Track C, heuristics
Instances

100 public and 100 private instances (from Steinlib & Vienna)

* grid graphs with rectangular holes and $\ell_1$-weights
* Wire-routing problems from industry
* random sparse instances resistant to preprocessing
* Rectilinear instances with low treewidth
* Real-world telecommunication networks
Instances and rules

100 public and 100 private instances (from Steinlib & Vienna)

* grid graphs with rectangular holes and $\ell_1$-weights
* Wire-routing problems from industry
* random sparse instances resistant to preprocessing
* Rectilinear instances with low treewidth
* Real-world telecommunication networks

Rules:

* All tracks: 30 minutes per instance, final score on the 100 private instances
* Tracks A and B: number of solved instances
* Track C: sum of the ratios opt/sol

A wrong answer disqualifies in Tracks A and B, and gives 0 for that instance in Track C
Selection of the instances

* Track A: few terminals, high treewidth
* Track B: low treewidth, many terminals
* Track C: many terminals, high treewidth, unsolved

<table>
<thead>
<tr>
<th>Track</th>
<th>$E[n]$</th>
<th>$E[m]$</th>
<th>$E[t]$</th>
<th>median $t$</th>
<th>$E[w]$</th>
<th>median $w$</th>
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</thead>
<tbody>
<tr>
<td>A</td>
<td>1.5K</td>
<td>8.5K</td>
<td>19.4</td>
<td>16</td>
<td>$\approx$ 100</td>
<td>$\approx$ 25</td>
</tr>
<tr>
<td>B</td>
<td>1.5K</td>
<td>2.8K</td>
<td>606</td>
<td>100</td>
<td><strong>14.9</strong></td>
<td><strong>19.5</strong></td>
</tr>
<tr>
<td>C</td>
<td>27K</td>
<td>48K</td>
<td>1114</td>
<td>360</td>
<td>$\approx$ 150</td>
<td>$\approx$ 50</td>
</tr>
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</table>

In Track B, a tree-decomposition was given with the input computed by Tamaki's and Strasser's codes of PACE 2017
The OPTIL.io platform hosted all three tracks

* Many languages supported; added more upon request
* Extra PACE participants among the OPTIL.io habitués
* Alleviates our workload in organizing PACE

Many thanks to Szymon Wasik and Jan Badura!
## Participation

<table>
<thead>
<tr>
<th>Country</th>
<th>Teams</th>
<th>Participants</th>
</tr>
</thead>
<tbody>
<tr>
<td>Austria</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>Brazil</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>Canada</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Czechia</td>
<td>2</td>
<td>4</td>
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<tr>
<td>Denmark</td>
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<tr>
<td>Poland</td>
<td>2</td>
<td>11</td>
</tr>
<tr>
<td>Romania</td>
<td>1</td>
<td>3</td>
</tr>
</tbody>
</table>

Complete submissions:
- Track A: 12
- Track B: 8
- Track C: 13
Implementations

A lot of preprocessing and...

FPT algorithms:

* DW(++)/EMV(++): 1st, 2nd, 4th to 9th in Track A, 2nd, 3rd, 4th in Track B
* DP $O^*(w^w)$: 2nd in Track B
* rank-based approach: 3rd to 8th in Track B
  solved instances that were not solved by other programs
* FPT approximation: 4th Track C

or other approaches:

* Branch-and-Cut: 3rd in Track A, 1st in B, 2nd in C
* Evolutionary algorithm: 1st in Track C
* Iterated local search with noising: 3rd in Track C
SCIP-Jack: A general Steiner tree solver

Daniel Rehfeldt · Thorsten Koch
Zuse Institute Berlin
Technische Universität Berlin
Berlin Mathematical School
The Steiner tree problem in graphs

Given:

- $G = (V, E)$: undirected graph
- $T \subseteq V$: subset of vertices
- $c \in \mathbb{R}^E_{>0}$: positive edge costs

A tree $S \subseteq G$ is called Steiner tree in $(G, T, c)$ if $T \subseteq V(S)$.

