6. Kernelization

COMP6741: Parameterized and Exact Computation

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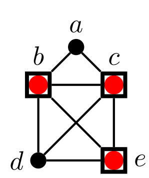
Contents

1 Vertex Cover

A *vertex cover* of a graph $G = (V, E)$ is a subset of vertices $S \subseteq V$ such that for each edge $\{u, v\} \in E$, we have $u \in S$ or $v \in S$.

VERTEX COVER	
Input:	A graph $G = (V, E)$ and an integer k
Parameter:	k
Question:	Does G have a vertex cover of size at most k?



1.1 Simplification rules

(Degree-0)
If $\exists v \in V$ such that $d_G(v) = 0$, then set $G \leftarrow G - v$.

Proving correctness. A simplification rule is *sound* if for any instance, it produces an equivalent instance. Two instances I, I' are *equivalent* if they are both YES-instances or they are both NO-instances.

Lemma 1. *(Degree-0) is sound.*

Proof. First, suppose $(G - v, k)$ is a YES-instance. Let S be a vertex cover for $G - v$ of size at most k. Then, S is also a vertex cover for G since no edge of G is incident to v. Thus, (G, k) is a YES-instance.

Now, suppose (G, k) is a YES-instance. For the sake of contradiction, assume $(G - v, k)$ is a NO-instance. Let S be a vertex cover for G of size at most k. But then, $S \setminus \{v\}$ is a vertex cover of size at most k for $G - v$; a contradiction. □

(Degree-1)
If $\exists v \in V$ such that $d_G(v) = 1$, then set $G \leftarrow G - N_G[v]$ and $k \leftarrow k - 1$.

Lemma 2. *(Degree-1) is sound.*

Proof. Let u be the neighbor of v in G. Thus, $N_G[v] = \{u, v\}$.

If S is a vertex cover of G of size at most k, then $S \setminus \{u, v\}$ is a vertex cover of $G - N_G[v]$ of size at most $k - 1$, because $u \in S$ or $v \in S$. If S' is a vertex cover of $G - N_G[v]$ of size at most $k - 1$, then $S' \cup \{u\}$ is a vertex cover of G of size at most k, since all edges that are in G but not in $G - N_G[v]$ are incident to v. □

(Large Degree)
If $\exists v \in V$ such that $d_G(v) > k$, then set $G \leftarrow G - v$ and $k \leftarrow k - 1$.

Lemma 3. *(Large Degree) is sound.*

Proof. Let S be a vertex cover of G of size at most k. If $v \notin S$, then $N_G(v) \subseteq S$, contradicting that $|S| \leq k$. □

(Number of Edges)
If $d_G(v) \leq k$ for each $v \in V$ and $|E| > k^2$ then return NO

Lemma 4. *(Number of Edges) is sound.*

Proof. Assume $d_G(v) \leq k$ for each $v \in V$ and $|E| > k^2$. Suppose $S \subseteq V$, $|S| \leq k$, is a vertex cover of G. We have that S covers at most k^2 edges. However, $|E| \geq k^2 + 1$. Thus, S is not a vertex cover of G. □

1.2 Preprocessing algorithm

VC-preprocess
Input: A graph G and an integer k.
Output: A graph G' and an integer k' such that G has a vertex cover of size at most k if and only if G' has a vertex cover of size at most k'.

$G' \leftarrow G$
$k' \leftarrow k$
repeat
| Execute simplification rules (Degree-0), (Degree-1), (Large Degree), and (Number of Edges) for (G', k')
until *no simplification rule applies*
return (G', k')

Effectiveness of preprocessing algorithms

- How effective is VC-preprocess?
- We would like to study preprocessing algorithms mathematically and quantify their effectiveness.

