Graph Modification Problems

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Description

The *P vs. NP* question is the most important and famous open question in Theoretical Computer Science. Almost all interesting computational problems arising from theory and applications are NP-complete, and graph problems are highly central in the theory of NP-completeness. It is well known that graphs, as well as providing a natural model for describing a wide range of real life problems that need algorithmic solutions, are involved in many of the most fundamental NP-complete problems. What is perhaps not so well known is that many of the famous NP-complete graph problems can be viewed as *graph modification problems*. In this proposed seminar we will systematically study how to cope with the intractability of NP-hard graph modification problems from the perspective of Parameterized Algorithms.

In a graph modification problem we are given a graph G, and the objective is to modify G by prescribed operations such that the resulting graph satisfies a certain property. For an example, Clique and Vertex Cover are two of the first NP-complete problems to be taught in complexity courses. The two problems can be viewed as *vertex deletion* problems; in the Vertex Cover problem the objective is to determine whether at most k vertices can be *deleted* from G so that the remaining graph has no edges. On the other hand, Clique can be restated as whether at most $n - k$ vertices can be *deleted* from G so that the remaining graph is complete. By allowing operations other than vertex deletions we obtain other graph modification problems. For example, if we only allow the operation of deleting edges, we get *edge deletion problems*; if we only allow the operation of *adding* edges we get *completion problems*; if we allow the combination of both deleting and adding edges, we get *editing problems*; while only allowing *edge contractions* yields *edge contraction problems*. Let us see how some important problems fit into this framework. Vertex Cover and Feedback Vertex Set are vertex deletion problems, Cluster Editing is an editing problem into the class of *cluster graphs*. Minimum Fill-in is a completion problem into the class of *chordal graphs*, while Odd Cycle Transversal has both a vertex deletion and an edge deletion version, and the goal here is to obtain a *bipartite graph*.

In all of the examples above the objective is to minimize the number of operations used. Sometimes we are not interested in the number of applied operations, but rather whether it is possible at all to use the allowed operations to modify the input graph G to obtain a graph with the desired properties. For example in the Induced Subgraph Isomorphism problem the objective is to delete vertices from G such that it becomes isomorphic to a given graph H. If additionally edge deletions are allwed we get the Subgraph Isomorphism problem while Minor Containment allows both vertex and edge deletions and edge contractions.

In other cases the goal is to minimize a parameter of the resulting graph after the application of the operations. The well-known Treewidth, Pathwidth, Bandwidth and Tree-Depth problems can all be reformulated as completion problems where the goal

is to minimize the size of the maximal clique in the resulting graph. In the TREEWIDTH problem the output graph must be *chordal*, while the three other problems require the output graph to be *interval*, *proper interval* and *trivially perfect*, respectively. These problems are heavily motivated from various application fields, such as biology (in particular phylogeny and DNA construction), data similarity in large sets, computer vision, sparse matrix computations, and image processing. More importantly, however, exact or approximate solutions to these completion problems are frequently used as subroutines in algorithms for seemingly unrelated graph problems.

Graph modification problems have attracted much attention in the field of Parameterized Algorithms. A graph problem with input G and k, parameterized by k, is called *fixed-parameter tractable* if there is an algorithm solving it in time $f(k) \cdot n^{O(1)}$, where f is a (typically exponential) function that does not depend on G, and n is the number of vertices in G. Several of the above listed problems are fixed-parameter tractable; however for example CLIQUE and BANDWIDTH are known not to be fixed parameter tractable assuming widely believed complexity assumptions.

As we can see from the above examples, there is a strong connection between graph modification problems and *graph classes*. A graph class is simply a set of graphs satisfying some common properties. Interestingly, some of the principal algorithmic graph problems correspond to completion problems into graph classes which have traditionally not been considered as important or large enough to warrant extensive study (such as trivially perfect graphs). The main objective of this proposal is to bring together experts within Parameterized Algorithms and experts within Graph Classes to join forces on graph modification problems. Experts within Graph Classes have traditionally concentrated on polynomial-time algorithms for NP-complete problems restricted to inputs of a specific type. In particular, the focus in Graph Classes is usually on the *input* of the problem. In the setting of graph modification problems we have no restrictions on the input graph, but the problem definitions dictate which graph class the *output* graph should belong to. Looking at traditional graph problems from the perspective of graph modification problems will potentially allow attacking these problems using *both* all the known properties of the target graph class *and* using all the well developed tools of Parameterized Algorithms.