Steiner tree Problem in Graphs (SPG)

Find a Steiner tree $S$ in $(G, T, c)$ with minimum edge costs

$\sum_{e \in E(S)} c(e)$

SPG is one of the classical combinatorial optimization problems; decision variant is one of Karp's 21 NP-complete problems.
The Steiner tree problem in graphs

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**Steiner tree Problem in Graphs (SPG)**

Find a Steiner tree $S$ in $(G, T, c)$ with minimum edge costs $\sum_{e \in E(S)} c(e)$

SPG is one of the classical combinatorial optimization problems; decision variant is one of Karp’s 21 $\mathcal{NP}$-complete problems.
Our submission to PACE 2018

SCIP-Jack:

- Solver for Steiner tree (and 11 related) problems
- part of the SCIP Optimization Suite
- was used with our LP solver SoPlex\(^1\) (default is CPLEX)

\(^1\)current developers: Leon Eifler, Matthias Miltenberger, D.R.
Some facts about SCIP

- **general setup**
  - plugin based system
  - default plugins handle MIPs and nonconvex MINLPs
  - support for branch-and-price and custom relaxations

- **documentation and guidelines**
  - more than 500,000 lines of C code, 20% documentation
    - 36,000 assertions, 5,000 debug messages
  - HowTos: plugins types, debugging, automatic testing
  - 11 examples and 5 applications illustrating the use of SCIP
  - active mailing list SCIP@ZIB.DE (300 members)

- **interface and usability**
  - user-friendly interactive shell
  - interfaces to AMPL, GAMS, ZIMPL, MATLAB, Python and Java
  - C++ wrapper classes
  - LP solvers: CLP, CPLEX, Gurobi, MOSEK, QSopt, SoPlex, Xpress
  - over 1,600 parameters and 15 emphasis settings
(Some) SCIP users all over the world

over 10,000 downloads per year
Why not using a general MIP solver?

Consider (small-scale) network design instance with:

\[
\begin{align*}
|V| &= 12,715 \\
|E| &= 41,264 \\
|T| &= 475
\end{align*}
\]

- CPLEX 12.7.1: Runs out of memory after 14 h
- SCIP-Jack: Solves to optimality in 7.5 seconds

For larger problems CPLEX runs out of memory almost immediately (largest real-world instance SCIP-Jack solved so far has 64 million edges, 11 million vertices)

Network telecommunication design for Austrian cities, see *New Real-world Instances for the Steiner Tree Problem in Graphs* (Leitner et al., 2014)
transform each SPG into Steiner arborescence problem and ...
transform each SPG into Steiner arborescence problem and ...
... use cutting plane algorithm based on flow balance directed-cut formulation:

Formulation

\[
\begin{align*}
\min \ c^T y \\
y(\delta^+_W) & \geq 1 \quad \text{for all } W \subset V, r \in W, (V \setminus W) \cap T \neq \emptyset \\
y(\delta^-_v) & \leq y(\delta^+_v) \quad \text{for all } v \in V \setminus T \\
y(\delta^-_v) & \geq y(a) \quad \text{for all } a \in \delta^+_v, v \in V \setminus T \\
y(a) & \in \{0, 1\} \quad \text{for all } a \in A
\end{align*}
\]
main features of SCIP-Jack for SPGs:

2 Latest version was not used at PACE 2018
main features of SCIP-Jack for SPGs:

- very fast separator routine based on new max-flow implementation\(^2\)
- preprocessing routines
- domain propagation routines
- primal and dual heuristics
- shared and distributed memory parallelizations

\(^2\)Latest version was not used at PACE 2018
Central feature: Reduction techniques

- reduction techniques try to transform an instance to an equivalent smaller one (e.g. by deleting edges or vertices)
- reduction techniques of SCIP-Jack typically reduce the number of edges by more than 70%
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- Reduction techniques of SCIP-Jack typically reduce the number of edges by more than 70%.

Original instance (5000 edges) vs. reduced instance (less edges).
Terminal regions decomposition

Example for (new) SPG reduction technique, implemented for PACE 2018:

Define distance function $d: \mathbb{V} \times \mathbb{V} \rightarrow \mathbb{R} \cup \{\infty\}$:

$$d(v_i, v_j) := \inf \{ P(Q) \mid Q \text{ is a } (v_i, v_j)-\text{path and } (\mathbb{V}(Q) \setminus \{v_i, v_j\}) \setminus T = \emptyset \}$$

Define decomposition $H = \{ H_t \subseteq \mathbb{V} \mid T \setminus H_t = \{t_i\} \}$ of $\mathbb{V}$ such that for each $t_i \in T$ the subgraph $(H_{t_i}, \mathbb{E}[H_{t_i}])$ is connected.

