4. Basics of Parameterized Complexity
COMP6741: Parameterized and Exact Computation

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Outline

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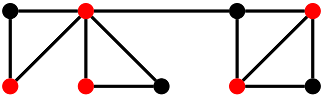
Vertex Cover

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

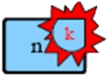
$n = 1000$ vertices,
$k = 20$ parameter

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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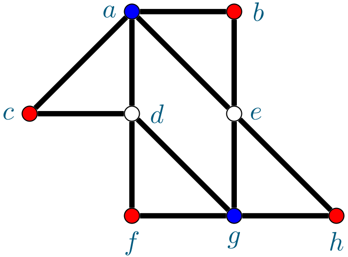
Coloring

A k-coloring of a graph $G = (V, E)$ is a function $f : V \rightarrow \{1, 2, ..., k\}$ 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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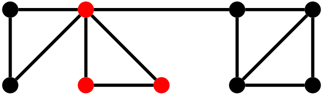
Clique

A clique in a graph $G = (V, E)$ is a subset of its vertices $S \subseteq V$ such that every two vertices from S are adjacent in G.

CLIQUE

Input:	Graph $G = (V, E)$, integer k
Parameter:	k
Question:	Does G have a clique of size k?



Is CLIQUE NP-complete when k is a fixed constant? Is it FPT?

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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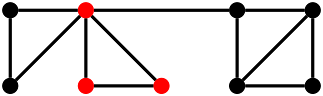
A different parameter for Clique

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

- If $k = 0$, answer $\textsc{Yes}$.
- If $k > \Delta + 1$, answer $\textsc{No}$.
- 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.
- Running time: $O^*((\Delta + 1)^k) \subseteq O^*((\Delta + 1)^\Delta)$. (FPT for parameter Δ)

Outline

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

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

Known: If FPT $=$ 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.

Outline

Further Reading

- Chapter 1, *Introduction* in
  Marek Cygan, Fedor V. Fomin, Łukasz Kowalik, Daniel Lokshtanov, Dániel Marx, Marcin Pilipczuk, MichałPilipczuk, 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 I, *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.