CS 5003: Parameterized Algorithms

Lectures 1 and 2

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* Text Books
  * Parameterized Algorithms by Cygan et al.
  * Kernelization by Fomin et al.

* Evaluation Scheme
  * Quiz 1 - 20%
  * Quiz 2 - 20%
  * Assignments - 15%
  * Endsem - 45%
  * Presentation (optional)

Review of Basic Concepts: Algorithms and Problems

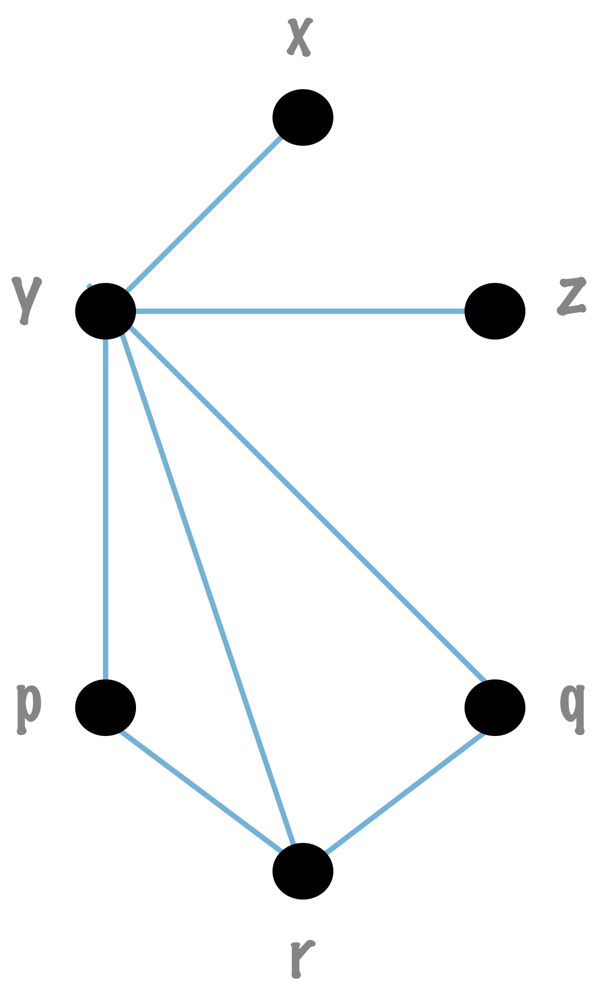
* Algorithm
    * A finite sequence of steps to solve a problem

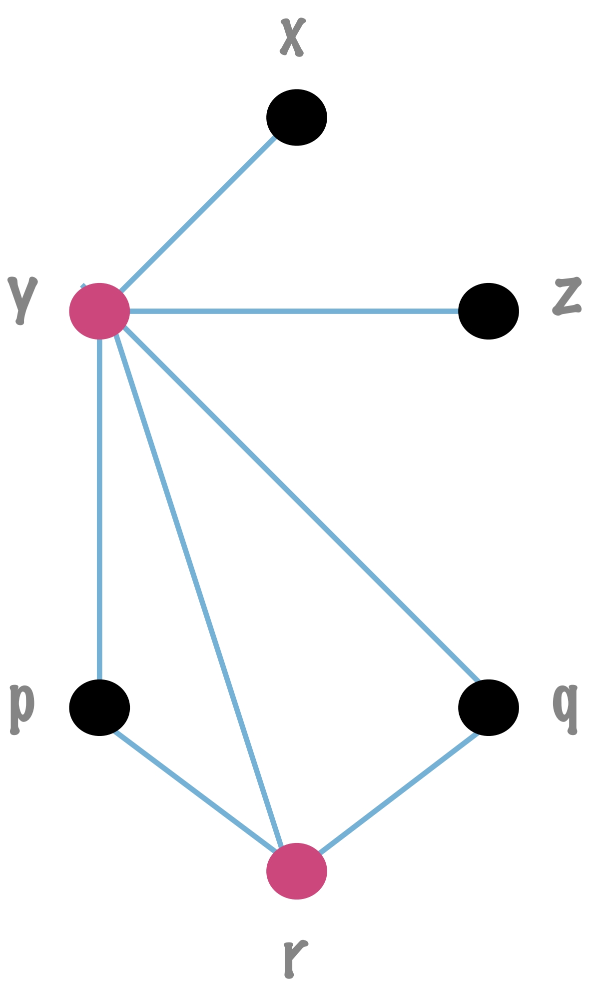
* Computational Problem
    * Input encoded in binary
    * Specification of the output desired for each input

