Reconfiguration on sparse graphs

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Abstract. A vertex-subset graph problem $\mathcal{Q}$ defines which subsets of the vertices of an input graph are feasible solutions. A reconfiguration variant of a vertex-subset problem asks, given two feasible solutions S_s and S_t of size k, whether it is possible to transform S_s into S_t by a sequence of vertex additions and deletions such that each intermediate set is also a feasible solution of size bounded by k. We study reconfiguration variants of two classical vertex-subset problems, namely Independent Set and Dominating Set. We denote the former by ISR and the latter by DSR. Both ISR and DSR are PSPACE-complete on graphs of bounded bandwidth and W[1]-hard parameterized by k on general graphs. We show that ISR is fixed-parameter tractable parameterized by k when the input graph is of bounded degeneracy or nowhere dense. As a corollary, we answer positively an open question concerning the parameterized complexity of the problem on graphs of bounded treewidth. Moreover, our techniques generalize recent results showing that ISR is fixed-parameter tractable on planar graphs and graphs of bounded degree. For DSR, we show the problem fixed-parameter tractable parameterized by k when the input graph does not contain large bicliques, a class of graphs which includes degenerate and nowhere dense graphs.

1 Introduction

Given an n-vertex graph G and two vertices s and t in G, determining whether there exists a path and computing the length of the shortest path between s and t are two of the most fundamental graph problems. In the classical battle of P versus NP or "easy" versus "hard", both of these problems are on the easy side. That is, they can be solved in $poly(n)$ time, where $poly$ is any polynomial

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function. But what if our input consisted of a 2^n-vertex graph? Of course, we can no longer assume G to be part of the input, as reading the input alone requires more than $poly(n)$ time. Instead, we are given an oracle encoded using $poly(n)$ bits and that can, in constant or $poly(n)$ time, answer queries of the form "is u a vertex in G" or "is there an edge between u and v?". Given such an oracle and two vertices of the 2^n-vertex graph, can we still determine if there is a path or compute the length of the shortest path between s and t in $poly(n)$ time?

This seemingly artificial question is in fact quite natural and appears in many practical and theoretical problems. In particular, these are exactly the types of questions asked under the reconfiguration framework, the main subject of this work. Under the reconfiguration framework, instead of finding a feasible solution to some instance $\mathcal{I}$ of a search problem $\mathcal{Q}$, we are interested in structural and algorithmic questions related to the solution space of $\mathcal{Q}$. Naturally, given some adjacency relation $\mathcal{A}$ defined over feasible solutions of $\mathcal{Q}$, the solution space can be represented using a graph $R_{\mathcal{Q}}(\mathcal{I})$. $R_{\mathcal{Q}}(\mathcal{I})$ contains one node for each feasible solution of $\mathcal{Q}$ on instance $\mathcal{I}$ and two nodes share an edge whenever their corresponding solutions are adjacent under $\mathcal{A}$. An edge in $R_{\mathcal{Q}}(\mathcal{I})$ corresponds to a *reconfiguration step*, a walk in $R_{\mathcal{Q}}(\mathcal{I})$ is a sequence of such steps, a *reconfiguration sequence*, and $R_{\mathcal{Q}}(\mathcal{I})$ is a *reconfiguration graph*.

Studying problems related to reconfiguration graphs has received considerable attention in the literature [3, 12, 15, 16, 20, 21], the most popular problem being to determine whether there exists a reconfiguration sequence between two given feasible solutions/configurations. In many cases, this problem was shown PSPACE-hard in general, although some polynomial-time solvable restricted cases have been identified. For PSPACE-hard cases, it is not surprising that shortest paths between solutions can have exponential length. More surprising is that for most known polynomial-time solvable cases the diameter of the reconfiguration graph has been shown to be polynomial. Some of the problems that have been studied under the reconfiguration framework include Independent Set [19], Shortest Path [2], Coloring [4], Boolean Satisfiability [12], and Flip Distance [3, 5]. We refer the reader to the recent survey by van den Heuvel [27] for a detailed overview of reconfiguration problems and their applications. Recently, a systematic study of the parameterized complexity [9] of reconfiguration problems was initiated by Mouawad et al. [21]; various problems were identified where the problem was not only NP-hard (or PSPACE-hard), but also W-hard under various parameterizations. The reader is referred to [9] for more on parameterized complexity.

Overview of our results. In this work, we focus on reconfiguration variants of the Independent Set (IS) and Dominating Set (DS) problems. Given two independent sets I_s and I_t of a graph G such that $|I_s| = |I_t| = k$, the Independent Set Reconfiguration (ISR) problem asks whether there exists a sequence of independents sets $\sigma = \langle I_0, I_1, \ldots, I_\ell \rangle$, for some ℓ, such that:

(1) $I_0 = I_s$ and $I_\ell = I_t$,
(2) I_i is an independent set of G for all $0 \leq i \leq \ell$,

(3) $|\{I_i \setminus I_{i+1}\} \cup \{I_{i+1} \setminus I_i\}| = 1$ for all $0 \leq i < \ell$, and
(4) $k - 1 \leq |I_i| \leq k$ for all $0 \leq i \leq \ell$.