Define radius:

$$r_H(t_i) := \min \{ d(t_i, v_k) \mid \exists \{v_j, v_j\} \in \mathbb{E}, v_j \in H_{t_i}, v_k /\in H_{t_i} \}$$
Example for (new) SPG reduction technique, implemented for PACE 2018:

Define distance function $d : V \times V \mapsto \mathbb{R} \cup \{\infty\}$:

$$d(v_i, v_j) := \inf \{ P(Q) \mid Q \text{ is a } (v_i, v_j)-\text{path and } (V(Q) \setminus \{v_i, v_j\}) \cap T = \emptyset \}$$

Define decomposition $H = \{ H_{t_i} \subseteq V \mid T \cap H_{t_i} = \{t_i\} \}$ of $V$ such that for each $t_i \in T$ the subgraph $(H_{t_i}, E[H_{t_i}])$ is connected.

Define radius:

$$r_H(t_i) := \min \{ d(t_i, v_k) \mid \exists \{v_j, v_j\} \in E, v_j \in H_{t_i}, v_k \notin H_{t_i} \}$$
Proposition

Let $H$ be a terminal regions decomposition and assume that $|T| \geq 2$. Let $v_i \in V \setminus T$, assume for each optimal solution $S$ that $v_i \in V(S)$. Then

$$\sum_{t \in T} r_H(t) - \max\{r_H(t) + r_H(t') \mid t, t' \in T, t \neq t'\} + d(v_i, v_{i,1}) + d(v_i, v_{i,2})$$

is lower bound on the weight of $S$.

Finding an optimal terminal regions decomposition is NP-hard!
Each SCIP-Jack Steiner tree reduction transforms SPG \((V, E, T, c)\) to SPG \((V', E', T', c')\) and provides function \(p : E' \to P(E)\) such that for each (optimal) solution \(S' \subseteq E'\) to transformed problem, set \(\bigcup_{e \in S'} p(e)\) is (optimal) solution to original problem.

**Observation**

Let \((V, E, T, c)\), \((V', E', T', c')\), and \(p\) as above. Define

\[
E'' := \bigcup_{e \in E'} p(e),
\]

\[
V'' := \{ v \in V \mid \exists (v, w) \in E'', w \in V \},
\]

\[
T'' := \{ t \in T \mid \exists (t, w) \in E'', w \in V \},
\]

\[
c'' := c|_{E''}.
\]

Each (optimal) solution to \((V'', E'', T'', c'')\) is (optimal) solution to \((V, E, T, c)\).

\[\Rightarrow\] allows to translate reductions into variable fixings during branch-and-bound
Further uses of reduction techniques

- **Primal heuristics**: Several heuristics of SCIP-Jack create subproblems (e.g. by merging feasible solutions), reduction techniques are vital to finding a good solution there.

- **Branch-and-bound**: SCIP-Jack branches on vertices, providing new opportunities for reduction techniques.
For PACE 2018

- new reduction techniques were designed and implemented (suitable for but not restricted to problems with few terminals)
For PACE 2018

- new reduction techniques were designed and implemented (suitable for but not restricted to problems with few terminals)
- reduction techniques and heuristics were performed far more aggressively to compensate for slower LP solver SoPlex
- ...still SCIP-Jack/Cplex shows a far stronger performance
For PACE 2018

- new reduction techniques were designed and implemented (suitable for but not restricted to problems with few terminals)
- reduction techniques and heuristics were performed far more aggressively to compensate for slower LP solver SoPlex
- ...still SCIP-Jack/CPLEX shows a far stronger performance
- most new algorithms are included in latest SCIP release

http://scip.zib.de
Thanks to the organizers of PACE 2018!
...thanks to NETWORKS for travel support!
...and thank you for your attention!
Track A results

1st place, 95: Yoichi Iwata and Takuto Shigemura
2nd place, 94: Krzysztof Maziarz and Adam Polak
3rd place, 93: Thorsten Koch and Daniel Rehfeldt
4th place, 92: Andre Schidler, Johannes Fichte, and Markus Hecher
5th place, 67: Krzysztof Kiljan, Dominik Klemba, Marcin Mucha, Wojciech Nadara, Marcin Pilipczuk, Mateusz Radecki, and Michał Ziobro
6th place, 66: Suhas Thejaswi
6th place, 66: Peter Mitura and Ondřej Suchý
6th place, 66: Johannes Varga