* Instance of a problem
    * Specific input to the problem

Review of Basic Concepts: Vertex Cover

Vertex cover - set of vertices that has at least one endpoint of each edge

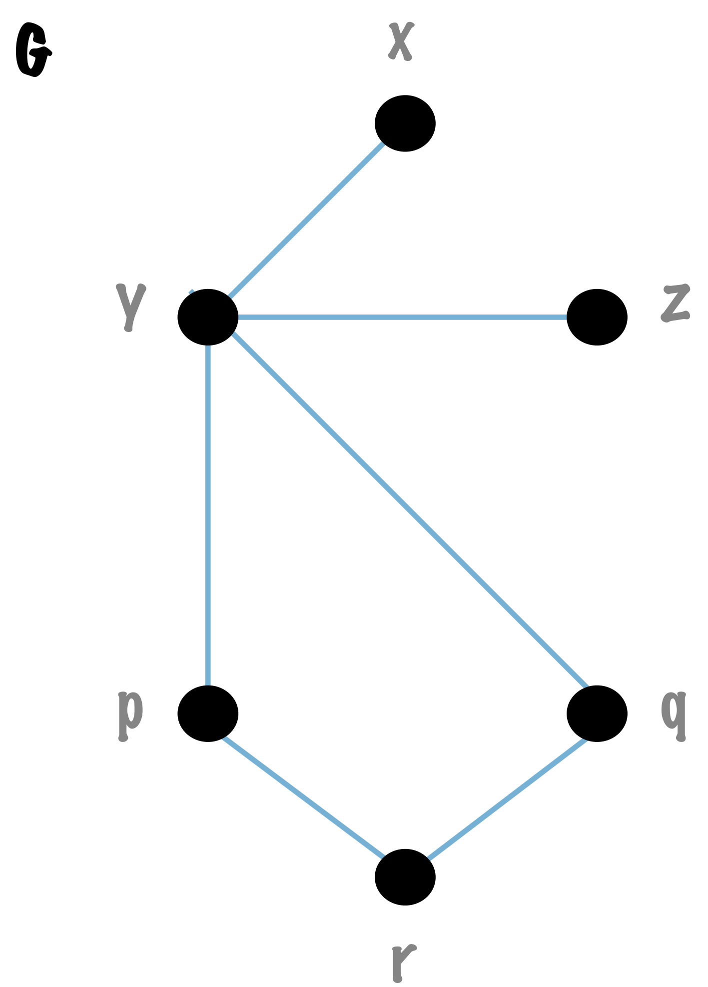