As we have seen, in many graph modification problems the objective is to change G into a graph belonging to a particular graph class by as few operations as possible. Since the problems themselves are NP-hard, researchers have turned to studying *minimal* operation sequences that change the input graph into a graph in the class. A sequence of operations is minimal if no subsequence of operations yields a graph in the graph class. For an example in MINIMUM FILL-IN the aim is to add as few edges as possible to the input graph G to make it chordal. The study of *minimal triangulations*, that is inclusion *minimal* edge sets whose addition makes the graph chordal, has led to faster algorithms for MINIMUM FILL-IN and TREEWIDTH. Additionally, minimal triangulations have recently been used to give faster algorithms for seemingly unrelated problems such as FEEDBACK VERTEX SET, PLANAR VERTEX DELETION and INDUCED SUBGRAPH ISOMORPHISM.

We believe that similar breakthrough results can be obtained by studying minimal operation sequences that change the input graph to other graph classes. Studying minimal operation sequences that make G an interval graph is particularly interesting, as this could help resolve two of the most interesting open problems in the field; whether INTERVAL DELETION is fixed-parameter tractable and whether INTERVAL COMPLETION has a polynomial kernel. We think that a better understanding of minimal operation sequences that make G an interval graph could be used to give faster algorithms for other problems as well.

Both the field of Graph Classes and the field of Parameterized Algorithms have independently flourished and gained great interest and success during the last two decades. The interest is constantly growing, which is evidenced by the thousands of papers published in each field, and the increasing number of papers from each field being accepted to the highest level theoretical computer science conferences, like STOC, FOCS, SODA, and ICALP. We would also like to mention that both national funding agencies and the European Research Council have recently granted several large proposals, including ERC starting and advanced grants, within these fields. In addition, each of these fields have a number of regular workshops and meetings, which we will list in the next section. Already several prominent researchers are working in both areas; however there is a great potential in bringing the experts of both fields together to work on important graph problems from the perspective of graph modification with the aim that several of the hard problems arising in real applications will eventually find practical solutions. The proposed seminar would provide an excellent opportunity for this.

To summarize, the goal of this proposal is to bring together experts in

- Graph classes
- Parameterized algorithms, and the closely related field of Exact exponential time algorithms

to find solutions to the following challenges:

- Bring down the running time of best known algorithms on problems that can be formulated as graph modification problems. There has been very promising progress on some problems recently, like the running time of Feedback Vertex Set which has been successively improved from $37.7^k n^{O(1)}$ to $10.57^k n^{O(1)}$, $5^k n^{O(1)}$, $3.83^k n^{O(1)}$, and randomized $3^k n^{O(1)}$ (FOCS 2011). Another exciting result is the recent subexponential time algorithm for the solution of Minimum Fill-In (SODA 2012), which is a first of its kind.
- Provide new characterizations of famous graph modification problems that might help solving other problems. As an example, in addition to the results mentioned above, the knowledge on chordal graphs and treewidth has given some exciting new results on separators and modifications into bipartite graphs.
- Provide new characterizations of important graph problems as graph modification problems. For some very important graph parameters, like *clique-width*, we do not have any tractability results in general, either in form of parameterized algorithms or exact exponential time algorithms. This is closely connected to the fact that we do not yet have a characterization of clique-width as a graph modification problem. Such a characterization would be of great help for pursuing tractability of its computation.

For each of these mentioned challenges, we see a great potential for important new results along the lines of the mentioned examples.

Relation to recent Dagstuhl Seminars and other conferences

Dagstuhl Seminars

(Upcoming) Seminar 13421 - Algorithms for Optimization Problems in Planar Graphs, October 2013, organized by G. Borradaile, P. Klein, D. Marx, and C. Mathieu. This seminar is related to ours as it also concerns coping with NP-hard problems and Graph Classes. However, it concerns only the class of planar graphs. Furthermore, whereas the *input* is restricted to planar graphs here, in our proposal the graph classes appear in the *output*.

(Upcoming) Seminar 12241 - Data Reduction and Problem Kernels, June 2012, organized by M. Fellows, J. Guo, D. Marx, and S. Saurabh. This seminar is related to ours as its topic is one of the subfields of Parameterized Algorithms, but it does not concentrate on graph modification problems using Graph Classes.