Alternatively, given a graph G and integer k, the reconfiguration graph $R_{\text{IS}}(G, k-1, k)$ has a node for each independent set of G of size k or $k - 1$ and two nodes are adjacent in $R_{\text{IS}}(G, k-1, k)$ whenever the corresponding independent sets can be obtained from one another by either the addition or the deletion of a single vertex. The reconfiguration graph $R_{\text{DS}}(G, k, k+1)$ is defined similarly for dominating sets. Hence, ISR and DSR can be formally stated as follows:

Independent Set Reconfiguration (ISR)
Input: Graph G, integer $k > 0$, and two independent sets I_s and I_t of size k
Question: Is there a path from I_s to I_t in $R_{\text{IS}}(G, k-1, k)$?

Dominating Set Reconfiguration (DSR)
Input: Graph G, integer $k > 0$, and two dominating sets D_s and D_t of size k
Question: Is there a path from D_s to D_t in $R_{\text{DS}}(G, k, k+1)$?

Note that since we only allow independent sets of size k and $k - 1$ the ISR problem is equivalent to reconfiguration under the token jumping model considered by Ito et al. [17, 18]. ISR is known to be PSPACE-complete on graphs of bounded bandwidth [28] (hence pathwidth and treewidth) and W[1]-hard when parameterized by k on general graphs [18]. On the positive side, the problem was shown fixed-parameter tractable, with parameter k, for graphs of bounded degree, planar graphs, and graphs excluding $K_{3,d}$ as a (not necessarily induced) subgraph, for any constant d [17, 18]. We push this boundary further by showing that the problem remains fixed-parameter tractable for graphs of bounded degeneracy and nowhere dense graphs. As a corollary, we answer positively an open question concerning the parameterized complexity of the problem parameterized by k on graphs of bounded treewidth.

For DSR, we show that the problem is fixed-parameter tractable, with parameter k, for graphs excluding $K_{d,d}$ as a (not necessarily induced) subgraph, for any constant d. Note that this class of graphs includes both nowhere dense and bounded degeneracy graphs and is the "largest" class on which the Dominating Set problem is known to be in FPT [25, 26].

Clearly, our main open question is whether ISR remains fixed-parameter tractable on graphs excluding $K_{d,d}$ as a subgraph. Intuitively, all of the classes we consider fall under the category of "sparse" graph classes. Hence, in some sense, one would not expect a sparse graph to have "too many" dominating sets of fixed small size k as n becomes larger and larger. For independent sets, the situation is reversed. As n grows larger, so does the number of independent sets of fixed size k. So it remains to be seen whether some structural properties of graphs excluding $K_{d,d}$ as a subgraph can be used to settle our open question or whether the problem becomes W[1]-hard. In the latter case, this would be the first example of a W[1]-hard problem (in general), which is in FPT on a class $\mathcal{C}$ of graphs but where the reconfiguration version is not; finding such a problem, we believe, is interesting in its own right. Another open question is whether we can adapt our results for ISR to find shortest reconfiguration sequences. Our algorithm for DSR does in fact guarantee shortest reconfiguration sequences but, as we shall see, the same does not hold for either of the two ISR algorithms. Due to space limitations, some proofs (marked with a star) have been omitted from the current version of the paper.

2 Preliminaries

For an in-depth review of general graph theoretic definitions we refer the reader to the book of Diestel [8]. Unless otherwise stated, we assume that each graph G is a simple, undirected graph with vertex set $V(G)$ and edge set $E(G)$, where $|V(G)| = n$ and $|E(G)| = m$. The *open neighborhood*, or simply *neighborhood*, of a vertex v is denoted by $N_G(v) = \{u \mid uv \in E(G)\}$, the *closed neighborhood* by $N_G[v] = N_G(v) \cup \{v\}$. Similarly, for a set of vertices $S \subseteq V(G)$, we define $N_G(S) = \{v \mid uv \in E(G), u \in S, v \notin S\}$ and $N_G[S] = N_G(S) \cup S$. The *degree* of a vertex is $|N_G(v)|$. We drop the subscript G when clear from context. A *subgraph* of G is a graph G' such that $V(G') \subseteq V(G)$ and $E(G') \subseteq E(G)$. The *induced subgraph* of G with respect to $S \subseteq V(G)$ is denoted by $G[S]$; $G[S]$ has vertex set S and edge set $E(G[S]) = \{uv \in E(G) \mid u, v \in S\}$. For $r \geq 0$, the *r-neighborhood* of a vertex $v \in V(G)$ is defined as $N^r_G[v] = \{u \mid dist_G(u, v) \leq r\}$, where $dist_G(u, v)$ is the length of a shortest uv-path in G.