9th place, 48: Saket Saurabh, P. S. Srinivasan, and Prafullkumar Tale
* 6th place, 66: Suhas Thejaswi
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Track A results

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* 6th place, 66: Johannes Varga

* 9th place, 48: Saket Saurabh, P. S. Srinivasan, and Prafullkumar Tale
This is to certify that the 2018 PACE Program Committee recognizes

Andre Schidler, Johannes Fichte, and Markus Hecher

Technische Universität Wien

for

Fourth Place in Track A: Exact Steiner Tree with Few Terminals

€ 225,-
* 3rd place, 93: Thorsten Koch and Daniel Rehfeldt

* 4th place, 92: Andre Schidler, Johannes Fichte, and Markus Hecher

* 5th place, 67: Krzysztof Kiljan, Dominik Klemba, Marcin Mucha, Wojciech Nadara, Marcin Pilipczuk, Mateusz Radecki, and Michał Ziobro

* 6th place, 66: Suhas Thejaswi

* 6th place, 66: Peter Mitura and Ondřej Suchý

* 6th place, 66: Johannes Varga

* 9th place, 48: Saket Saurabh, P. S. Srinivasan, and Prafullkumar Tale
This is to certify that the 2018 PACE Program Committee recognizes

Daniel Rehfeldt and Thorsten Koch

Zuse Institute Berlin TU Berlin

for

Third Place in Track A: Exact Steiner Tree with Few Terminals

€ 300,-

Édouard Bonnet, ENS de Lyon

Florian Sikora, Université Paris-Dauphine

2018 PACE Program Committee Co-chairs
* 2nd place, 94: Krzysztof Maziarz and Adam Polak
* 3rd place, 93: Thorsten Koch and Daniel Rehfeldt
* 4th place, 92: Andre Schidler, Johannes Fichte, and Markus Hecher

* 5th place, 67: Krzysztof Kiljan, Dominik Klemba, Marcin Mucha, Wojciech Nadara, Marcin Pilipczuk, Mateusz Radecki, and Michał Ziobro

* 6th place, 66: Suhas Thejaswi
* 6th place, 66: Peter Mitura and Ondřej Suchý
* 6th place, 66: Johannes Varga

* 9th place, 48: Saket Saurabh, P. S. Srinivasan, and Prafullkumar Tale
This is to certify that the 2018 PACE Program Committee recognizes

Krzysztof Maziarz and Adam Polak
Jagiellonian University
for
Second Place in Track A: Exact Steiner Tree with Few Terminals

€ 350,-
Track A results

* 1st place, 95: Yoichi Iwata and Takuto Shigemura
* 2nd place, 94: Krzysztof Maziarz and Adam Polak
* 3rd place, 93: Thorsten Koch and Daniel Rehfeldt
* 4th place, 92: Andre Schidler, Johannes Fichte, and Markus Hecher

* 5th place, 67: Krzysztof Kiljan, Dominik Klemba, Marcin Mucha, Wojciech Nadara, Marcin Pilipczuk, Mateusz Radecki, and Michał Ziobro
* 6th place, 66: Suhas Thejaswi
* 6th place, 66: Peter Mitura and Ondřej Suchý
* 6th place, 66: Johannes Varga
* 9th place, 48: Saket Saurabh, P. S. Srinivasan, and Prafullkumar Tale
This is to certify that the 2018 PACE Program Committee recognizes

Yoichi Iwata and Takuto Shigemura
National Institute of Informatics, Japan
University of Tokyo

for First Place in Track A: Exact Steiner Tree with Few Terminals

€ 450,-

Édouard Bonnet, ENS de Lyon
Florian Sikora, Université Paris-Dauphine

2018 PACE Program Committee Co-chairs
* Honorable mention: Sharat Ibrahimpur solved 69 out of 100 instances but was incorrect on one instance

* 11th place, 14: S. Vaishali and Rathna Subramanian

* 12th place, 9: R. Vijayaragunathan, N. S. Narayanaswamy, and Rajesh Pandian M.