Seminar 11182 - Exploiting graph structure to cope with hard problems, May 2011, organized by A. Brandstädt, M. Golumbic, P. Heggernes, and R. McConnell. This seminar is highly related to ours as it concerns graph classes and how to cope with hard problems on these using various techniques. The difference from the proposed seminar is that there the *input* graphs are required to belong to graph classes, whereas in the proposed seminar the input graphs are not restricted, but the problem definition translates as requiring the *output* graph to belong to some graph class.

Seminar 11071 - Theory and Applications of Graph Searching Problems, February 2011, organized by F. Fomin, P. Fraigniaud, S. Kreutzer, D. Thilikos. This seminar is related to ours as some versions of graph searching are equivalent to well known width parameters and completion problems into chordal and interval graphs.

Seminar 10441: Exact Complexity of NP-hard Problems, May 2010, organized by T. Husfeldt, D. Kratsch, R. Paturi, G. Sorkin. This seminar is related to ours since it also concerns hard problems and how to cope with them, but there is no focus on Graph Classes or graph modification problems.

Seminar 09511: Parameterized complexity and approximation algorithms, December 2009, organized by E. Demaine, M. HajiAghayi, and D. Marx. This seminar overlaps with the proposed seminar in the field of Parameterized Algorithms, but whereas we combine it with Graph Classes, they combine it with Approximation Algorithms.

Seminar 07211: Exact, Approximative, Robust and Certifying Algorithms on Particular Graph Classes, May 2007, organized by A. Brandstädt, K. Jansen, D. Kratsch, and J. Spinrad. This is related to ours as it also concerns Graph Classes. However, the whereas restrictions are placed on the *input* in this seminar, in our proposal the problems dictate restrictions on the *output* in form of belonging to a graph class.

Seminar 04221: Robust and Approximative Algorithms on Particular Graph Classes, April 2004, organized by A. Brandstädt, D. Corneil, K. Jansen, and J. Spinrad. The same can be said about this seminar as the above seminar, with respect to relation to our proposed seminar.

Seminar 01251: Graph Decompositions and Algorithmic Applications, June 2001, organized by A. Brandstädt and J.Spinrad (Vanderbilt US). This seminar overlaps with the proposed seminar only in width parameters corresponding to graph decomposition.

Seminar 01311: Parameterized Complexity, August 2001, organized by R. Downey, M.

Fellows, R. Niedermeier, and P. Rossmanith. This is a broader seminar on the field of Parameterized Algorithms and Parameterized Complexity.

Other conferences

The following regular conferences contain contributions related to the topics of the proposed seminar.

The annual conference *WG - Graph Theoretic Concepts in Computer Science*, which was organized for the 37th time this year in Czech Republic, accepts high quality contributions in the field. As evident from the title, this conference is much broader in scope than our proposed seminar.

The bi-annual workshop *GROW - Graph classes, Optimization, and Width parameters*, which is organized for the 5th time this year in Korea, invites researchers in the fields mentioned in the title. However, the focus is not necessarily on hard problems, and the algorithmic tools mentioned in our proposed seminar are neither given special emphasis in these meetings.

The annual conference *IPEC - International Symposium on Parameterized and Exact Computation*, which was organized for the 6th time this year in Germany, has as its scope all aspects of Parameterized and Exact Computation, both algorithms and complexity results. Although Parameterized Algorithms is also a part of our focus, the scope is this conference is of course much broader.

The annual workshop *WorKer - Workshop on Kernelization*, which was organized for the 3rd time this year in Austria, focuses on polynomial time preprocessing methods to get smaller equivalent problem instances that can be solved by brute force. Kernelization can be considered as a subfield of Parameterized Algorithms, and hence it is related to our topics and the studied problems contain also graph modification problems. However, in our proposed seminar we will not restrict ourselves to the method of kernelization.

Information about the organizers

The three organizers of this proposed seminar all have their background both in Graph Classes and in Parameterized Algorithms and Complexity. In age, gender, and localization, they cover to a large extent the required qualities of Dagstuhl Seminar organizers. All three organizers are currently leading large research grants within the topics of this proposed seminar.

Hans Bodlaender is one of the most prominent and established experts in the field of Parameterized and Exact Computations. Since his early career he has been very active on algorithms involving graph classes, especially problems related to chordal graphs. At the same time, he was among the first researchers to contribute to the younger field of Parameterized Algorithms, and very quickly he became one of the main contributors and promoters of the field. Pinar Heggernes is one of the (unfortunately) few female experts in the field of Graph Classes and coping with intractability using structure. She is also very active in the field of Parameterized Algorithms, especially on graph modification problems. She has experience in organizing a Dagstuhl Seminar. Daniel Lokshtanov, despite his young age, is already one of the leading experts in the field of Parameterized Algorithms and Complexity. At the same time, he continuously publishes results related to algorithms on Graph Classes. The three organizers are the authors or co-authors of in total more than 330 distinct published papers.