Contracting an edge uv of G results in a new graph H in which the vertices u and v are deleted and replaced by a new vertex w that is adjacent to $N_G(u) \cup N_G(v) \setminus \{u, v\}$. If a graph H can be obtained from G by repeatedly contracting edges, H is said to be a *contraction* of G. If H is a subgraph of a contraction of G, then H is said to be a *minor* of G, denoted by $H \preceq_m G$. An equivalent characterization of minors states that H is a minor of G if there is a map that associates to each vertex v of H a non-empty connected subgraph G_v of G such that G_u and G_v are disjoint for $u \neq v$ and whenever there is an edge between u and v in H there is an edge in G between some node in G_u and some node in G_v. The subgraphs G_v are called *branch sets*. H is a *minor at depth r of G*, $H \preceq^r_m G$, if H is a minor of G which is witnessed by a collection of branch sets $\{G_v \mid v \in V(H)\}$, each of which induces a graph of radius at most r. That is, for each $v \in V(H)$, there is a $w \in V(G_v)$ such that $V(G_v) \subseteq N^r_{G_v}[w]$.

Sparse graph classes. We define the three main classes we consider.

Definition 1 ([24, 22]). *A class of graphs $\mathcal{C}$ is said to be* nowhere dense *if for every $d \geq 0$ there exists a graph H_d such that $H_d \not\preceq^d_m G$ for all $G \in \mathcal{C}$. $\mathcal{C}$ is* effectively nowhere dense *if the map $d \mapsto H_d$ is computable. Otherwise, $\mathcal{C}$ is said to be* somewhere dense*.*

Nowhere dense classes of graphs were introduced by Nesetril and Ossona de Mendez [22, 24] and "nowhere density" turns out to be a very robust concept with several natural characterizations [13]. We use one such characterization in Section 3.2. It follows from the definition that planar graphs, graphs of bounded treewidth, graphs of bounded degree, H-minor-free graphs, and H-topological-minor-free graphs are nowhere dense [22, 24]. As in the work of Dawar and Kreutzer [7], we are only interested in effectively nowhere dense classes; all natural nowhere dense classes are effectively nowhere dense, but it is possible to construct artificial classes that are nowhere dense, but not effectively so.

Definition 2. *A class of graphs* $\mathcal{C}$ *is said to be* d-degenerate *if every induced subgraph of any graph* $G \in \mathcal{C}$ *has a vertex of degree at most* d.

Graphs of bounded degeneracy and nowhere dense graphs are incomparable [14]. In other words, graphs of bounded degeneracy are somewhere dense. Degeneracy is a hereditary property, hence any induced subgraph of a d-degenerate graph is also d-degenerate. It is well-known that graphs of treewidth at most d are also d-degenerate. Moreover a d-degenerate graph cannot contain $K_{d+1,d+1}$ as a subgraph, which brings us to the class of biclique-free graphs. The relationship between bounded degeneracy, nowhere dense, and $K_{d,d}$-free graphs was shown by Philip et al. and Telle and Villanger [25, 26].

Definition 3. *A class of graphs* $\mathcal{C}$ *is said to be* d-biclique-free*, for some* $d > 0$*, if* $K_{d,d}$ *is not a subgraph of any* $G \in \mathcal{C}$*, and it is said to be* biclique-free *if it is* d*-biclique-free for some* d.

Proposition 1 ([25, 26]). *Any degenerate or nowhere dense class of graphs is biclique-free, but not vice-versa.*

Reconfiguration. For any vertex-subset problem $\mathcal{Q}$, graph G, and positive integer k, we consider the *reconfiguration graph* $R_{\mathcal{Q}}(G, k, k+1)$ when $\mathcal{Q}$ is a minimization problem (e.g. Dominating Set) and the reconfiguration graph $R_{\mathcal{Q}}(G, k-1, k)$ when $\mathcal{Q}$ is a maximization problem (e.g. Independent Set). A set $S \subseteq V(G)$ has a corresponding node in $V(R_{\mathcal{Q}}(G, r_l, r_u))$, $r_l \in \{k-1, k\}$ and $r_u \in \{k, k+1\}$, if and only if S is a feasible solution for $\mathcal{Q}$ and $r_l \leq |S| \leq r_u$. We refer to *vertices* in G using lower case letters (e.g. u, v) and to the *nodes* in $R_{\mathcal{Q}}(G, r_l, r_u)$, and by extension their associated feasible solutions, using upper case letters (e.g. A, B). If $A, B \in V(R_{\mathcal{Q}}(G, r_l, r_u))$ then there exists an edge between A and B in $R_{\mathcal{Q}}(G, r_l, r_u)$ if and only if there exists a vertex $u \in V(G)$ such that $\{A \setminus B\} \cup \{B \setminus A\} = \{u\}$. Equivalently, for $A \Delta B = \{A \setminus B\} \cup \{B \setminus A\}$ the *symmetric difference* of A and B, A and B share an edge in $R_{\mathcal{Q}}(G, r_l, r_u)$ if and only if $|A \Delta B| = 1$.