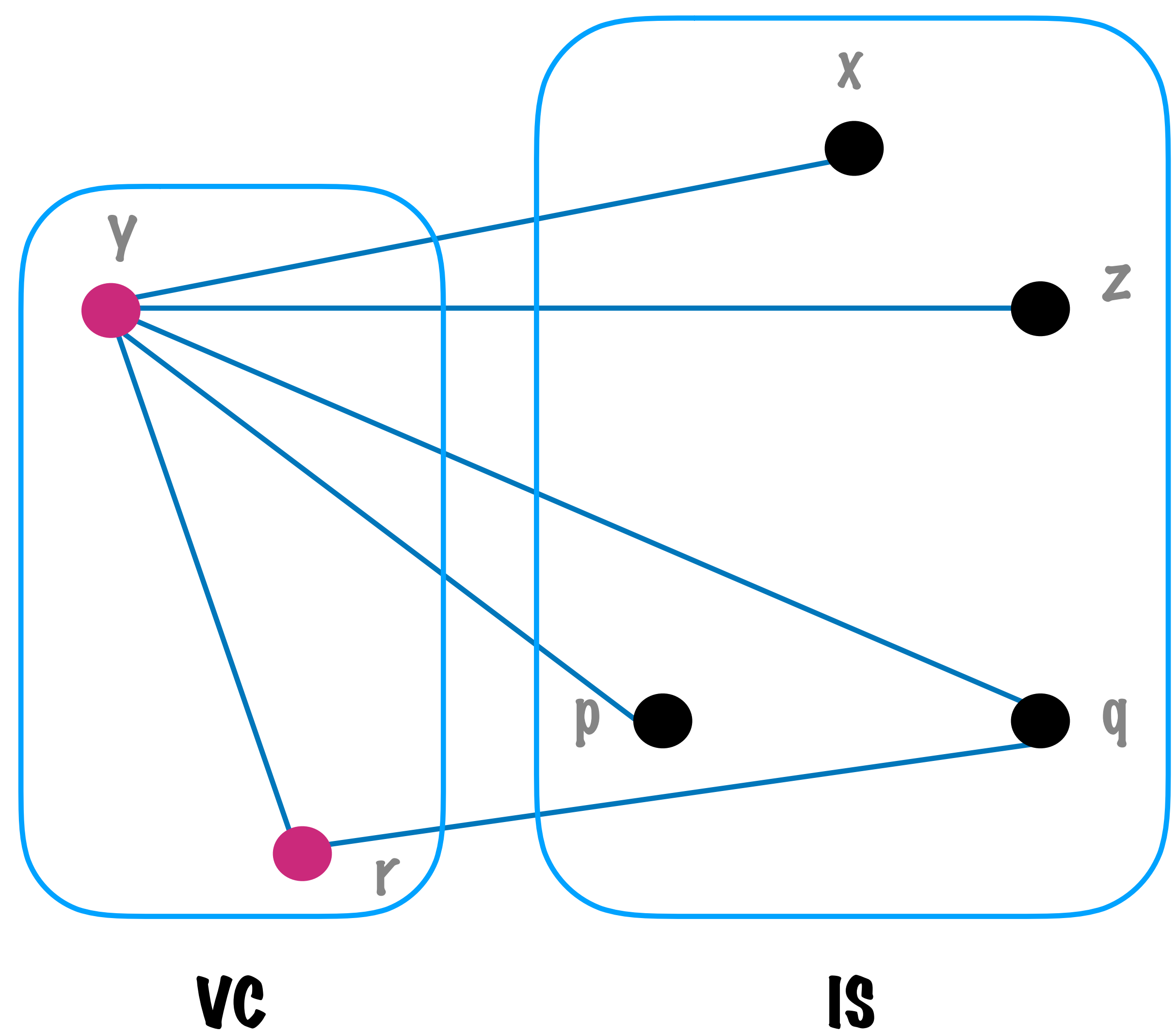


Review of Basic Concepts: Independent Set

Independent set - set of vertices that are pairwise non-adjacent

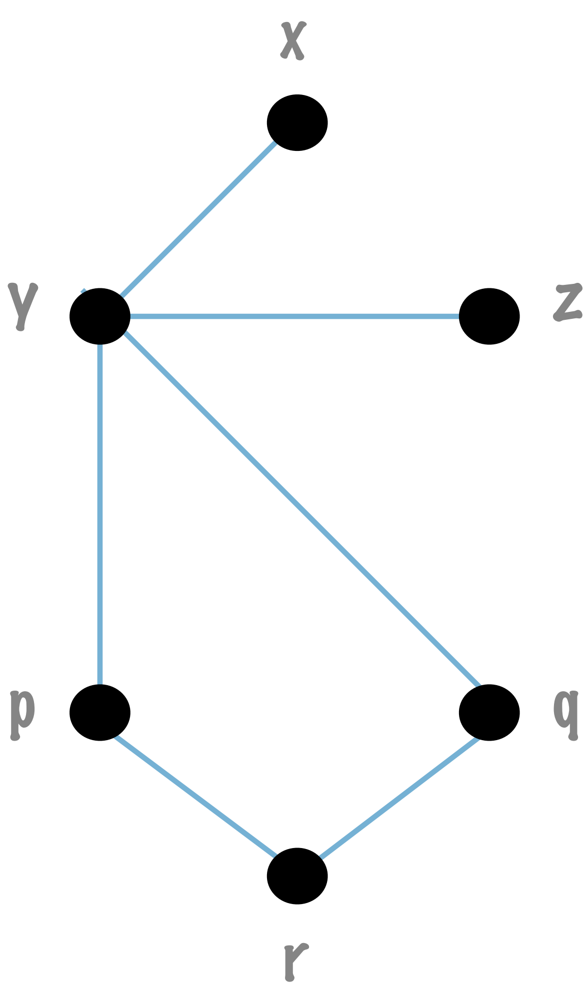
S is a vertex cover => V(G)-S is an independent set

