PACE 2019: The 4th Iteration

Johannes K. Fichte, TU Dresden
Markus Hecher, TU Wien & Univ. of Potsdam
IPEC 2019, TU Munich, Germany
History & Mission of PACE

Bart M.P. Jansen
History

- Conceived in fall 2015
  
  *parameterized algorithmics should have a greater impact on practice*

- First iteration: 2015/16
  - Track A: *Treewidth*
  - Track B: *Feedback Vertex Set*

- Second iteration: 2016/17
  - Track A: *Treewidth*
  - Track B: *Minimum Fill-In*

- Third iteration: 2017/18
  - Track 1: *Steiner tree exact with few terminals*
  - Track 2: *Steiner tree exact with low treewidth*
  - Track 3: *Steiner tree heuristic*

- Currently: Fourth iteration
Mission

Investigate applicability of algorithmic ideas from parameterized complexity

1. Bridge gap between theory and practice
2. Inspire new theoretical developments
3. Investigate theoretical algorithms in practice
4. Produce accessible implementations & benchmarks
5. Encourage dissemination in scientific papers
Outcome

- Previous iterations *inspired* long list of follow-up works
- Follow-up *Applications and Frameworks*
- Increased *awareness* of Parameterized Complexity
  - SAT community was particularly interested (this year)
- Usage of *Benchmark instances*
  - Almost 12,000 publicly available, citable instances published (this year)
- Scientific *Papers*
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- Scientific Papers
  - Finding Hamiltonian Cycle in Graphs of Bounded Treewidth: Experimental Evaluation
    - Michał Ziobro
      Theoretical Computer Science Department, Faculty of Mathematics and Computer Science, Jagiellonian University, Kraków, Poland
      michal.18.ziobro@student.uj.edu.pl
    - Marcin Pilipczuk
      Institute of Informatics, University of Warsaw, Poland
      makcin@mimuw.edu.pl
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  - Finding Hamiltonian Cycle in Graphs
  - Treewidth: Experimental Evaluation
- Scientific Papers

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An Improved GPU-Based SAT Model Counter

Published (this year)
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An Improved GPU-Based SAT Model Counter

Johannes K. Fichte\textsuperscript{1(✉)}, Markus Hecher\textsuperscript{2,3,*}, and Markus Zisser\textsuperscript{2}

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Article

Practical Access to Dynamic Programming on Tree Decompositions

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2 Department of Computer Science, Kiel University, 24103 Kiel, Germany
* Correspondence: seb@informatik.uni-kiel.de
† This paper is an extended version of our paper published in ESA 2018.

Received: 18 July 2019; Accepted: 13 August 2019; Published: 16 August 2019
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An Experimental Study of the Treewidth of Real-World Graph Data

An Improved GPU-Based SAT Model Counter

Tuukka Korhonen, Jeremias Berg and Matti Järvisalo
HIIT, Department of Computer Science, University of Helsinki, Finland

Proceedings of the Twenty-Eighth International Joint Conference on Artificial Intelligence (IJCAI-19)
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Article

An Improved GPU-Based SAT Model Counter

An Experimental Study of the Treewidth of Real-World Graph Data

On the Relevance of Optimal Tree Decompositions for Constraint Networks

Practical Tree Dec

via SAT and ASP

Received: 18 July 2019; Accepted: 13 August 2019; Published: 16 August 2019
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An Improved GPU-Based SAT Model Counter

Francesco Calimeri, Simona Perri and Jessica Zangari

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Tuukka Korhonen, Jeremias Berg and Matti Järvisalo

HIIT, Department of Computer Science, University of Helsinki, Finland
via SAT and ASP

An Experimental Study of the Treewidth of Real-World Graph Data

Optimizing Answer Set Computation via Zisser²

Heuristic-Based Decomposition *

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An Experimental Study of the Treewidth of Real-World Graph Data
Philippe Jégou
Aix Marseille Univ, Université de Toulon, CNRS, LIS
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An Experimental Study of the Treewidth of Real-World Graph Data

Optimizing Answer Set Computation via Zisser

Heuristic-Based Decomposition *

Francesco Calimeri, Simona Perri and Jessica Zangari

Improved Analysis of Highest-Degree Branching for Feedback Vertex Set

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An Improved GPU-Based SAT Model Counter
The Thirty-Third AAAI Conference on Artificial Intelligence (AAAI-19)