The winning heuristic for Track C actually solved all 100 private\(^1\) instances in track A!

\(^1\)it returned a wrong answer on some public instance
Track B results

* 1st place, 92: Thorsten Koch and Daniel Rehfeldt
* 2nd place, 77: Yoichi Iwata and Takuto Shigemura
* 3rd place, 58: Tom van der Zanden
* 4th place, 52: Peter Mitura and Ondřej Suchý
* 6th place, 49: Akio Fujiyoshi
* 7th place, 33: Krzysztof Kiljan, Dominik Klemba, Marcin Mucha, Wojciech Nadara, Marcin Pilipczuk, Mateusz Radecki, and Michał Ziobro
* 7th place, 33: Dilson Guimarães, Guilherme Gomes, João Gonçalves, and Vinícius dos Santos
* 6th place, 49: Akio Fujiyoshi

* 7th place, 33: Krzysztof Kiljan, Dominik Klemba, Marcin Mucha, Wojciech Nadara, Marcin Pilipczuk, Mateusz Radecki, and Michał Ziobro

* 7th place, 33: Dilson Guimarães, Guilherme Gomes, João Gonçalves, and Vinícius dos Santos
* 4th place, 52: Peter Mitura and Ondřej Suchý
* 4th place, 52: Yasuaki Kobayashi
* 6th place, 49: Akio Fujiyoshi
* 7th place, 33: Krzysztof Kiljan, Dominik Klemba, Marcin Mucha, Wojciech Nadara, Marcin Pilipczuk, Mateusz Radecki, and Michał Ziobro
* 7th place, 33: Dilson Guimarães, Guilherme Gomes, João Gonçalves, and Vinícius dos Santos
Track B results

* 3rd place, 58: Tom van der Zanden

* 4th place, 52: Peter Mitura and Ondřej Suchý

* 4th place, 52: Yasuaki Kobayashi

* 6th place, 49: Akio Fujiyoshi

* 7th place, 33: Krzysztof Kiljan, Dominik Klemba, Marcin Mucha, Wojciech Nadara, Marcin Pilipczuk, Mateusz Radecki, and Michał Ziobro

* 7th place, 33: Dilson Guimarães, Guilherme Gomes, João Gonçalves, and Vinícius dos Santos
This is to certify that the 2018 PACE Program Committee recognizes

Tom van der Zanden
Utrecht University

for
Third Place in Track B: Exact Steiner Tree with Small Treewidth

€ 300,-

Édouard Bonnet, ENS de Lyon

Florian Sikora, Université Paris-Dauphine

2018 PACE Program Committee Co-chairs
* 2nd place, 77: Yoichi Iwata and Takuto Shigemura
* 3rd place, 58: Tom van der Zanden
* 4th place, 52: Peter Mitura and Ondřej Suchý
* 4th place, 52: Yasuaki Kobayashi
* 6th place, 49: Akio Fujiyoshi
* 7th place, 33: Krzysztof Kiljan, Dominik Klemba, Marcin Mucha, Wojciech Nadara, Marcin Pilipczuk, Mateusz Radecki, and Michał Ziobro
* 7th place, 33: Dilson Guimarães, Guilherme Gomes, João Gonçalves, and Vinícius dos Santos
This is to certify that the 2018 PACE Program Committee recognizes

Yoichi Iwata
National Institute of Informatics, Japan

and

Takuto Shigemura
University of Tokyo

for

Second Place in Track B: Exact Steiner Tree with Small Treewidth

€ 350,-
>>> Track B results

* 1st place, 92: Thorsten Koch and Daniel Rehfeldt
* 2nd place, 77: Yoichi Iwata and Takuto Shigemura
* 3rd place, 58: Tom van der Zanden

* 4th place, 52: Peter Mitura and Ondřej Suchý
* 4th place, 52: Yasuaki Kobayashi
* 6th place, 49: Akio Fujiyoshi
* 7th place, 33: Krzysztof Kiljan, Dominik Klemba, Marcin Mucha, Wojciech Nadara, Marcin Pilipczuk, Mateusz Radecki, and Michał Ziobro
* 7th place, 33: Dilson Guimarães, Guilherme Gomes, João Gonçalves, and Vinícius dos Santos
This is to certify that the 2018 PACE Program Committee recognizes