First try

- Say that a preprocessing algorithm for a problem Π is *nice* if it runs in polynomial time and for each instance for Π, it returns an instance for Π that is strictly smaller.
- $\rightarrow$ executing it a linear number of times reduces the instance to a single bit
- $\rightarrow$ such an algorithm would solve Π in polynomial time
- For NP-hard problems this is not possible unless P = NP
- We need a different measure of effectiveness

Measuring the effectiveness of preprocessing algorithms

- We will measure the effectiveness in terms of the *parameter*
- How large is the resulting instance in terms of the parameter?

Effectiveness of VC-preprocess

Lemma 5. *For any instance (G, k) for* Vertex Cover*, VC-preprocess produces an equivalent instance (G', k') of size $O(k^2)$.*

Proof. Since all simplification rules are sound, $(G = (V, E), k)$ and $(G' = (V', E'), k')$ are equivalent. By (Number of Edges), $|E'| \leq (k')^2 \leq k^2$. By (Degree-0) and (Degree-1), each vertex in V' has degree at least 2 in G'. Since $\sum_{v \in V'} d_{G'}(v) = 2|E'| \leq 2k^2$, this implies that $|V'| \leq k^2$. Thus, $|V'| + |E'| \subseteq O(k^2)$. □

2 Kernelization algorithms

Kernelization: definition

Definition 6. A *kernelization* for a parameterized problem Π is a **polynomial time** algorithm, which, for any instance I of Π with parameter k, produces an **equivalent** instance I' of Π with parameter k' such that $|I'| \leq f(k)$ and $k' \leq f(k)$ for a computable function f. We refer to the function f as the *size* of the kernel.

Note: We do not formally require that $k' \leq k$, but this will be the case for many kernelizations.

VC-preprocess is a quadratic kernelization

Theorem 7. *VC-preprocess is a $O(k^2)$ kernelization for* Vertex Cover*.*

Can we obtain a kernel with fewer vertices?

Exercise

A *dominating set* of a graph $G = (V, E)$ is a set of vertices $S \subseteq V$ such that $N_G[S] = V$.

Degree-5 Dominating Set	
Input:	A graph $G = (V, E)$ with maximum degree at most 5 and an integer k
Parameter:	k
Question:	Does G have a dominating set of size at most k?

Design a linear kernel for Degree-5 Dominating Set.
Hint: How many vertices can a Yes-instance have at most, as a function of k?

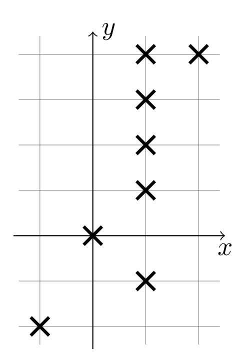
Solution sketch

Simplification rule: If $|V| > 6 \cdot k$, then return No.

Exercise

Point Line Cover	
Input:	A set of points P in the plane $\mathbb{R}^2$, and an integer k.
Parameter:	k.
Question:	Is there a set L of at most k lines in $\mathbb{R}^2$ such that each point in P lies on at least one line in L?

Example: $(P = \{(-1,-2), (0,0), (1,-1), (1,1), (1,2), (1,3), (1,4), (2,4)\}, k = 2)$ is a Yes-instance since the lines $y = 1$ and $y = 2x$ cover all the points.



Show that POINT LINE COVER has a polynomial kernel.

Hints:
(1) Show that the algorithm can restrict its attention to a polynomial number of *candidate lines* (aim for $O(|P|^2)$).
(2) Design a simplification rule for the case where one candidate line covers many points in P.
(3) Design a simplification rule that solves POINT LINE COVER when $|P|$ is large compared to t.

Exercise
A *cluster graph* is a graph where every connected component is a complete graph.

CLUSTER EDITING	
Input:	Graph $G = (V, E)$, integer k
Parameter:	k
Question:	Is it possible to edit (add or delete) at most k edges of G so that it becomes a cluster graph?

1. Show that G is a cluster graph iff G contains no induced P_3 (path with 3 vertices).
2. Design a kernel for CLUSTER EDITING with $O(k^2)$ vertices.