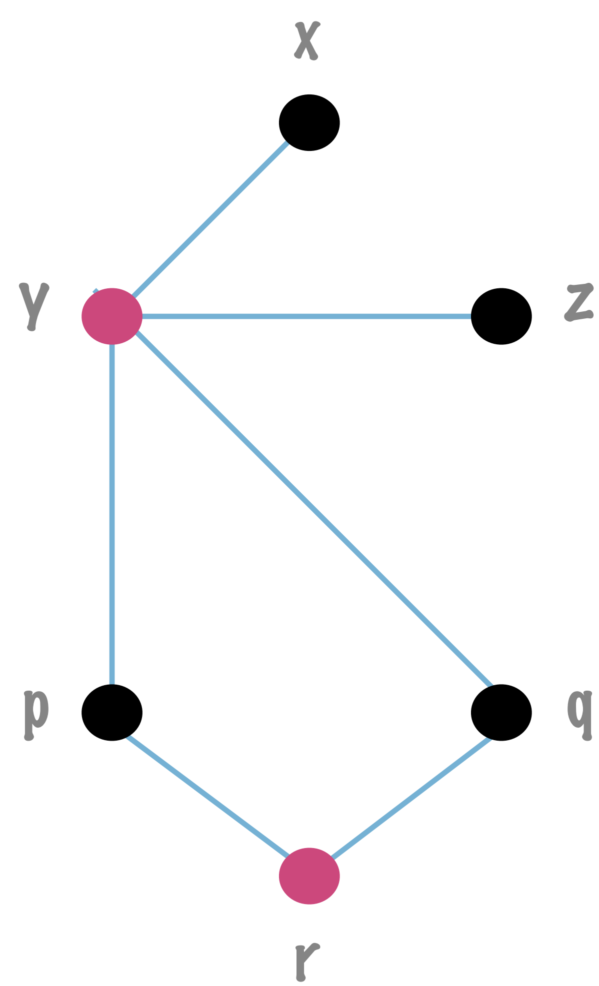




Review of Basic Concepts: Example of a Problem

Minimum Vertex Cover
Instance: An undirected graph G
Output: A minimum-size vertex cover of G

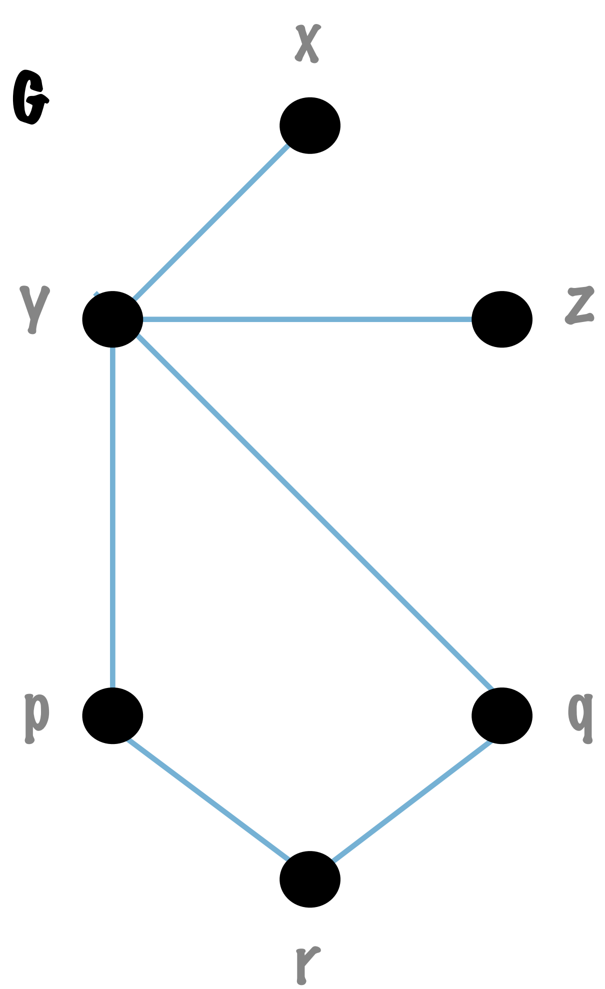




Review of Basic Concepts: Decision Problems

* Decision Problem: answer is yes or no

Vertex Cover
Instance: An undirected graph G and an integer k
Question: Does there exist a vertex cover of G of size at most k?