More details about the organizers are given in the following CVs.

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Employment

2003: Associate professor, Utrecht University, the Netherlands

1987 - 2003: Assistant professor, Utrecht University, the Netherlands

1987: Postdoc, M.I.T., Boston, USA

1983 - 1986: PhD student, Utrecht University, the Netherlands

Education

1986: PhD in Computer Science, Utrecht University, the Netherlands

Academic recognition and service

Program committee member of conferences: STACS 2012, WALCOM 2012, IPEC 2011, TAMC 2010, ESA 2010, SWAT 2010, IWPEC 2009, TAMC 2009, WG 2009, COCOA 2008, AAIM 2007, WG 2007, SOFSEM 2007, AAIM 2006, IWPEC 2006, ICALP 2005, WG 2005, IWPEC 2004, WG 2004, WG 2003, WADS 2003, ISAAC 2002, WG 2002, WG 2001, WG 2000, ESA 1999, WG 1999, WG 1998, SIROCCO 1997, WG 1997, CIAC 1997, WG 1996, STACS 1993.

Chair of program committee: IWPEC 2006; WG 2003.

Conference organisation: WORKER 2010 (Lorentz Institute Leiden); WG 2003

Chair steering committee WG (2007-now); I(W)PEC (2009 - 2011).

Selected invited lectures: ALGO 2009; SIROCCO 2007; WG 2006; SOFSEM 2005; Int. Conf. Graph Theory 2000; MFCS 1997.

Selected publications

[1] Hans L. Bodlaender and Thomas C. van Dijk. A cubic kernel for feedback vertex set and loop cutset. *Theory of Computing Systems*, 46:566–597, 2010.

[2] Hans L. Bodlaender, Michael R. Fellows, Michael A. Langston, Mark A. Ragan, Frances A. Rosamond, and Mark Weyer. Quadratic kernelization for convex recoloring of trees. Information and Computation, to appear.

[3] Hans L. Bodlaender, Bart M. P. Jansen, and Stefan Kratsch. Cross-composition: A new technique for kernelization lower bounds. In Thomas Schwentick and Christoph Dürr, editors, *Proceedings 28th International Symposium on Theoretical Aspects of Computer Science, STACS 2011*, volume 9 of *Leibniz International Proceedings in Informatics (LIPIcs)*, pages 165–176. Schloss Dagstuhl – Leibnitz-Zentrum fuer Informatik, 2011.

[4] Bart M. P. Jansen and Hans L. Bodlaender. Vertex cover kernelization revisited: Upper and lower bounds for a refined parameter. In Thomas Schwentick and Christoph Dürr, editors, *Proceedings 28th International Symposium on Theoretical Aspects of Computer Science, STACS 2011*, volume 9 of *Leibniz International Proceedings in Informatics (LIPIcs)*, pages 177–188. Schloss Dagstuhl – Leibnitz-Zentrum fuer Informatik, 2011.

[5] Hans L. Bodlaender, Michael R. Fellows, Pinar Heggernes, Federico Mancini, Charis Papadopoulos, and Frances Rosamond. Clustering with partial information. *Theoretical Computer Science*, 411:1202–1211, 2010.

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Employment

Full professor of computer science, Department of Informatics, University of Bergen, Norway (since 2003. Associate professor between 2001 and 2003.)

Courtesy professor of computer science, Department of Computer and Information Science, University of Oregon, Eugene, USA (September 2007 - June 2008).

Postdoctoral fellowship, Research Council of Norway (1999-2000).

Senior Scientist, The supercomputing center Parallab, Bergen, Norway (1997-1999).

Education

2002: University Pedagogics, University of Bergen, Norway.

1996: PhD in Computer Science, University of Bergen, Norway.

Academic recognition and service

Program committee member of conferences ESA 2012, IPEC 2011, WG 2011, SIROCCO 2010, COCOON 2010, FAW 2009, WG 2009, FAW 2008, SWAT 2006, WG 2006, SWAT 2002.

Organizer of conferences SWAT 2010, GROW 2009, WG 2006, ALGO 2004, SWAT 2000, and of Dagstuhl Seminar 11182 (2011).

Steering committee member of GROW workshops.