Hints for 2: design simplification rules for (1) a vertex that does not occur in any P_3, (2) an edge that occurs in many P_3s, and (3) a non-edge that occurs in many P_3s

3 A smaller kernel for Vertex Cover

Integer Linear Program for Vertex Cover

The VERTEX COVER problem can be written as an Integer Linear Program (ILP). For an instance $(G = (V, E), k)$ for VERTEX COVER with $V = \{v_1, \ldots, v_n\}$, create a variable x_i for each vertex v_i, $1 \le i \le n$. Let $X = \{x_1, \ldots, x_n\}$.

$$\text{ILP}_{\text{VC}}(G) = \quad \text{Minimize} \sum_{i=1}^{n} x_i$$
$$x_i + x_j \ge 1 \qquad \text{for each } \{v_i, v_j\} \in E$$
$$x_i \in \{0, 1\} \qquad \text{for each } i \in \{1, \ldots, n\}$$

Then, (G, k) is a YES-instance iff the objective value of $\text{ILP}_{\text{VC}}(G)$ is at most k.

LP relaxation for Vertex Cover

$$\text{LP}_{\text{VC}}(G) = \quad \text{Minimize} \sum_{i=1}^{n} x_i$$
$$x_i + x_j \ge 1 \qquad \text{for each } \{v_i, v_j\} \in E$$
$$x_i \ge 0 \qquad \text{for each } i \in \{1, \ldots, n\}$$

Note: the value of an optimal solution for the Linear Program $\text{LP}_{\text{VC}}(G)$ is at most the value of an optimal solution for $\text{ILP}_{\text{VC}}(G)$

Properties of LP optimal solution

- Let $\alpha : X \to \mathbb{R}_{\geq 0}$ be an optimal solution for $\mathrm{LP}_{\mathrm{VC}}(G)$. Let

$$\begin{aligned} V_- &= \{v_i : \alpha(x_i) < 1/2\} \\ V_{1/2} &= \{v_i : \alpha(x_i) = 1/2\} \\ V_+ &= \{v_i : \alpha(x_i) > 1/2\} \end{aligned}$$

Lemma 8. *For each $i, 1 \leq i \leq n$, we have that $\alpha(x_i) \leq 1$.*

Lemma 9. *V_- is an independent set.*

Lemma 10. $N_G(V_-) = V_+$.

Lemma 11. *For each $S \subseteq V_+$ we have that $|S| \leq |N_G(S) \cap V_-|$.*

Proof. For the sake of contradiction, suppose there is a set $S \subseteq V_+$ such that $|S| > |N_G(S) \cap V_-|$. Let $\epsilon = \min_{v_i \in S}\{\alpha(x_i) - 1/2\}$ and $\alpha' : X \to \mathbb{R}_{\geq 0}$ s.t.

$$\alpha'(x_i) = \begin{cases} \alpha(x_i) & \text{if } v_i \notin S \cup (N_G(S) \cap V_-) \\ \alpha(x_i) - \epsilon & \text{if } v_i \in S \\ \alpha(x_i) + \epsilon & \text{if } v_i \in N_G(S) \cap V_- \end{cases}$$

Note that α' is an improved solution for $\mathrm{LP}_{\mathrm{VC}}(G)$, contradicting that α is optimal. □

Theorem 12 (Hall's marriage theorem)**.** *A bipartite graph $G = (V \uplus U, E)$ has a matching saturating $S \subseteq V$ if and only if for every subset $W \subseteq S$ we have $|W| \leq |N_G(W)|$.* [1]

Consider the bipartite graph $B = (V_- \uplus V_+, \{\{u, v\} \in E : u \in V_-, v \in V_+\})$.

