

Hans L. Bodlaender  
Michael A. Langston (Eds.)

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# Parameterized and Exact Computation

Second International Workshop, IWPEC 2006  
Zürich, Switzerland, September 2006  
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## Volume Editors

Hans L. Bodlaender  
Utrecht University  
Department of Information and Computing Sciences  
P.O. Box 80089, 3508 TB Utrecht, The Netherlands  
E-mail: hansb@cs.uu.nl

Michael A. Langston  
University of Tennessee  
Department of Computer Science  
203 Claxton Complex, 1122 Volunteer Boulevard, Knoxville, TN 37996-3450, USA  
E-mail: langston@cs.utk.edu

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# Preface

The Second International Workshop on Parameterized and Exact Computation (IWPEC) was held in Zürich, Switzerland, during September 13–15, 2006. It was organized as a component of ALGO 2006, which also hosted the 14<sup>th</sup> Annual European Symposium on Algorithms, the 6<sup>th</sup> Workshop on Algorithms in Bioinformatics, the 4<sup>th</sup> Workshop on Approximation and Online Algorithms, and the 6<sup>th</sup> Workshop on Algorithmic Methods and Models for Optimization of Railways.

This meeting was the second in the IWPEC series, with the first having been held in Bergen, Norway, during September 14–16, 2004. The field continues to experience rapid growth, in part due to its appeal as an alternative to traditional complexity theory, and in part due to the powerful practical applications it has spawned. IWPEC events are intended to cover research in all aspects of parameterized and exact computation and complexity, including but not limited to new techniques for the design and analysis of parameterized and exact algorithms, parameterized complexity theory, relationships between parameterized complexity and traditional complexity, applications of parameterized and exact computation, implementation issues and high-performance computing. A major goal is to disseminate the latest research results, including significant work-in-progress, and to identify, define and explore directions for future study.

The papers accepted for presentation and printed in these proceedings represent a diverse spectrum of the latest developments on parameterized and exact algorithm design, analysis, application and implementation. We hope that you will read them, and that you find the time spent a rewarding experience. Each submission was thoroughly reviewed by at least three members of the IWPEC 2006 Program Committee. We are certain that many of them will find their way to archival journal publication in more complete and polished form. We wish to thank all authors for contributing their work for review. Many more meritable papers were submitted than can be accommodated in the schedule. In addition, three invited lectures were given by leading experts in the field of parameterized and exact computation: Frank Dehne, Uwe Schöning, and Michael Fellows.

It has been a privilege to serve as Program Committee Co-chairs. Assembling this slate of first-rate papers would not have been possible without the tireless and professional efforts of the remainder of the IWPEC 2006 Program Committee, who are:

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We also wish to acknowledge the assistance of the numerous external reviewers who have been an immense technical help during committee deliberations.

Zürich, Switzerland  
September 2006

Hans Bodlaender and  
Michael A. Langston

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# Applying Modular Decomposition to Parameterized Bicluster Editing

Fábio Protti<sup>1</sup>, Maise Dantas da Silva<sup>2</sup>,  
and Jayme Luiz Szwarcfiter<sup>3</sup>

<sup>1</sup> Instituto de Matemática and Núcleo de Computação Eletrônica  
Universidade Federal do Rio de Janeiro  
Caixa Postal 2324, 20001-970, Rio de Janeiro, RJ, Brasil  
`fabiop@nce.ufrj.br`

<sup>2</sup> COPPE-Sistemas

Universidade Federal do Rio de Janeiro  
Caixa Postal 68511, 21945-970, Rio de Janeiro, RJ, Brasil  
`maiseds@cos.ufrj.br`

<sup>3</sup> Instituto de Matemática, Núcleo de Computação Eletrônica and COPPE-Sistemas  
Universidade Federal do Rio de Janeiro  
Caixa Postal 68511, 21945-970, Rio de Janeiro, RJ, Brasil  
`jayme@nce.ufrj.br`

**Abstract.** A graph  $G$  is said to be a *cluster graph* if  $G$  is a disjoint union of cliques (complete subgraphs), and a *bicluster graph* if  $G$  is a disjoint union of bicliques (complete bipartite subgraphs). In this work, we study the parameterized version of the NP-hard BICLUSTER GRAPH EDITING problem, which consists of obtaining a bicluster graph by making the minimum number of modifications in the edge set of an input bipartite graph. When at most  $k$  modifications are allowed in the edge set of any input graph (BICLUSTER( $k$ ) GRAPH EDITING problem), this problem is FPT, solvable in  $O(4^k m)$  time by applying a search tree algorithm. It is shown an algorithm with  $O(4^k + n + m)$  time, which uses a new strategy based on modular decomposition techniques. Furthermore, the same techniques lead to a new form of obtaining a problem kernel with  $O(k^2)$  vertices for the CLUSTER( $k$ ) GRAPH EDITING problem, in  $O(n + m)$  time. This problem consists of obtaining a cluster graph by modifying at most  $k$  edges in an input graph. A previous FPT algorithm for this problem was presented by Gramm *et al.* [11]. In their solution, a problem kernel with  $O(k^2)$  vertices and  $O(k^3)$  edges is built in  $O(n^3)$  time.