Managing guest editor of three special issues of *Discrete Applied Mathematics* on Graph Classes, Optimization, and Width Parameters.

Member of several national planning committees and boards of research programmes within information technology at the Research Council of Norway.

Project manager of several research grants from the Research Council of Norway.

Selected publications

[1] P. Heggernes, P. van 't Hof, D. Lokshtanov, and C. Paul: Obtaining a Bipartite Graph by Contracting Few Edges. *FSTTCS 2011*, LIPIcs. To appear.

[2] H. Bodlaender, P. Heggernes, and Y. Villanger: Faster parameterized algorithms for Minimum Fill-In. *Algorithmica*. To appear.

[3] P. Heggernes, C. Paul, J. A. Telle, and Y. Villanger: Interval Completion is Fixed Parameter Tractable. *SIAM Journal on Computing* 38 (2009): 2007-2020. (Preliminary version appeared at *STOC 2007*).

[4] P. Heggernes, K. Suchan, I. Todinca, and Y. Villanger: Characterizing minimal interval completions: Towards better understanding of profile and pathwidth *STACS 2007*, LNCS 4393: 236 - 247, Springer.

[5] P. Heggernes: Minimal triangulations of graphs - A survey. *Discrete Mathematics* 306-3 (2006): 297-317.

Daniel Lokshtanov

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Employment

Simons Postdoctoral Fellow, Department of Computer Science and Engineering, University of California San Diego, USA.

Research Fellow, Department of Informatics, University of Bergen, Aug 2009 - Aug 2010

Education

2009: PhD in Computer Science, University of Bergen, Norway.

Academic recognition and service

Program committee member of conferences SWAT 2012, IPEC 2011, ESA 2011, MFCS 2011, IPEC 2010.

Invited Speaker at FCT 2011 and MFCS 2010 conferences, GROW 2011, WORKER 2011, 2010 CIRM Workshop on Graph Decomposition and WORKER 2010 workshops, and the AGAPE 2009 Spring School on Exact and Parameterized Algorithms.

Received the Meltzer Outstanding Young Researcher Award for 2009.

Organizer of the WORKER 2009 workshop. Organizing committee member of SWAT 2010.

Awarded Bergen Science Foundation Research Grant

Selected publications

[1] F.V Fomin, D. Lokshtanov and S. Saurabh: Bidimensionality and Geomertric Graphs. Proceedings of ACM-SIAM Symposium on Discrete Algorithms (*SODA 2012*), SIAM Proceedings: To appear.

[2] D. Lokshtanov, D. Marx and S. Saurabh: Known Algorithms on Graphs of Bounded Treewidth are Probably Optimal. Proceedings of ACM-SIAM Symposium on Discrete Algorithms (*SODA 2011*), pages 777-789.

[3] F.V. Fomin, P.A. Golovach, D. Lokshtanov and S. Saurabh: Intractability of Clique-Width Parameterizations. *SIAM Journal on Computing* 39(5): 1941-1956 (2010). A preliminary version of the paper appeared in the proceedings of ACM-SIAM Symposium on Discrete Algorithms (*SODA 2009*) under the title "Clique-width: on the price of generality".

[4] H.L. Bodlaender, F.V. Fomin, D. Lokshtanov, E. Penninkx, S. Saurabh and D.M. Thilikos. (Meta) Kernelization. Proceedings of IEEE Symposium on Foundations of Computer Science (*FOCS 2009*), pages 629-638.

[5] N. Alon, D. Lokshtanov and S. Saurabh: Fast FAST. Proceedings of the International Colloquium on Automata, Languages and Programming (*ICALP 2009*) LNCS 5555, pages 49-58, Springer.

List of invitees

Many of the invitees are established researchers in several areas and leading experts of their specialization. Here we only list the areas of their expertise which are most relevant to this seminar.

1. Isolde Adler *(female)* : Parameterized algorithms
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2. **Hans Bodlaender**
3. Rémy Belmonte *(young researcher)* : Graph classes
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4. Andreas Brandstädt : Graph classes
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9. Marek Cygan *(young researcher)* : Parameterized and exact algorithms
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13. Mike Fellows : Parameterized algorithms
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22. Michel Habib : Graph classes
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23. **Pinar Heggernes**

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25. Pim van 't Hof *(young researcher)* : Graph classes and parameterized algorithms
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37. **Daniel Lokshtanov**

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39. Paul Medvedev : Bioinformatics and Graph Algorithms
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