We write $A \leftrightarrow B$ if there exists a path in $R_{\mathcal{Q}}(G, r_l, r_u)$, a reconfiguration sequence, joining A and B. Any reconfiguration sequence from *source* feasible solution S_s to *target* feasible solution S_t, which we sometimes denote by $\sigma = \langle S_0, S_1, \ldots, S_\ell \rangle$, for some ℓ, has the following properties:

- $S_0 = S_s$ and $S_\ell = S_t$,
- S_i is a feasible solution for $\mathcal{Q}$ for all $0 \leq i \leq \ell$,
- $|S_i \Delta S_{i+1}| = 1$ for all $0 \leq i < \ell$, and
- $r_l \leq |S_i| \leq r_u$ for all $0 \leq i \leq \ell$.

We denote the *length* of σ by $|\sigma|$. For $0 < i \leq |\sigma|$, we say vertex $v \in V(G)$ is *added* at step/index/position/slot i if $v \notin S_{i-1}$ and $v \in S_i$. Similarly, a vertex v is *removed* at step/index/position/slot i if $v \in S_{i-1}$ and $v \notin S_i$. A vertex $v \in V(G)$ is *touched* in the course of a reconfiguration sequence if v is either added or removed at least once; it is *untouched* otherwise. A vertex is *removable* (*addable*) from feasible solution S if $S \setminus \{v\}$ ($S \cup \{v\}$) is also a feasible solution for $\mathcal{Q}$. For any pair of consecutive solutions (S_{i-1}, S_i) in σ, we say S_i (S_{i-1}) is the *successor* (*predecessor*) of S_{i-1} (S_i). A reconfiguration sequence $\sigma' = \langle S_0, S_1, \ldots, S_{\ell'} \rangle$ is a *prefix* of $\sigma = \langle S_0, S_1, \ldots, S_\ell \rangle$ if $\ell' < \ell$.

We adapt the concept of irrelevant vertices from parameterized complexity to introduce the notions of irrelevant and strongly irrelevant vertices for reconfiguration. Since these notions apply to almost any reconfiguration problem, we give general definitions.

Definition 4. *For any vertex-subset problem $\mathcal{Q}$, n-vertex graph G, positive integers r_l and r_u, and $S_s, S_t \in V(R_{\mathcal{Q}}(G, r_l, r_u))$ such that there exists a reconfiguration sequence from S_s to S_t in $R_{\mathcal{Q}}(G, r_l, r_u)$, we say a vertex $v \in V(G)$ is* irrelevant *(with respect to S_s and S_t) if and only if $v \notin S_s \cup S_t$ and there exists a reconfiguration sequence from S_s to S_t in $R_{\mathcal{Q}}(G, r_l, r_u)$ which does not touch v. We say v is* strongly irrelevant *(with respect to S_s and S_t) if it is irrelevant and the length of a shortest reconfiguration sequence from S_s to S_t which does not touch v is no greater than the length of a shortest reconfiguration sequence which does (if the latter sequence exists).*

At a high level, it is enough to ignore irrelevant vertices when trying to find *any* reconfiguration sequence between two feasible solutions, but only strongly irrelevant vertices can be ignored if we wish to find a *shortest* reconfiguration sequence. As we shall see, our kernelization algorithm for DSR does in fact find strongly irrelevant vertices and can therefore be used to find shortest reconfiguration sequences. For ISR, we are only able to find irrelevant vertices and reconfiguration sequences are not guaranteed to be of shortest possible length.

3 Independent set reconfiguration

3.1 Graphs of bounded degeneracy

To show that the ISR problem is fixed-parameter tractable on d-degenerate graphs, for some integer d, we will proceed in two stages. In the first stage, we will show, for an instance (G, I_s, I_t, k), that as long as the number of low-degree vertices in G is "large enough" we can find an irrelevant vertex (Definition 4). Once the number of low-degree vertices is bounded, a simple counting argument (Proposition 2) shows that the size of the remaining graph is also bounded and hence we can solve the instance by exhaustive enumeration.