**Keywords:** NP-complete problems, fixed-parameter tractability, edge modification problems, cluster graphs, bicluster graphs.

## 1 Introduction

Many NP-hard problems can be formulated with a parameter  $k$ , so that polynomial-time algorithms can be designed for them when  $k$  is fixed. The parameterized complexity theory was developed by Downey and Fellows [6,7], as an alternative to deal with such problems. They defined the class of *fixed-parameter*

*tractable* (FPT) problems, which admit algorithms of complexity  $O(f(k)n^\alpha)$ , where  $f$  is an arbitrary function and  $\alpha$  is a constant independent of both  $n$  and  $k$ . They also defined a hierarchy of parameterized decision problem classes,  $FPT \subseteq W[1] \subseteq W[2] \subseteq \dots$ , with appropriate reducibility and completeness notions, and conjectured that each of the containments in this hierarchy is proper. More details about this theory can be found in [6,7,8,9].

Let  $u, v \in V(G)$ . An *edge modification* or *edge edition* with respect to  $u, v$  is either the deletion of  $(u, v)$  if  $(u, v) \in E(G)$ , or the addition of  $(u, v)$  if  $(u, v) \notin E(G)$ .

In this paper, we study the parameterized version of the BICLUSTER GRAPH EDITING problem. In the optimization version, this problem consists of editing the minimum number of edges in a bipartite graph so that it becomes a vertex-disjoint union of bicliques (complete bipartite subgraphs), called *bicluster graph*. The NP-hardness of this problem was proved by Amit [1]. The parameterized version of this problem is the BICLUSTER( $k$ ) GRAPH EDITING problem, whose goal is to obtain a bicluster graph by editing at most  $k$  edges from any input graph (not necessarily bipartite). This problem is FPT, solvable in  $O(4^k m)$  time by applying a search tree algorithm. We propose an  $O(4^k + n + m)$  time algorithm, which works in two stages: firstly, a problem kernel is built, using a new strategy based on modular decomposition. Following, a bounded search tree is applied.

By using this strategy based on modular decomposition, we propose a new form of obtaining a problem kernel for the CLUSTER( $k$ ) GRAPH EDITING problem, whose optimization version consists of editing the minimum number of edges from a graph so that it becomes a vertex-disjoint union of cliques (complete subgraphs), called *cluster graph*. This problem was studied by Shamir *et al.* [19] and proved to be NP-hard. The tractability of the parameterized version proceeds directly from Cai's result [4]. From the more general view of graph modification problems, Cai proved the fixed-parameter tractability of deciding whether an input graph can be transformed into a graph with a specified hereditary property by deleting vertices and/or edges, and adding edges, when the hereditary property can be characterized by a finite set of forbidden induced subgraphs. His result provides an  $O(3^k n^4)$  time algorithm for CLUSTER( $k$ ) GRAPH EDITING. In [11], Gramm *et al.* present an  $O(2.27^k + n^3)$  time algorithm, which builds a problem kernel with  $O(k^2)$  vertices and  $O(k^3)$  edges in  $O(n^3)$  time, and then applies a bounded search tree in  $O(2.27^k)$  time. In [12], the time complexity of the search tree algorithm was improved to  $O(1.92^k)$  time. We propose an algorithm that builds a problem kernel with  $O(k^2)$  vertices in  $O(n + m)$  time. For a more detailed study on edge modification problems, see [17].

This paper is organized as follows. Section 2 contains the definitions and notation used in the paper. In Section 3, we provide an overview about modular decomposition of graphs and propose some definitions used along this paper. In Section 4, the new FPT solution for BICLUSTER( $k$ ) GRAPH EDITING is explained. Finally, Section 5 presents how to obtain a problem kernel for CLUSTER( $k$ ) GRAPH EDITING in  $O(n + m)$  time.

## 2 Basic Definitions and Notation

In this work,  $G$  denotes a finite graph, without loops nor multiple edges. The vertex set and the edge set of  $G$  are denoted by  $V(G)$  and  $E(G)$ , respectively. Assume  $|V(G)| = n$  and  $|E(G)| = m$ .

A *clique* is a complete subgraph. A *cluster graph* is a vertex-disjoint union of cliques. It is easy to see that  $G$  is a cluster graph if and only if it contains no  $P_3$  as an induced subgraph.