Separator-Based Pruned Dynamic Programming for Steiner Tree

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Program and Steering Committee

- **Program Committee**
  
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  Markus Hecher  
  TU Wien, University of Potsdam

  **Intern:**
  
  Muhammad A. Dzulfikar  
  University of Indonesia @TU Dresden

- **Steering Committee**
  
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  Middlesex University

  Holger Dell  
  IT University of Copenhagen

  Bart M. P. Jansen  
  Eindhoven University of Technology

  Thore Husfeldt  
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  Petteri Kaski  
  Aalto University

  Christian Komusiewicz  
  Philipps-Universität Marburg

  Frances A. Rosamond  
  University of Bergen

  Florian Sikora  
  LAMSADÉ, Université Paris Dauphine
We would like to thank our Sponsors...

- ... for prizes
- ... for computing resources

NETWORKS is a project of
University of Amsterdam
Eindhoven University of Technology
Leiden University
Center for Mathematics and
Computer Science (CWI)

ziH
Zentrum für Informationsdienste
und Hochleistungsrechnen

data experts
Systemberatung
Softwareentwicklung
Informationsverarbeitung
Thanks go to

- All the **participants of PACE**!

- Intern **Muhammad A. Dzulfikar** from the University of Indonesia
  - Performing instance selection
  - Support for validating results
  - ....

- **Jan Badura** at **optil.io**, who quickly implemented our requests
  - Using results of several runs for the final results
  - Customizing our judges for optil.io
  - ...

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[Image -4x-25 to 211x30]
Tracks of PACE 2019
Track 1: Vertex Cover

- Among the famous **21 first NP-complete** problems by Karp
- One of the famous, if not the most famous, graph problems
- Great tradition in parameterized complexity
  - Well studied problem variants
  - Different parameters
  - Kernelizations
  - Applications
  - ...

- Track 1a: Compute a Minimum Vertex Cover (Exact)

<table>
<thead>
<tr>
<th>Problem:</th>
<th>MINVERTEXCOVER</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input:</td>
<td>Graph $G$</td>
</tr>
<tr>
<td>Task:</td>
<td>Output a minimum vertex cover for $G$.</td>
</tr>
</tbody>
</table>
Instance Selection for Vertex Cover

- 9,591 instances among 8 different origins
  - PACE 2016
  - TransitGraphs, Road-graphs
  - SNAP
  - frb
  - ASP Horn backdoors, SAT Horn backdoors
  - SAT2VC
- Classification by “Difficulty”
  (via Gurobi, numVC, Glucose) in intervals

| instances | $|V_{\min}|$ | $|V_{\max}|$ | $|V_{\text{avg}}|$ | $|V_{\text{med}}|$ | $|E_{\min}|$ | $|E_{\max}|$ | $|E_{\text{avg}}|$ | $|E_{\text{med}}|$ | $\text{tw}_{\text{med}}$ |
|-----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|
| public    | 198      | 138.14k  | 16.44k   | 14.69k   | 813      | 227.24k  | 30.95k   | 24.66k   | 105.0    |
| private   | 153      | 98.13k   | 16.30k   | 13.59k   | 625      | 161.36k  | 30.50k   | 27.15k   | 103.5    |
| all       | 153      | 138.14k  | 16.37k   | 13.59k   | 625      | 227.24k  | 30.73k   | 24.66k   | 107.0    |
Track 2: Hypertree Decompositions

- Motivation: Success of PACE 2016 & 2017 (Treewidth)
- Applications for (Hyper-)tree Decompositions
  - Databases
  - Constraint Programming
- Track 2a (EXACT): Compute a hypertree decomposition of minimum width

\[
\begin{align*}
\text{Problem:} & \quad \text{MinHypertreeWidth} \\
\text{Input:} & \quad \text{Hypergraph } H \\
\text{Task:} & \quad \text{Output a hypertree decomposition of } H \text{ of minimum width.}
\end{align*}
\]

- Track 2b (HEUR): Heuristically compute a hypertree decomposition of small width

\[
\begin{align*}
\text{Problem:} & \quad \text{HeurHypertreeWidth} \\
\text{Input:} & \quad \text{Hypergraph } H \\
\text{Task:} & \quad \text{Output a hypertree decomposition of } H \text{ of small width.}
\end{align*}
\]
Hypertree Decompositions