Proposition 2 ($\star$). *Let G be an n-vertex d-degenerate graph, $S_1 \subseteq V(G)$ be the set of vertices of degree at most $2d$, and $S_2 = V(G) \setminus S_1$. If $|S_1| < s$, then $|V(G)| \leq (2d+1)s$.*

To find irrelevant vertices, we make use of the following classical result of Erdős and Rado [11], also known in the literature as the sunflower lemma. We first define the terminology used in the statement of the theorem. A *sunflower* with k *petals* and a *core* Y is a collection of sets $S_1, \ldots, S_k$ such that $S_i \cap S_j = Y$ for all $i \neq j$; the sets $S_i \setminus Y$ are petals and we require all of them to be non-empty. Note that a family of pairwise disjoint sets is a sunflower (with an empty core).

Theorem 1 (Sunflower Lemma [11]). *Let $\mathcal{A}$ be a family of sets (without duplicates) over a universe $\mathcal{U}$, such that each set in $\mathcal{A}$ has cardinality at most d. If $|\mathcal{A}| > d!(k-1)^d$, then $\mathcal{A}$ contains a sunflower with k petals and such a sunflower can be computed in time polynomial in $|\mathcal{A}|$, $|\mathcal{U}|$, and k.*

Lemma 1. *Let (G, I_s, I_t, k) be an instance of* ISR *and let B be the set of vertices in $V(G) \setminus \{I_s \cup I_t\}$ of degree at most $2d$. If $|B| > (2d+1)!(2k-1)^{2d+1}$, then there exists an irrelevant vertex $v \in V(G) \setminus \{I_s \cup I_t\}$ such that (G, I_s, I_t, k) is a yes-instance if and only if (G', I_s, I_t, k) is a yes-instance, where G' is obtained by deleting v and all edges incident on v.*

Proof. Let b_1, b_2, …, $b_{|B|}$ denote the vertices in B and let $\mathcal{A} = \{N_G[b_1], N_G[b_2], \ldots, N_G[b_{|B|}]\}$ denote the family of the closed neighborhoods of each vertex in B and set $\mathcal{U} = \bigcup_{b \in B} N[b]$. Since $|B|$ is greater than $(2d+1)!(2k-1)^{2d+1}$, we know from Theorem 1 that $\mathcal{A}$ contains a sunflower with $2k$ petals and such a sunflower can be computed in time polynomial in $|\mathcal{A}|$ and k. Note that we assume, without loss of generality, that there are no two vertices u and v in $V(G) \setminus \{I_s \cup I_t\}$ such that $N_G[u] = N_G[v]$, as we can safely delete one of them from the input graph otherwise, i.e. $uv \in E(G)$ and one of the two is (strongly) irrelevant. Let v_{ir} be a vertex whose closed neighborhood is one of those $2k$ petals. We claim that v_{ir} is irrelevant and can therefore be deleted from G to obtain G'.

To see why, consider any reconfiguration sequence $\sigma = \langle I_s = I_0, I_1, \ldots, I_t = I_\ell \rangle$ from I_s to I_t in $R_{\text{IS}}(G, k-1, k)$. Since $v_{ir} \notin I_s \cup I_t$, we let p, $0 < p < \ell$, be the first index in σ at which v_{ir} is added, i.e. $v_{ir} \in I_p$ and $v_{ir} \notin I_i$ for all $i < p$. Moreover, we let $q+1$, $p < q+1 \leq \ell$ be the first index after p at which v_{ir} is removed, i.e. $v_{ir} \in I_q$ and $v_{ir} \notin I_{q+1}$. We will consider the subsequence $\sigma_s = \langle I_p, \ldots, I_q \rangle$ and show how to modify it so that it does not touch v_{ir}. Applying the same procedure to every such subsequence in σ suffices to prove the lemma.

Since the sunflower constructed to obtain v_{ir} has $2k$ petals and the size of any independent set in σ (or any reconfiguration sequence in general) is at most k, there must exist another *free* vertex v_{fr} whose closed neighborhood corresponds to one of the remaining $2k-1$ petals which we can add at index p instead of v_{ir}, i.e. $v_{fr} \notin N_G[I_p]$. We say v_{fr} *represents* v_{ir}. Assume that no such vertex exists. Then we know that either some vertex in the core of the sunflower is in I_p contradicting the fact that we are adding v_{ir}, or every petal of the sunflower contains a vertex in I_p, which is not possible since the size of any independent set is at most k and the number of petals is larger. Hence, we first modify the subsequence σ_s by adding v_{fr} instead of v_{ir}. Formally, we have $\sigma'_s = \langle (I_p \setminus \{v_{ir}\}) \cup \{v_{fr}\}, \ldots, (I_q \setminus \{v_{ir}\}) \cup \{v_{fr}\} \rangle$.