A *biclique* is a complete bipartite subgraph. A *bicluster graph* is a vertex-disjoint union of bicliques. This class of graphs is the intersection of two other classes, bipartite graphs and cographs (graphs containing no  $P_4$  as an induced subgraph), inheriting therefore their forbidden induced subgraphs. Thus,  $G$  is a bicluster graph if and only if it contains no  $P_4$  nor  $C_{2k+1}$  as induced subgraphs.

An *edge modification set*  $F$  is a set of pairs of vertices, where each pair has a mark  $+$  or  $-$  such that:

- $+(a, b)$  represents the addition of the edge  $(a, b)$ ,
- $-(a, b)$  represents the deletion of the edge  $(a, b)$ .

$G + F$  represents the addition to  $G$  of the edges  $(a, b)$  marked by  $+(a, b)$  in  $F$  (assuming that they are not in  $E(G)$ ) and the deletion of the edges  $(a, b)$  marked by  $-(a, b)$  in  $F$  (assuming that they belong to  $E(G)$ ). Similarly,  $G - F$  represents the addition of the edges marked by  $-(a, b)$  in  $F$  and the deletion of the edges marked by  $+(a, b)$  in  $F$ . Clearly,  $G' = G + F$  if and only if  $G = G' - F$ .

In the remainder of this work,  $F$  denotes an edge modification set for  $G$ , and  $G'$  denotes the graph  $G + F$ .

## 3 Modular Decompositions of Graphs

Important references for this section are [2,5,10,13,14,15,16].

The subset  $M \subseteq V(G)$  is a *module* in  $G$  if for all  $u, v \in M$  and  $w \in V(G) \setminus M$ ,  $(u, w) \in E(G)$  if and only if  $(v, w) \in E(G)$ .

**Theorem 1.** *If  $X$  and  $Y$  are disjoint modules of a graph, then either every element of  $X$  is adjacent to every element of  $Y$  ("adjacent modules"), or no element of  $X$  is adjacent to an element of  $Y$  ("nonadjacent modules").*

If  $M = V(G)$  or  $|M| = 1$ , then  $M$  is a *trivial* module. All graphs have trivial modules. If  $G$  has no nontrivial modules, then  $G$  is called *prime*. A module  $M$  is *strong* if, for every module  $M'$ , either  $M \cap M' = \emptyset$  or one module is included into the other.

There exist three types of modules: *parallel*, *series* and *neighbourhood*. A module is *parallel* when the subgraph induced by its vertices is disconnected, *series* when the complement of the subgraph induced by its vertices is disconnected, and *neighbourhood* when both the subgraph induced by its vertices and its complement are connected.

The process of decomposing a graph into modules is called *modular decomposition*. The modular decomposition of  $G$  is represented by a *modular decomposition tree*  $T_G$ . The nodes of  $T_G$  correspond to strong modules of  $G$ . The root corresponds to  $V(G)$ , and the leaves correspond to all vertices of  $G$ . Each internal node of  $T_G$  is labeled  $P$  (parallel),  $S$  (series) or  $N$  (neighbourhood), according to the type of the module. The children of every internal node  $M$  of  $T_G$  are the maximal submodules of  $M$ . The modular decomposition tree of a graph is unique up to isomorphism and can be obtained in linear time [13].

As an important special case, modular decomposition trees containing only series and parallel internal nodes correspond precisely to the class of cographs. It is easy to see that  $P_4$  is the smallest nontrivial prime graph.

### 3.1 P-Quotient and s-Quotient Graphs

Let  $\Pi$  be a partition of  $V(G)$  such that each member of  $\Pi$  is a module. Then  $\Pi$  is said to be a *congruence partition*. The graph whose vertices are the members of  $\Pi$  and whose edges correspond to the adjacency relationships involving members of  $\Pi$  is called *quotient graph*  $G/\Pi$ .

In this section we define special types of auxiliary quotient graphs, namely the *p-quotient* and *s-quotient graphs*. Those graphs are obtained from specific congruence partitions, defined as follows.

**Definition 2.** Let  $\Pi$  be a congruence partition of  $V(G)$ .

1.  $\Pi$  is the **p-partition** of  $V(G)$  if, for every internal node  $M$  of  $T_G$ :
  - if  $M$  is labeled  $S$  or  $N$  then every leaf child of  $M$  is a unitary member of  $\Pi$ ;
  - if  $M$  is labeled  $P$ , then all leaf children of  $M$  form a member of  $\Pi$ .
2.  $\Pi$  is the **s-partition** of  $V(G)$  if, for every internal node  $M$  of  $T_G$ :
  - if  $M$  is labeled  $P$  or  $N$ , then every leaf child of  $M$  is a unitary member of  $\Pi$ ;
  - if  $M$  is labeled  $S$  then all leaf children of  $M$  form a member of  $\Pi$ .

Clearly, every member of the p-partition (s-partition) is a strong module in  $G$ . Since the modular decomposition tree of a graph is unique, the p-partition and the s-partition are also unique.

