

5. Basics of Parameterized Complexity

COMP6741: Parameterized and Exact Computation

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- 1 Introduction
 - Vertex Cover
 - Coloring
 - Clique
 - Δ -Clique
- 2 Basic Definitions
- 3 Further Reading

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Vertex Cover

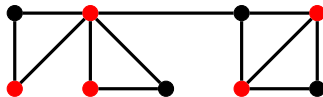
A **vertex cover** in a graph $G = (V, E)$ is a subset of its vertices $S \subseteq V$ such that every edge of G has at least one endpoint in S .

VERTEX COVER

Input: A graph $G = (V, E)$ and an integer k

Parameter: k

Question: Does G have a vertex cover of size k ?



Algorithms for Vertex Cover

- brute-force: $O^*(2^n)$
- brute-force: $O^*(n^k)$
- vc1: $O^*(2^k)$ (cf. Lecture 1)
- vc2: $O^*(1.4656^k)$ (cf. Lecture 1)
- fastest known: $O(1.2738^k + k \cdot n)$ [Chen, Kanj, Xia, 2010]

Running times in practice

$n = 1000$ vertices,
 $k = 20$ parameter

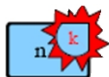
Theoretical	Running Time	
	Nb of Instructions	Real
2^n	$1.07 \cdot 10^{301}$	$4.941 \cdot 10^{282}$ years
n^k	10^{60}	$4.611 \cdot 10^{41}$ years
$2^k \cdot n$	$1.05 \cdot 10^9$	15.26 milliseconds
$1.4656^k \cdot n$	$2.10 \cdot 10^6$	0.31 milliseconds
$1.2738^k + k \cdot n$	$2.02 \cdot 10^4$	0.0003 milliseconds

Notes:

- We assume that 2^{36} instructions are carried out per second.
- The Big Bang happened roughly $13.5 \cdot 10^9$ years ago.

Goal of Parameterized Complexity

Confine the combinatorial explosion to a parameter k .



(1) Which problem–parameter combinations are fixed-parameter tractable (FPT)?
In other words, for which problem–parameter combinations are there algorithms with running times of the form

$$f(k) \cdot n^{O(1)},$$

where the f is a computable function independent of the input size n ?

(2) How small can we make the $f(k)$?

Examples of Parameters

A Parameterized Problem

Input: an instance of the problem

Parameter: a parameter

Question: a **YES-NO** question about the instance and the parameter

- A parameter can be
 - solution size
 - input size (trivial parameterization)
 - related to the structure of the input (maximum degree, treewidth, branchwidth, genus, ...)
 - combinations of parameters
 - etc.

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Coloring

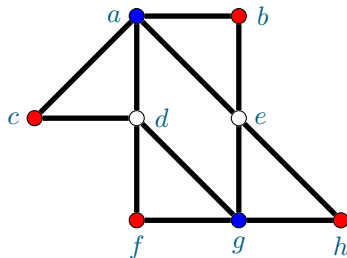
A k -coloring of a graph $G = (V, E)$ is a function $f : V \rightarrow \{1, 2, \dots, k\}$ assigning colors to V such that no two adjacent vertices receive the same color.

COLORING

Input: Graph G , integer k

Parameter: k

Question: Does G have a k -coloring?



Brute-force: $O^*(k^n)$, where $n = |V(G)|$.

Inclusion-Exclusion: $O^*(2^n)$.

FPT?

Coloring is probably not FPT

- Known: COLORING is NP-complete when $k = 3$
- Suppose there was a $O^*(f(k))$ -time algorithm for COLORING
 - Then, 3-COLORING can be solved in $O^*(f(3)) \subseteq O^*(1)$ time
 - Therefore, $P = NP$
- Therefore, COLORING is not FPT unless $P = NP$

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Algorithm for Clique

- For each subset $S \subseteq V$ of size k , check whether all vertices of S are adjacent
- Running time: $O^* \left(\binom{n}{k} \right) \subseteq O^*(n^k)$
- When $k \in O(1)$, this is polynomial
- But: we do not currently know an **FPT** algorithm for **CLIQUE**
- Since **CLIQUE** is **W[1]**-hard, we believe it is not **FPT**. (See lecture on **W**-hardness.)

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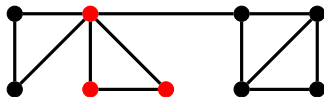
A different parameter for Clique

Δ -CLIQUE

Input: Graph $G = (V, E)$, integer k

Parameter: $\Delta(G)$, i.e., the maximum degree of G

Question: Does G have a clique of size k ?



Is Δ -CLIQUE FPT?

Algorithm for Δ -Clique

- If $k = 0$, answer **YES**.
- If $k > \Delta + 1$, answer **NO**.
- Otherwise,
 - // A clique of size k contains at least one vertex v . We try all possibilities for v .

Algorithm for Δ -Clique

- If $k = 0$, answer **YES**.
- If $k > \Delta + 1$, answer **NO**.
- Otherwise,
 - // A clique of size k contains at least one vertex v . We try all possibilities for v .
 - // For each $v \in V$, we will check whether G has a clique of size k containing v .
 - // Note that for a clique S containing v , we have $S \subseteq N_G[v]$.
 - For each $v \in V$, check for each vertex subset $S \subseteq N_G[v]$ of size k whether S is a clique in G .

Algorithm for Δ -Clique

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 - // Note that for a clique S containing v , we have $S \subseteq N_G[v]$.
 - For each $v \in V$, check for each vertex subset $S \subseteq N_G[v]$ of size k whether S is a clique in G .
- Running time: $O^*((\Delta + 1)^k) \subseteq O^*((\Delta + 1)^\Delta)$. (**FPT** for parameter Δ)

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Main Parameterized Complexity Classes

n : instance size

k : parameter

P: class of problems that can be solved in $n^{O(1)}$ time

FPT: class of parameterized problems that can be solved in $f(k) \cdot n^{O(1)}$ time

W[.]: parameterized intractability classes

XP: class of parameterized problems that can be solved in $f(k) \cdot n^{g(k)}$ time
(“polynomial when k is a constant”)

$$P \subseteq \text{FPT} \subseteq \text{W}[1] \subseteq \text{W}[2] \cdots \subseteq \text{W}[P] \subseteq \text{XP}$$

Known: If $\text{FPT} = \text{W}[1]$, then the Exponential Time Hypothesis fails, i.e. 3-SAT can be solved in $2^{o(n)}$ time, where n is the number of variables.

Note: We assume that f is **computable** and **non-decreasing**.

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- Chapter 1, *Introduction* in Marek Cygan, Fedor V. Fomin, Łukasz Kowalik, Daniel Lokshtanov, Dániel Marx, Marcin Pilipczuk, Michał Pilipczuk, and Saket Saurabh. *Parameterized Algorithms*. Springer, 2015.
- Chapter 2, *The Basic Definitions* in Rodney G. Downey and Michael R. Fellows. *Fundamentals of Parameterized Complexity*. Springer, 2013.
- Chapter 1, *Foundations* in Rolf Niedermeier. *Invitation to Fixed Parameter Algorithms*. Oxford University Press, 2006.
- *Preface* in Jörg Flum and Martin Grohe. *Parameterized Complexity Theory*. Springer, 2006.