To be able to replace σ_s by σ'_s in σ and obtain a reconfiguration sequence from I_s to I_t, then all of the following conditions must hold:

(1) $|(I_q \setminus \{v_{ir}\}) \cup \{v_{fr}\}| = k$.
(2) $(I_i \setminus \{v_{ir}\}) \cup \{v_{fr}\}$ is an independent set of G for all $p \leq i \leq q$,
(3) $|(I_i \setminus \{v_{ir}\}) \cup \{v_{fr}\} \Delta (I_{i+1} \setminus \{v_{ir}\}) \cup \{v_{fr}\}| = 1$ for all $p \leq i < q$, and
(4) $k - 1 \leq |(I_i \setminus \{v_{ir}\}) \cup \{v_{fr}\}| \leq k$ for all $p \leq i \leq q$.

It is not hard to see that if there exists no i, $p < i \leq q$, such that σ'_s adds a vertex in $N[v_{fr}]$ at position i, then all four conditions hold. If there exists such a position, we will modify σ'_s into yet another subsequence σ''_s by finding a new vertex to represent v_{ir}. The length of σ''_s will be two greater than that of σ'_s.

We let i, $p < i \leq q$, be the first position in σ'_s at which a vertex in $u \in N[v_{fr}]$ (possibly equal to v_{fr}) is added (hence $|I_{i-1}| = k-1$). Using the same arguments discussed to find v_{fr}, and since we constructed a sunflower with $2k$ petals, we can find another vertex v'_{fr} such that $N[v_{fr}] \cap ((I_{i-1} \setminus \{v_{ir}\}) \cup \{v_{fr}\}) = \emptyset$. This new vertex will represent v_{ir} instead of v_{fr}. We construct σ''_s from σ'_s as follows: $\sigma''_s = \langle (I_p \setminus \{v_{ir}\}) \cup \{v_{fr}\}, \ldots, (I_{i-1} \setminus \{v_{ir}\}) \cup \{v_{fr}\}, (I_{i-1} \setminus \{v_{ir}\}) \cup \{v_{fr}\} \cup \{v'_{fr}\}, (I_{i-1} \setminus \{v_{ir}\}) \cup \{v'_{fr}\}, (I_i \setminus \{v_{ir}\}) \cup \{v'_{fr}\}, \ldots, (I_q \setminus \{v_{ir}\}) \cup \{v'_{fr}\} \rangle$. If σ''_s now satisfies all four conditions then we are done. Otherwise, we repeat the same process (at most $q - p$ times) until we reach such a subsequence. □

Theorem 2. ISR *on d-degenerate graphs is fixed-parameter tractable parameterized by $k + d$.*

Proof. For an instance (G, I_s, I_t, k) of ISR, we know from Lemma 1 that as long as $V(G) \setminus \{I_s \cup I_t\}$ contains more than $(2d+1)!(2k-1)^{2d+1}$ vertices of degree at most $2d$ we can find an irrelevant vertex and reduce the size of the graph. After exhaustively reducing the graph to obtain G', we known that $G'[V(G') \setminus \{I_s \cup I_t\}]$, which is also d-degenerate, has at most $(2d+1)!(2k-1)^{2d+1}$ vertices of degree at most $2d$. Hence, applying Proposition 2, we know that $|V(G') \setminus \{I_s \cup I_t\}| \leq (2d+1)(2d+1)!(2k-1)^{2d+1}$ and $|V(G')| \leq (2d+1)(2d+1)!(2k-1)^{2d+1} + 2k$. □

3.2 Nowhere dense graphs

Nesetril and Ossona de Mendez [23] showed an interesting relationship between nowhere dense classes and a property of classes of structures introduced by Dawar [6] called *quasi-wideness*. We will use quasi-wideness and show a rather interesting relationship between ISR on graphs of bounded degeneracy and nowhere dense graphs. That is, our algorithm for nowhere dense graphs will closely mimic the previous algorithm in the following sense. Instead of using the sunflower lemma to find a large sunflower, we will use quasi-wideness to find a "large enough almost sunflower" with an initially "unknown" core and then use structural properties of the graph to find this core and complete the sunflower. We first state some of the results that we need. Given a graph G, a set $S \subseteq V(G)$ is called *r-scattered* if $N^r_G(u) \cap N^r_G(v) = \emptyset$ for all distinct $u, v \in S$.

Proposition 3. *Let G be a graph and let $S = \{s_1, s_2, ..., s_k\} \subseteq V(G)$ be a 2-scattered set of size k in G. Then the closed neighborhoods of the vertices in S form a sunflower with k petals and an empty core.*

Definition 5 ([7, 23]). *A class $\mathcal{C}$ of graphs is* uniformly quasi-wide *with* margin *$s_{\mathcal{C}} : \mathbb{N} \to \mathbb{N}$ and $N_{\mathcal{C}} : \mathbb{N} \times \mathbb{N} \to \mathbb{N}$ if for all $r, k \in \mathbb{N}$, if $G \in \mathcal{C}$ and $W \subseteq V(G)$ with $|W| > N_{\mathcal{C}}(r, k)$, then there is a set $S \subseteq W$ with $|S| < s_{\mathcal{C}}(r)$, such that W contains an r-scattered set of size at least k in $G[V(G) \setminus S]$. $\mathcal{C}$ is* effectively uniformly quasi-wide *if $s_{\mathcal{C}}(r)$ and $N_{\mathcal{C}}(r, k)$ are computable.*

Examples of effectively uniformly quasi-wide classes include graphs of bounded degree with margin 1 and H-minor-free graphs with margin $|V(H)|-1$.