- Given: Hypergraph $H$ (higher arity edges)

- A Hypertree Decomposition $D$ of $H$ is, roughly speaking,
  - A Tree Decomposition of $H$
  - + a bag covering function (edge cover) over hyperedges
  - + a certain monotonicity property (Descendent Condition) for the edge cover

- width($D$) is size of the largest edge cover
- htw($H$) smallest width over all Hypertree Decompositions of $H$
Instance Selection for Hypertree Decompositions

- 2,191 instances from hyperbench, originating from the area of CSP
  - DaimlerChrysler
  - Grid2D
  - MaxSAT, csp_application, csp_random, csp_other
  - CQ
- Classification of “Difficulty” by means of
  - htdcomp, kdetdecomp
  - Frasmt using the more generalized (fractional / generalized) hypertree decompositions

| Track  | instances | $|V_{min}|$ | $|V_{max}|$ | $|V_{med}|$ | $|E_{min}|$ | $|E_{max}|$ | $|E_{med}|$ |
|--------|-----------|---------|---------|---------|---------|---------|---------|
| Track 2a | public    | 3       | 130     | 24.0    | 3       | 100     | 61.5    |
| Track 2a | private   | 10      | 351     | 25.0    | 5       | 250     | 60.0    |
| Track 2a | all       | 3       | 351     | 24.0    | 3       | 250     | 60.0    |
| Track 2b | public    | 12      | 694     | 40.0    | 5       | 526     | 84.0    |
| Track 2b | private   | 12      | 694     | 40.0    | 5       | 495     | 90.0    |
| Track 2b | all       | 12      | 694     | 40.0    | 5       | 526     | 84.0    |
PACE 2019: Submission Requirements
Submission Requirements

1. Solvers + Dependencies have to be open source
2. Source code of solver is maintained on public repository + long term data library
3. A dedicated solver description is required
4. Solvers for Tracks 1a and 2a are provably optimal

Submission Limits

1. Submission on optil.io
2. 30 minutes per instance
3. 8 GB RAM per instance
Participants of PACE 2019
Participants

- 18 teams and 33 participants from 10 countries

<table>
<thead>
<tr>
<th>Region</th>
<th>Country</th>
<th>Teams</th>
<th>Participants</th>
<th>Tracks</th>
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Results of PACE 2019
# Results of Track 1: Vertex Cover

- **Track 1a: Minimum Vertex Cover**

<table>
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<tr>
<th>POS</th>
<th>Team</th>
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<th>TLE</th>
<th>RTE</th>
<th>$t_{sum}[h]$</th>
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<td>69</td>
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<td>52.1</td>
</tr>
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</table>
This is to certify that the 2019 PACE Program Committee recognizes

Falko Hegerfeld and Florian Nelles
Humboldt-Universität zu Berlin, Germany

for

Eighth Place in Track 1A: Vertex Cover

Johannes K. Fichte, TU Dresden
Markus Hecher, TU Wien

2019 PACE Program Committee Co-chairs
## Results of Track 1: Vertex Cover

- **Track 1a: Minimum Vertex Cover**

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**Vasily Alferov**
National Research University Higher School of Economics, Russia

for

**Seventh Place in Track 1A: Vertex Cover**

225 €

__________________________  ________________________
Johannes K. Fichte, TU Dresden  Markus Hecher, TU Wien

*2019 PACE Program Committee Co-chairs*
## Results of Track 1: Vertex Cover

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**Jiehua Chen**  
University of Warsaw, Poland

**and**

**Sven Grottke**  
TU Berlin, Germany

for

**Sixth Place in Track 1A: Vertex Cover**

250 €

__________________________  __________________________
Johannes K. Fichte, TU Dresden  Markus Hecher, TU Wien

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This is to certify that the 2019 PACE Program Committee recognizes

Aleksander Figiel

TU Berlin, Germany

for

Fifth Place in Track 1A: Vertex Cover

275 €

Johannes K. Fichte, TU Dresden

Markus Hecher, TU Wien

2019 PACE Program Committee Co-chairs
Results of Track 1: Vertex Cover

- Track 1a: Minimum Vertex Cover

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This is to certify that the 2019 PACE Program Committee recognizes

Christophe Crespelle, Eduard Eiben, and Kirill Simonov
University of Bergen, Norway
for
Fourth Place in Track 1A: Vertex Cover