Daniel Rehfeldt  
Zuse Institute Berlin

and

Thorsten Koch  
TU Berlin

for

First Place in Track B: Exact Steiner Tree with Small Treewidth

€ 450,-

Édouard Bonnet, ENS de Lyon

Florian Sikora, Université Paris-Dauchine
* 13th place, 80.73: Harumi Haraguchi, Hiroshi Arai, Shiyougo Akiyama, and Masaki Kubonoya
* 12th place, 82.61: Saket Saurabh, P. S. Srinivasan, and Prafullkumar Tale

* 13th place, 80.73: Harumi Haraguchi, Hiroshi Arai, Shiyougo Akiyama, and Masaki Kubonoya
11th place, 94.37: Sharat Ibrahimpur

12th place, 82.61: Saket Saurabh, P. S. Srinivasan, and Prafullkumar Tale

13th place, 80.73: Harumi Haraguchi, Hiroshi Arai, Shiyougo Akiyama, and Masaki Kubonoya
Track C results

* 10th place, 94.57: R. Vijayaragunathan, N. S. Narayanaswamy, and Rajesh Pandian M.
* 11th place, 94.37: Sharat Ibrahimpur
* 12th place, 82.61: Saket Saurabh, P. S. Srinivasan, and Prafullkumar Tale
* 13th place, 80.73: Harumi Haraguchi, Hiroshi Arai, Shiyougo Akiyama, and Masaki Kubonoya
* 9th place, 96.92: Dimitri Watel and Marc-Antoine Weisser
* 10th place, 94.57: R. Vijayaragunathan, N. S. Narayanaswamy, and Rajesh Pandian M.
* 11th place, 94.37: Sharat Ibrahimpur
* 12th place, 82.61: Saket Saurabh, P. S. Srinivasan, and Prafullkumar Tale
* 13th place, 80.73: Harumi Haraguchi, Hiroshi Arai, Shiyougo Akiyama, and Masaki Kubonoya
Track C results

* 8th place, 97.15: Max Hort, Marciano Geijselaers, Joshua Scheidt, Pit Schneider, and Tahmina Begum
* 9th place, 96.92: Dimitri Watel and Marc-Antoine Weisser
* 10th place, 94.57: R. Vijayaragunathan, N. S. Narayanaswamy, and Rajesh Pandian M.
* 11th place, 94.37: Sharat Ibrahimpur
* 12th place, 82.61: Saket Saurabh, P. S. Srinivasan, and Prafullkumar Tale
* 13th place, 80.73: Harumi Haraguchi, Hiroshi Arai, Shiyougo Akiyama, and Masaki Kubonoya
Track C results

* 7th place, 97.54: Stéphane Grandcolas
* 8th place, 97.15: Max Hort, Marciano Geijselaers, Joshua Scheidt, Pit Schneider, and Tahmina Begum
* 9th place, 96.92: Dimitri Watel and Marc-Antoine Weisser
* 10th place, 94.57: R. Vijayaragunathan, N. S. Narayanaswamy, and Rajesh Pandian M.
* 11th place, 94.37: Sharat Ibrahimpur
* 12th place, 82.61: Saket Saurabh, P. S. Srinivasan, and Prafullkumar Tale
* 13th place, 80.73: Harumi Haraguchi, Hiroshi Arai, Shiyougo Akiyama, and Masaki Kubonoya
Track C results

* 6th place, 98.27: Krzysztof Kiljan, Dominik Klemba, Marcin Mucha, Wojciech Nadara, Marcin Pilipczuk, Mateusz Radecki, and Michał Ziobro

* 7th place, 97.54: Stéphane Grandcolas

* 8th place, 97.15: Max Hort, Marciano Geijselaers, Joshua Scheidt, Pit Schneider, and Tahmina Begum

* 9th place, 96.92: Dimitri Watel and Marc-Antoine Weisser

* 10th place, 94.57: R. Vijayaragunathan, N. S. Narayanaswamy, and Rajesh Pandian M.