Lemma 13. *There exists a matching M in B of size $|V_+|$.*

Proof. The lemma follows from the previous lemma and Hall's marriage theorem. □

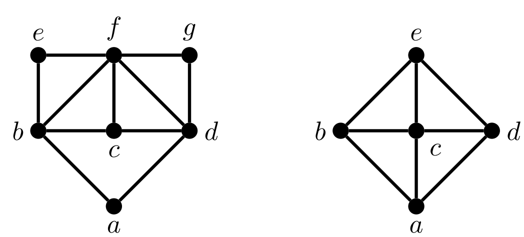
Crown Decomposition: Definition

Definition 14 (Crown Decomposition)**.** A crown decomposition (C, H, B) of a graph $G = (V, E)$ is a partition of V into sets C, H, and B such that

- the crown C is a non-empty independent set,
- the head $H = N_G(C)$,
- the body $B = V \setminus (C \cup H)$, and
- there is a matching of size $|H|$ in $G[H \cup C]$.

By the previous lemmas, we obtain a crown decomposition $(V_-, V_+, V_{1/2})$ of G if $V_- \neq \emptyset$.

Crown Decomposition: Examples



crown decomposition $(\{a, e, g\}, \{b, d, f\}, \{c\})$

has no crown decomposition

[1] A *matching* M in a graph G is a set of edges such that no two edges in M have a common endpoint. A matching *saturates* a set of vertices S if each vertex in S is an end point of an edge in M.

Using the crown decomposition

Lemma 15. *Suppose that $G = (V, E)$ has a crown decomposition (C, H, B). Then,*

$$vc(G) \leq k \quad \Leftrightarrow \quad vc(G[B]) \leq k - |H|,$$

where $vc(G)$ denotes the size of the smallest vertex cover of G.

Proof. ($\Rightarrow$): Let S be a vertex cover of G with $|S| \leq k$. Since S contains at least one vertex for each edge of a matching, $|S \cap (C \cup H)| \geq |H|$. Therefore, $S \cap B$ is a vertex cover for $G[B]$ of size at most $k - |H|$.

($\Leftarrow$): Let S be a vertex cover of $G[B]$ with $|S| \leq k - |H|$. Then, $S \cup H$ is a vertex cover of G of size at most k, since each edge that is in G but not in G' is incident to a vertex in H. ☐

Nemhauser-Trotter

Corollary 16 ([Nemhauser, Trotter, 1974])**.** *There exists a smallest vertex cover S of G such that $S \cap V_- = \emptyset$ and $V_+ \subseteq S$.*

Crown reduction

(Crown Reduction)
If solving $\text{LP}_{VC}(G)$ gives an optimal solution with $V_- \neq \emptyset$, then return $(G - (V_- \cup V_+), k - |V_+|)$.

(Number of Vertices)
If solving $\text{LP}_{VC}(G)$ gives an optimal solution with $V_- = \emptyset$ and $|V| > 2k$, then return No.

Lemma 17. *(Crown Reduction) and (Number of Vertices) are sound.*

Proof. (Crown Reduction) is sound by previous Lemmas. Let α be an optimal solution for $\text{LP}_{VC}(G)$ and suppose $V_- = \emptyset$. The value of this solution is at least $|V|/2$. Thus, the value of an optimal solution for $\text{ILP}_{\text{VC}}(G)$ is at least $|V|/2$. Since G has no vertex cover of size less than $|V|/2$, we have a No-instance if $k < |V|/2$. ☐

Linear vertex-kernel for Vertex Cover

Theorem 18. Vertex Cover *has a kernel with $2k$ vertices and $O(k^2)$ edges.*

This is the smallest known kernel for Vertex Cover. See `http://fpt.wikidot.com/fpt-races` for the current smallest kernels for various problems.