Theorem 3 ([7]). *A class $\mathcal{C}$ of graphs is effectively nowhere dense if and only if $\mathcal{C}$ is effectively uniformly quasi-wide.*

Theorem 4 ([7]). *Let $\mathcal{C}$ be an effectively nowhere dense class of graphs and h be the computable function such that $K_{h(r)} \not\preceq_m^r G$ for all $G \in \mathcal{C}$. Let G be an n-vertex graph in $\mathcal{C}$, $r, k \in \mathbb{N}$, and $W \subseteq V(G)$ with $|W| \geq N(h(r), r, k)$, for some computable function N. Then in $\mathcal{O}(n^2)$ time, we can compute a set $B \subseteq V(G)$, $|B| \leq h(r) - 2$, and a set $A \subseteq W$ such that $|A| \geq k$ and A is an r-scattered set in $G[V(G) \setminus B]$.*

Lemma 2. *Let $\mathcal{C}$ be an effectively nowhere dense class of graphs and h be the computable function such that $K_{h(r)} \not\preceq_m^r G$ for all $G \in \mathcal{C}$. Let (G, I_s, I_t, k) be an instance of* ISR *where $G \in \mathcal{C}$ and let R be the set of vertices in $V(G) \setminus \{I_s \cup I_t\}$. Moreover, let $\mathcal{P} = \{P_1, P_2, \ldots\}$ be a family of sets which partitions R such that for any two distinct vertices $u, v \in R$, $u, v \in P_i$ if and only if $N_G(u) \cap \{I_s \cup I_t\} = N_G(v) \cap \{I_s \cup I_t\}$. If there exists a set $P_i \in \mathcal{P}$ such that $|P_i| > N(h(2), 2, 2^{h(2)+1}k)$, for some computable function N, then there exists an irrelevant vertex $v \in V(G) \setminus \{I_s \cup I_t\}$ such that (G, I_s, I_t, k) is a yes-instance if and only if (G', I_s, I_t, k) is a yes-instance, where G' is obtained from G by deleting v and all edges incident on v.*

Proof. By construction, we known that the family $\mathcal{P}$ contains at most 4^k sets, as we partition R based on their neighborhoods in $I_s \cup I_t$. Note that some vertices in R have no neighbors in $I_s \cup I_t$ and will therefore belong to the same set in $\mathcal{P}$.

Assume that there exists a $P \in \mathcal{P}$ such that $|P| > N(h(2), 2, 2^{h(2)+1}k)$. Consider the graph $G[R]$. By Theorem 4, we can, in $\mathcal{O}(|R|^2)$ time, compute a set $B \subseteq R$, $|B| \leq h(2) - 2$, and a set $A \subseteq P$ such that $|A| \geq 2^{h(2)+1}k$ and A is a 2-scattered set in $G[R \setminus B]$. Now let $\mathcal{P}' = \{P'_1, P'_2, \ldots\}$ be a family of sets which partitions A such that for any two distinct vertices $u, v \in A$, $u, v \in P'_i$ if and only if $N_G(u) \cap B = N_G(v) \cap B$. Since $|A| \geq 2^{h(2)+1}k$ and $|\mathcal{P}'| \leq 2^{h(2)}$, we know that at least one set in $\mathcal{P}'$ will contain at least $2k$ vertices of A. Denote these $2k$ vertices by A'. All vertices in A' have the same neighborhood in B and the same neighborhood in $I_s \cup I_t$ (as all vertices in A' belonged to the same set $P \in \mathcal{P}$). Moreover, A' is a 2-scattered set in $G[R \setminus B]$. Hence, the sets $\{N_G[a'_1], N_G[a'_2], \ldots, N_G[a'_{2k}]\}$, i.e. the closed neighborhoods of the vertices in

A', form a sunflower with $2k$ petals (Proposition 3); the core of this sunflower is contained in $B \cup I_s \cup I_t$. Using the same arguments as we did in the proof of Lemma 1, we can show that there exists at least one irrelevant vertex $v \in V(G) \setminus \{B \cup I_s \cup I_t\}$. □

Theorem 5. ISR *restricted to any effectively nowhere dense class $\mathcal{C}$ of graphs is fixed-parameter tractable parameterized by k.*