* (G,1) is a no-instance of Vertex Cover
* (G,2) is an yes-instance of Vertex Cover
* (G,3) is an yes-instance of Vertex Cover

Review of Basic Concepts: Classes P and EXP

- Complexity Class P
  - P is the set of all decision problems solvable in polynomial time
  - $O(n^c)$ time for some constant c where n is the input size
  - Examples: Shortest Path, Matching, Longest Path in directed acyclic graphs

- Complexity Class EXP
  - EXP is the set of all decision problems solvable in exponential time
  - $O(2^{n^c})$ time for some constant c where n is the input size
  - Examples: Vertex Cover, Travelling Salesperson, Longest Path

Review of Basic Concepts: Class NP

NP is the set of decision problems for which the problem instances, where the ans

- Complexity Class NP
  - A problem is in NP if any yes-instance can be verified that it is indeed an yes-instance in polynomial time
    - polynomial-size certificate

- Vertex Cover
  - Certificate is a vertex cover of size at most k
    - Certificate is polynomial-size
    - Can verify if a set of vertices is a vertex cover or not in polynomial time

$NP \subseteq EXP$

Review of Basic Concepts: Reductions

* Polynomial-time Reductions
    * Problem A reduces to problem B if there is a polynomial time algorithm h such that for every instance x of A
        * h(x) is an instance of B
        * x is an yes-instance of A if and only if h(x) is an yes-instance of B
* Complexity Classes NP-hard and NP-complete
    * Problem A is NP-hard if every problem in NP reduces to it in polynomial time
        * If an NP-hard problem has a polynomial-time algorithm then P=NP
    * Problem A is NP-complete if it is in NP and NP-hard

Review of Basic Concepts: Approaches to NP-hardness

* Consequence of a problem being NP-hard
    * No polynomial time (in the worst case) algorithm that solves all instances optimally is likely to exist
        * Near-optimum solution: approximation algorithms
        * Average case: Randomized algorithms
        * Restrict the input
        * Exponential time

Parameterized algorithms (or) Fixed-parameter tractable algorithms

Parameterized Problem

* Each instance is associated with a non-negative integer called parameter

Parameterized Graph Problem Template
Instance: A graph G and integer k
Question: Does G have a solution of size k?
Parameter: k

$2^{O(k^2)}$ poly(n)

$2^{O(k \log k)}$ poly(n)

size of an instance (G,k) is |G| + k

|G| is in binary whereas k is in unary

Goal: Design f(k) poly(n) algorithm

n - input size   k - parameter

fixed-parameter tractable algorithm
or
parameterized algorithm

Complexity Class FPT
is the set of all parameterized problems that are fixed-parameter tractable

Parameterized Algorithms

- Find solution in exponential time
  - Exponential factor in running time is restricted to only the parameter

Vertex Cover (parameterized by solution size)
Instance: A graph G on n vertices m edges and integer k
Question: Does G have a vertex cover of size at most k?
Parameter: k

Goal: f(k) poly(n,m) algorithm

Multiple Parameterizations

Vertex Cover (parameterized by max degree)
Instance: A graph G with max degree r and integer k
Question: Does G have a vertex cover of size at most k?
Parameter: r

Goal: f(r) poly(n,m) algorithm

Vertex Cover (parameterized by min degree)
Instance: A graph G with min degree q and integer k
Question: Does G have a vertex cover of size at most k?
Parameter: q

Goal: f(q) poly(n,m) algorithm

Not all parameterized problems are FPT

Vertex Cover Parameterized by Solution Size

<u>Instance:</u> A graph G on n vertices m edges and integer k
<u>Question:</u> Does G have a vertex cover of size at most k?
<u>Parameter:</u> k

Instance: (G,k)

Preprocessing Rule 1: Delete isolated vertices u

Resulting Instance: $(G-u,k)$

(G,k) is an yes-instance => $(G-u,k)$ is an yes-instance

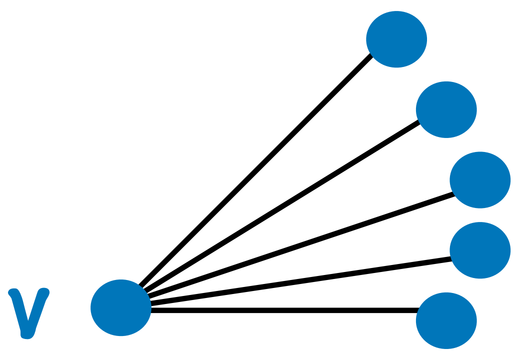
$(G-u,k)$ is an yes-instance => (G,k) is an yes-instance