* 11th place, 94.37: Sharat Ibrahimpur

* 12th place, 82.61: Saket Saurabh, P. S. Srinivasan, and Prafullkumar Tale

* 13th place, 80.73: Harumi Haraguchi, Hiroshi Arai, Shiyougo Akiyama, and Masaki Kubonoya
Track C results

* 5th place, 98.93: Mateus Oliveira and Emmanuel Arrighi
* 6th place, 98.27: Krzysztof Kiljan, Dominik Klemba, Marcin Mucha, Wojciech Nadara, Marcin Pilipczuk, Mateusz Radecki, and Michał Ziobro
* 7th place, 97.54: Stéphane Grandcolas
* 8th place, 97.15: Max Hort, Marciano Geijselaers, Joshua Scheidt, Pit Schneider, and Tahmina Begum
* 9th place, 96.92: Dimitri Watel and Marc-Antoine Weisser
* 10th place, 94.57: R. Vijayaragunathan, N. S. Narayanaswamy, and Rajesh Pandian M.
* 11th place, 94.37: Sharat Ibrahimpur
* 12th place, 82.61: Saket Saurabh, P. S. Srinivasan, and Prafullkumar Tale
* 13th place, 80.73: Harumi Haraguchi, Hiroshi Arai, Shiyougo Akiyama, and Masaki Kubonoya
The top 4 got an average ratio above 0.997

* 4th place, 99.72: Radek Hušek, Tomáš Toufar, Dušan Knop, Tomáš Masařík, and Eduard Eiben
This is to certify that the 2018 PACE Program Committee recognizes

Radek Hušek, Tomáš Toufar, Tomáš Masarík, Dušan Knop, and Eduard Eiben

Charles University & University of Bergen, Norway

for

Fourth Place in Track C: Heuristic Steiner Tree

€ 225,-

Édouard Bonnet, ENS de Lyon

Florian Sikora, Université Paris-Dauphine

2018 PACE Program Committee Co-chairs
The top 4 got an average ratio above 0.997

* 3rd place, 99.80: Martin J. Geiger
* 4th place, 99.72: Radek Hušek, Tomáš Toufar, Dušan Knop, Tomáš Masařík, and Eduard Eiben
This is to certify that the 2018 PACE Program Committee recognizes

**Martin Geiger**

Helmut Schmidt Universität, Hamburg

for

**Third Place in Track C: Heuristic Steiner Tree**

€ 300,–
Track C results - 2

The top 4 got an average ratio above 0.997

* 2nd place, 99.85: Thorsten Koch and Daniel Rehfeldt
* 3rd place, 99.80: Martin J. Geiger
* 4th place, 99.72: Radek Hušek, Tomáš Toufar, Dušan Knop, Tomáš Masařík, and Eduard Eiben
This is to certify that the 2018 PACE Program Committee recognizes Daniel Rehfeldt and Thorsten Koch for Second Place in Track C: Heuristic Steiner Tree.

Daniel Rehfeldt
Zuse Institute Berlin

Thorsten Koch
TU Berlin

€ 350,-
The top 4 got an average ratio above 0.997

* 1st place, 99.93: Emmanuel Romero Ruiz, Emmanuel Antonio Cuevas, Irwin Enrique Villalobos López, and Carlos Segura González
* 2nd place, 99.85: Thorsten Koch and Daniel Rehfeldt
* 3rd place, 99.80: Martin J. Geiger
* 4th place, 99.72: Radek Hušek, Tomáš Toufar, Dušan Knop, Tomáš Masařík, and Eduard Eiben
This is to certify that the 2018 PACE Program Committee recognizes

Emmanuel Romero Ruiz, Emmanuel Antonio Cuevas, Irwin Enrique Villalobos Lopez, and Carlos Segura González
Center for Research in Mathematics, Guanajuato, Mexico
for
First Place in Track C: Heuristic Steiner Tree

€ 450,-
The next PACE

*PACE 2018-2019 program committee*

Markus Hecher  
TU Wien

Johannes Fichte  
TU Dresden
The next PACE

PACE 2018-2019 program committee

Markus Hecher       TU Wien
Johannes Fichte    TU Dresden
PACE timeline in 2018-2019

**Tentative time schedule**

- Today: Announcement of the PC & challenge problem
- October 1\textsuperscript{st} 2018: Announcement of challenge problems & tracks
- November 1\textsuperscript{st} 2018: Announcement of detailed problem setting and inputs
- At least 2 weeks before IPEC deadline: Result communicated to participants
- September 10-14 2019: Award ceremony at IPEC