Proof. If after partitioning $V(G) \setminus \{I_s \cup I_t\}$ into at most 4^k sets the size of every set $P \in \mathcal{P}$ is bounded by $N(h(2), 2, 2^{h(2)+1}k)$, then we can solve the problem by exhaustive enumeration, as $|V(G)| \leq 2k + 4^k N(h(2), 2, 2^{h(2)+1}k)$. Otherwise, we can apply Lemma 2 and reduce the size of the graph in polynomial time. □

4 Dominating set reconfiguration

4.1 Graphs excluding $K_{d,d}$ as a subgraph

The parameterized complexity of the Dominating Set problem (parameterized by k the solution size) on various classes of graphs has been studied extensively in the literature; the main goal has been to push the tractability frontier as far as possible. The problem was shown fixed-parameter tractable on nowhere dense graphs by Dawar and Kreutzer [7], on degenerate graphs by Alon and Gutner [1], and on $K_{d,d}$-free graphs by Philip et al. [25] and Telle and Villanger [26]. Our fixed-parameter tractable algorithm relies on many of these earlier results. Interestingly, and since the class of $K_{d,d}$-free graphs includes all those other graph classes, our algorithm (Theorem 6) implies that the diameter of the reconfiguration graph $R_{\text{DS}}(G, k, k+1)$ (or of its connected components), for G in any of the aforementioned classes, is bounded above by $f(k, c)$, where f is a computable function and c is constant which depends on the graph class at hand. We start with some definitions and needed lemmas.

Definition 6. *A bipartite graph G with bipartition (A, B) is B-*twinless *if there are no vertices $u, v \in B$ such that $N(u) = N(v)$.*

Lemma 3 ($\star$). *If G is a bipartite graph with bipartition (A, B) such that $|A| \geq 2(d-1)$, G is B-twinless, and G excludes $K_{d,d}$ as a subgraph, then $|B| \leq 2d|A|^d$.*

Definition 7 ([10]). *Given a graph G, the* domination core *of G is a set $C \subseteq V(G)$ such that any set $D \subseteq V(G)$ is a dominating set of G if and only if D dominates C, i.e. D is a dominating set of G if and only if $C \subseteq N_G[D]$.*

Lemma 4 ($\star$). *If G is a graph which excludes $K_{d,d}$ as a subgraph and G has a dominating set of size at most k then the size of the domination core C of G is at most $2dk^{2d}$ and C can be computed in $\mathcal{O}^*(dk^d)$ time.*

Since Lemma 4 implies a bound on the size of the domination core and allows us to compute it efficiently, our main concern is to deal with vertices outside of the core, i.e. vertices in $V(G) \setminus C$. The next lemma shows that we can in fact find strongly irrelevant vertices outside of the domination core.

Lemma 5 ($\star$). *For G an n-vertex graph, C the domination core of G, and D_s and D_t two dominating sets of G, if there exist $u, v \in V(G) \setminus \{C \cup D_s \cup D_t\}$ such that $N_G(u) \cap C = N_G(v) \cap C$ then u (or v) is strongly irrelevant.*

Theorem 6. DSR *parameterized by $k+d$ is fixed-parameter tractable on graphs that exclude $K_{d,d}$ as a subgraph.*

Proof. Given a graph G, integer k, and two dominating sets D_s and D_t of G of size at most k, we first compute the domination core C of G, which by Lemma 4 can be accomplished in $\mathcal{O}^*(dk^d)$ time. Next, and due to Lemma 5, we can delete all strongly irrelevant vertices from $V(G) \setminus \{C \cup D_s \cup D_t\}$. We denote this new graph by G'.

Now consider the bipartite graph G'' with bipartition ($A = C \setminus \{D_s \cup D_t\}, B = V(G') \setminus \{C \cup D_s \cup D_t\}$). This graph is B-twinless, since for every pair of vertices $u, v \in V(G) \setminus \{C \cup D_s \cup D_t\}$ such that $N_G(u) \cap C = N_G(v) \cap C$ either u or v is strongly irrelevant and is therefore not in $V(G')$ nor $V(G'')$. Moreover, since every subgraph of a $K_{d,d}$-free graph is also $K_{d,d}$-free, G'' is $K_{d,d}$-free. Hence, if $|A| < 2(d-1)$ then $|B| \leq 2^{2(d-1)} = 4^{d-1}$. Otherwise, by Lemmas 3 and 4, we have $|B| \leq 2d|A|^d \leq 2d(2dk^{2d})^d$.

Putting it all together, we know that after deleting all strongly irrelevant vertices, the number of vertices in the resulting graph G' is at most $|V(G')| = |V(C)| + |D_s \cup D_t| + |V(G') \setminus \{C \cup D_s \cup D_t\}| \leq 2dk^{2d} + 2k + 2d(2dk^{2d})^d$.

Hence, we can solve DSR by exhaustively enumerating all $2^{|V(G')|}$ subsets of $V(G')$ and building the reconfiguration graph $R_{\text{DS}}(G', k, k+1)$. $\square$

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