300 €

Johannes K. Fichte, TU Dresden
Markus Hecher, TU Wien

2019 PACE Program Committee Co-chairs
Results of Track 1: Vertex Cover

- Track 1a: Minimum Vertex Cover

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Sándor Szabó and Bogdán Zaválnij
University of Pecs, Hungary Hungarian Academy of Sciences, Hungary

for
Third Place in Track 1A: Vertex Cover

450 €

Johannes K. Fichte, TU Dresden
Markus Hecher, TU Wien

2019 PACE Program Committee Co-chairs
## Results of Track 1: Vertex Cover

- **Track 1a: Minimum Vertex Cover**

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</table>
This is to certify that the 2019 PACE Program Committee recognizes

**Patrick Prosser and James Trimble**
University of Glasgow, Scotland

for

**Second Place in Track 1A: Vertex Cover**

450 €

__________________________  _________________________
Johannes K. Fichte, TU Dresden  Markus Hecher, TU Wien

2019 PACE Program Committee Co-chairs
Results of Track 1: Vertex Cover

- Track 1a: Minimum Vertex Cover

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</table>
This is to certify that the 2019 PACE Program Committee recognizes

**Demian Hespe, Sebastian Lamm, Christian Schulz, and Darren Strash**

Karlsruhe Institute of Technology, Germany  University of Vienna, Austria  Hamilton College, USA

for

**First Place in Track 1A: Vertex Cover**

750 €

______________________________  ________________________________
Johannes K. Fichte, TU Dresden  Markus Hecher, TU Wien

2019 PACE Program Committee Co-chairs
# Results of Track 1: Vertex Cover

- **Track 1a: Minimum Vertex Cover**

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Results of Track 2: Hypertree Decompositions
Results of Track 2: Hypertree Decompositions

- **Track 2a: MinHypertreeWidth**

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This is to certify that the 2019 PACE Program Committee recognizes

Patrick Prosser and James Trimble
University of Glasgow, Scotland

for
Third Place in Track 2A: Exact Hypertree Width

__________________________  ________________________
Johannes K. Fichte, TU Dresden  Markus Hecher, TU Wien

2019 PACE Program Committee Co-chairs
Results of Track 2: Hypertree Decompositions

- **Track 2a: MinHypertreeWidth**

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This is to certify that the 2019 PACE Program Committee recognizes

Davide Mario Longo
TU Wien
for
Second Place in Track 2A: Exact Hypertree Width

Johannes K. Fichte, TU Dresden
Markus Hecher, TU Wien

2019 PACE Program Committee Co-chairs
Results of Track 2: Hypertree Decompositions

- **Track 2a: MinHypertreeWidth**

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This is to certify that the 2019 PACE Program Committee recognizes

André Schidler and Stefan Szeider
TU Dresden		TU Wien

for
First Place in Track 2A: Exact Hypertree Width

Johannes K. Fichte, TU Dresden
Markus Hecher, TU Wien

2019 PACE Program Committee Co-chairs
Results of Track 2: Hypertree Decompositions

- **Track 2a: MinHypertreeWidth**

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This is to certify that the 2019 PACE Program Committee recognizes

**André Schidler and Stefan Szeider**

TU Dresden  
TU Wien

for

Third Place in Track 2B: Heuristic Hypertree Width

__________________________  _______________________
Johannes K. Fichte, TU Dresden  Markus Hecher, TU Wien

2019 PACE Program Committee Co-chairs
Results of Track 2: Hypertree Decompositions

- **Track 2a: MinHypertreeWidth**

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- **Track 2b: HeurHypertreeWidth**

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</table>
This is to certify that the 2019 PACE Program Committee recognizes

Davide Mario Longo
TU Wien
for
Second Place in Track 2B: Heuristic Hypertree Width

Johannes K. Fichte, TU Dresden
Markus Hecher, TU Wien

2019 PACE Program Committee Co-chairs
Results of Track 2: Hypertree Decompositions

- **Track 2a: MinHypertreeWidth**

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- **Track 2b: HeurHypertreeWidth**

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Patrick Prosser and James Trimble
University of Glasgow, Scotland

for

First Place in Track 2B: Heuristic Hypertree Width

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2019 PACE Program Committee Co-chairs
Conclusion & Future of PACE
Lessons Learned