**Definition 3.** Let  $\Pi$  be a congruence partition of  $V(G)$ .

1. If  $\Pi$  is the p-partition of  $V(G)$ , then  $G/\Pi$  is the **p-quotient graph** of  $G$ , denoted by  $G_p$ .
2. If  $\Pi$  is the s-partition of  $V(G)$ , then  $G/\Pi$  is the **s-quotient graph** of  $G$ , denoted by  $G_s$ .

A vertex of  $G_p$  (resp.  $G_s$ ) corresponding to a member of  $\Pi$  with size larger than one is called *p-vertex* (resp. *s-vertex*), whereas a vertex corresponding to a unitary member  $\{v\}$  of  $\Pi$  is called *u-vertex*.

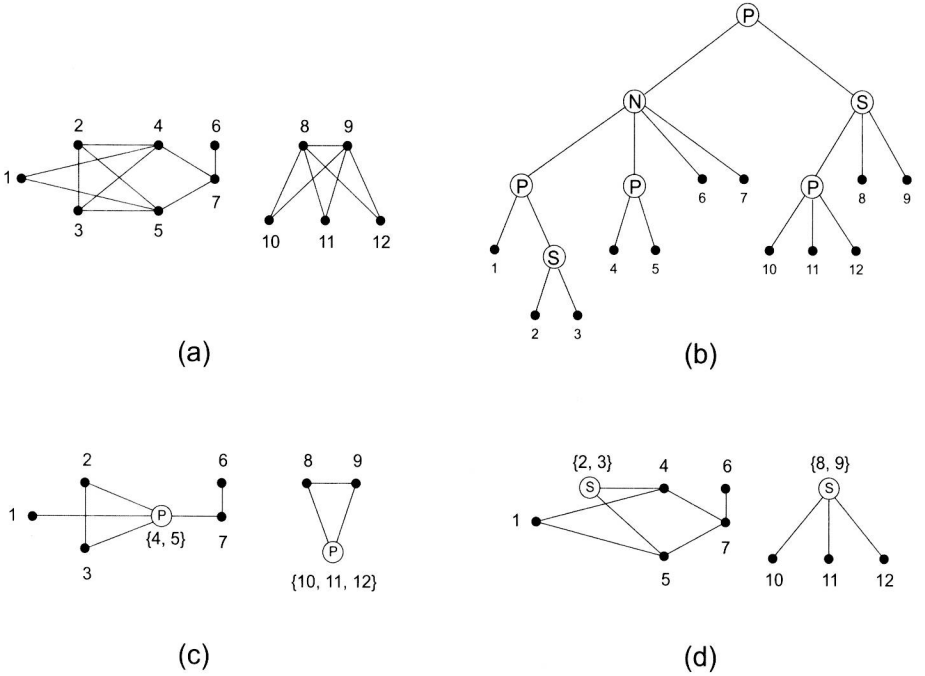
For simplicity, if a p-vertex (resp. s-vertex) corresponds to a module  $M \subseteq V(G)$ , then we write  $M$  to stand for both the module and the p-vertex (resp.



s-vertex); and if a  $u$ -vertex corresponds to a member  $\{v\}$  of  $\Pi$  then we write  $v$  to stand for the  $u$ -vertex. We also say that a vertex  $v \in V(G)$  belongs to a p-vertex  $M \in V(G_p)$  (resp. s-vertex  $M \in V(G_s)$ ) when  $v \in M$ .

If  $H$  is a p-quotient (resp. s-quotient) graph, denote by  $V_p(H)$  (resp.  $V_s(H)$ ) the set of p-vertices (resp. s-vertices) of  $H$ , and by  $V_u(H)$  the set of  $u$ -vertices of  $H$ .

Figure 1 depicts a graph  $G$ , its modular decomposition tree  $T_G$  and the graphs  $G_p$  and  $G_s$ , where p-vertices are graphically represented by the symbol  $\textcircled{P}$ , and s-vertices by  $\textcircled{S}$ .



**Fig. 1.** (a) A graph  $G$  (b) The modular decomposition tree  $T_G$  (c)  $G_p$  (d)  $G_s$

The next lemma presents useful bounds on the sizes of  $V_u(G'_p)$ ,  $V_p(G'_p)$  and  $V(G'_p)$  for the case of one edge modification in  $G$ .

**Lemma 4.** *If  $|F| = 1$  then the following inequalities hold:*

- (1)  $|V_u(G'_p)| \leq |V_u(G_p)| + 4$
- (2)  $|V_p(G'_p)| \leq |V_p(G_p)| + 2$
- (3)  $|V(G'_p)| \leq |V(G_p)| + 2$

**Proof.** Let  $(u, v)$  be the modified edge. The proof is based on the analysis of the local modifications made in  $G_p$  in order to obtain  $G'_p$ , by considering the new