4 More on Crown Decompositions

Crown Lemma

Lemma 19 (Crown Lemma)**.** *Let $G = (V, E)$ be a graph without isolated vertices and with $|V| \geq 3k + 1$. There is a polynomial time algorithm that either*

- *finds a matching of size $k + 1$ in G, or*
- *finds a crown decomposition of G.*

To prove the lemma, we need Kőnig's Theorem

Theorem 20 ([Kőnig, 1916])**.** *In every bipartite graph the size of a maximum matching is equal to the size of a minimum vertex cover.*

Proof of the Crown Lemma. Compute a maximum matching M of G. If $|M| \geq k + 1$, we are done. Note that $I := V \setminus V(M)$ is an independent set with $|V| - |V(M)| \geq k + 1$ vertices. Consider the bipartite graph B formed by edges with one endpoint in $V(M)$ and the other in I. Compute a minimum vertex cover X and a maximum matching M' of B. We know: $|X| = |M'| \leq |M| \leq k$. Hence, $X \cap V(M) \neq \emptyset$. Let $M^* = \{e \in M' : e \cap (X \cap V(M)) \neq \emptyset\}$. We obtain a crown decomposition with

- crown $C = V(M^*) \cap I$
- head $H = X \cap V(M) = X \cap V(M^*)$, and
- body $B = V \setminus (C \cup H)$.

As an exercise, verify that (C, H, B) is indeed a crown decomposition. ☐

Exercise
A *k-coloring* of a graph $G = (V, E)$ is a function $f : V \to \{1, 2, ..., k\}$ such that $f(u) \neq f(v)$ if $uv \in E$.

Saving Colors	
Input:	Graph G, integer k
Parameter:	k
Question:	Does G have a $(n-k)$-coloring?

Design a kernel for Saving Colors with $O(k)$ vertices.

Hint: Get rid of vertices v with $N_G[v] = V$ and consider the dual of G, i.e., the graph $\overline{G} = (V, \{uv : u, v \in V \text{ and } uv \notin E\})$. Use the Crown Lemma with $\overline{G}$ and $k - 1$.

5 Kernels and Fixed-parameter tractability

Theorem 21. *Let* Π *be a decidable parameterized problem.* Π *has a kernelization algorithm* $\Leftrightarrow$ Π *is* FPT*.*

Proof. ($\Rightarrow$): An FPT algorithm is obtained by first running the kernelization, and then any brute-force algorithm on the resulting instance.

($\Leftarrow$): Let A be an FPT algorithm for Π with running time $O(f(k)n^c)$. If $f(k) < n$, then A has running time $O(n^{c+1})$. In this case, the kernelization algorithm runs A and returns a trivial Yes- or No-instance depending on the answer of A. Otherwise, $f(k) \geq n$. In this case, the kernelization algorithm outputs the input instance. □

After computing a kernel ...

- ... we can use any algorithm to compute an actual solution.
- Brute-force, faster exponential-time algorithms, parameterized algorithms, often also approximation algorithms

Kernels

- A parameterized problem may not have a kernelization algorithm
  - Example, Coloring[2] parameterized by k has no kernelization algorithm unless P = NP.
  - A kernelization would lead to a polynomial time algorithm for the NP-complete 3-Coloring problem
- Kernelization algorithms lead to FPT algorithms ...
- ... FPT algorithms lead to kernels

Exercise
An *edge clique cover* of a graph G is a set of cliques in G so that each edge of G is contained in at least one of these cliques.

Edge Clique Cover	
Input:	graph G, integer k
Parameter:	k
Question:	Does G have an edge clique cover with k cliques?

Design a kernel for Edge Clique Cover with $O(2^k)$ vertices.

Hint: consider 2 vertices that are contained in exactly the same cliques.

[2] Can one color the vertices of an input graph G with k colors such that no two adjacent vertices receive the same color?

6 Further Reading

- Chapter 2, *Kernelization* in Marek Cygan, Fedor V. Fomin, Łukasz Kowalik, Daniel Lokshtanov, Dániel Marx, Marcin Pilipczuk, MichałPilipczuk, and Saket Saurabh. Parameterized Algorithms. Springer, 2015.
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- Chapter 7, *Data Reduction and Problem Kernels* in Rolf Niedermeier. Invitation to Fixed Parameter Algorithms. Oxford University Press, 2006.
- Chapter 9, *Kernelization and Linear Programming Techniques* in Jörg Flum and Martin Grohe. Parameterized Complexity Theory. Springer, 2006.