- **Solver description and public library essential**
  - Maybe set solver description (abstract) deadline even at the beginning
- **Selecting instances of moderate difficulty (vertex cover)**
  - Possible, but not easy
  - Requires to collect numerous instances
- **Problems and instances should be ready by the end of September**
  - Some students lost attention due to late problem announcement
- **Cluster resources essential**
  - optil.io troubles during final submission phase
  - optil.io runtime difference was in some cases up to 7 minutes between same instance + solver
- **Score hard to comprehend for submitters**
  - limitation of optil.io: normalized scoreboard 0..1 depending on performance of individual solver and instance
Future Editions

- Next year PACE Deadline will be later
- Process of selecting new PCs ongoing

Problems?

- Subscribe to the newsletter and stay tuned!

pacechallenge.org

Hope we see you at PACE 2020.
The Winning Team of Track 1a (Vertex Cover)
WeGotYouCovered
The Winning Solver from the PACE 2019 Implementation Challenge, Vertex Cover Track

IPEC’19 · September 11, 2019
Demian Hespe, Sebastian Lamm, Christian Schulz, Darren Strash
Vertex Cover and Complementary Problems

Input graph

- Vertex cover
- Independent Set
- Clique
Techniques

Kernelization

Branch-and-Bound

Branch-and-Reduce

Iterated Local Search

- Reduce
- Backtrack
- Branch
- Reduce
- (1,2)-Swap
Kernelization [AI2016]

- Technique from FPT algorithms
- Applies rich set of reduction rules
- Significantly reduces graph size
Iterated Local Search [ARW2012]

- Originally developed for independent sets
- Perturbation to escape local optima
- Can often find (near-)optimal solutions
Branch and Reduce [AI2016]

- Reduce graph after each branch
- Additional branching rules to reduce graph size
- Prune search based on lower bounds
Branch and Bound [LJM2017]

- Originally developed for maximum cliques
- Incremental MaxSAT reasoning to prune search
- Combination of static and dynamic vertex ordering
Algorithm Overview

1. Input Graph
   - Kernelization

2. Kernel
   - Initial Solution
     - Iterated Local Search

3. 6. Branch-and-Bound
    - long run

4. 5. Branch-and-Reduce
    - short burst
    - Branch-and-Bound
    - short burst
    - Branch-and-Reduce
    - long run
Algorithm Overview

1. Input Graph
2. Kernelization
3. Kernel
4. Iterated Local Search
5. Initial Solution
6. Branch-and-Bound
   long run
7. Branch-and-Reduce
   short burst
8. Branch-and-Bound
   short burst
9. Branch-and-Reduce
   long run
Algorithm Overview

1. Input Graph
   - Kernelization

2. Kernel
   - Iterated Local Search

3. Initial Solution
   - Branch-and-Reduce (short burst)

4. Initial Solution
   - Branch-and-Bound (short burst)

5. Initial Solution
   - Branch-and-Reduce (long run)

6. Initial Solution
   - Branch-and-Bound (long run)
Algorithm Overview

1. Input Graph
   Kernelization
   1. Kernel

2. Initial Solution
   Iterated Local Search
   2. Initial Solution

3. Branch-and-Reduce
   short burst
   3. Branch-and-Reduce
   short burst

4. Branch-and-Bound
   short burst
   4. Branch-and-Bound
   short burst

5. Branch-and-Reduce
   long run
   5. Branch-and-Reduce
   long run

6. Branch-and-Bound
   long run
   6. Branch-and-Bound
   long run
Algorithm Overview

1. Input Graph

2. Kernelization

3. Kernel

4. Iterated Local Search

5. Initial Solution

6. 6. Branch-and-Bound
    long run

7. 3. Branch-and-Reduce
    short burst

8. 4. Branch-and-Bound
    short burst

9. 5. Branch-and-Reduce
    long run
Algorithm Overview

1. Input Graph
   - Kernelization
   - Kernel

2. Initial Solution
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3. Branch-and-Reduce
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6. Branch-and-Bound
   - long run
Instances Solved Over Time

- **Instances solved**
- **Time t (s)**

- **Lines and Labels**
  - BnB
  - Kern. + BnB
  - ILS + BnR
  - WeGotYouCovered
  - BnR
References


Thanks again for participating

See you outside at the Poster Session & PACE2020