Time: $O(n)$

Vertex Cover Parameterized by Solution Size

Instance: (G′,k′)

Preprocessing Rule 2: Delete high degree vertices



>= k′+1 neighbours

Add v into the solution

Resulting Instance: (G′-v,k′-1)

(G′,k′) is an yes-instance => (G′-v,k′-1) is an yes-instance

(G′-v,k′-1) is an yes-instance => (G′,k′) is an yes-instance

We have to repeatedly apply this preprocessing rules

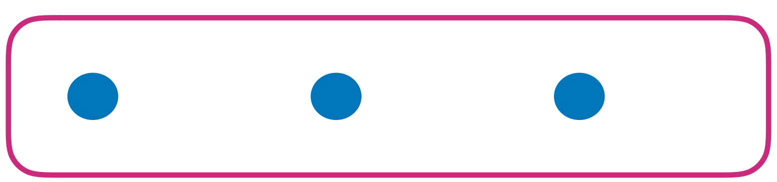
Time: $O(nk^2)$

Vertex Cover Parameterized by Solution Size

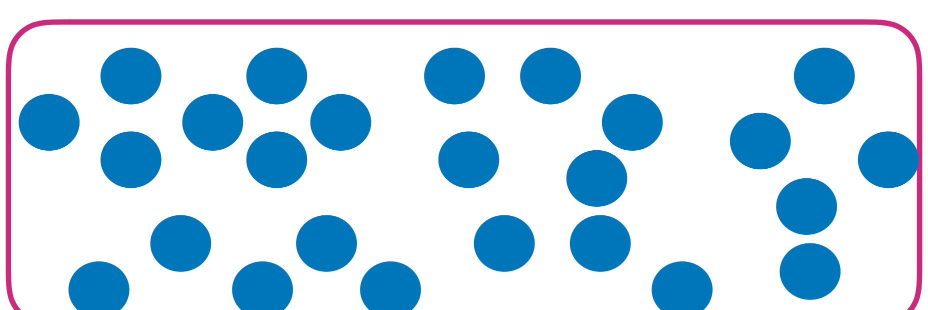
Instance: (H,r)

(G,k) is an yes-instance iff (H,r) is an yes-instance

Suppose (H,r) is an yes-instance



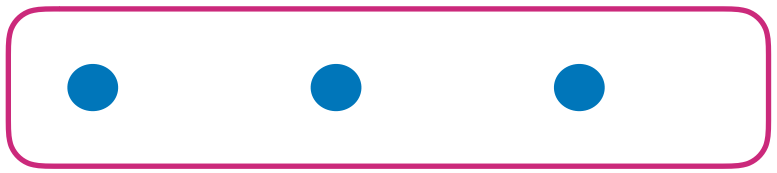
S a vertex cover of H with |S| <= r <=k



Independent Set

Vertex Cover Parameterized by Solution Size

Suppose (H,r) is an yes-instance



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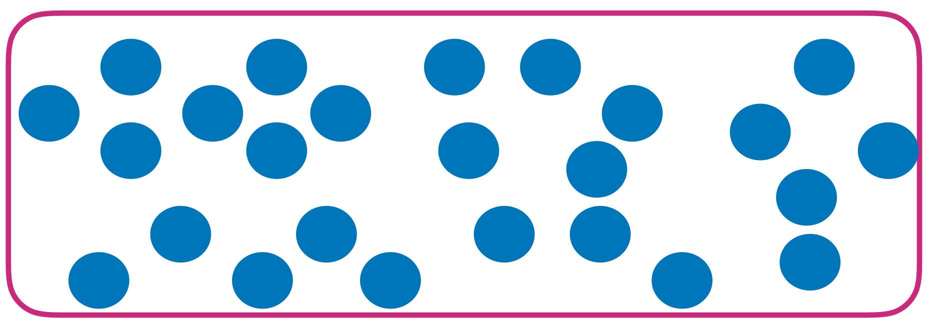


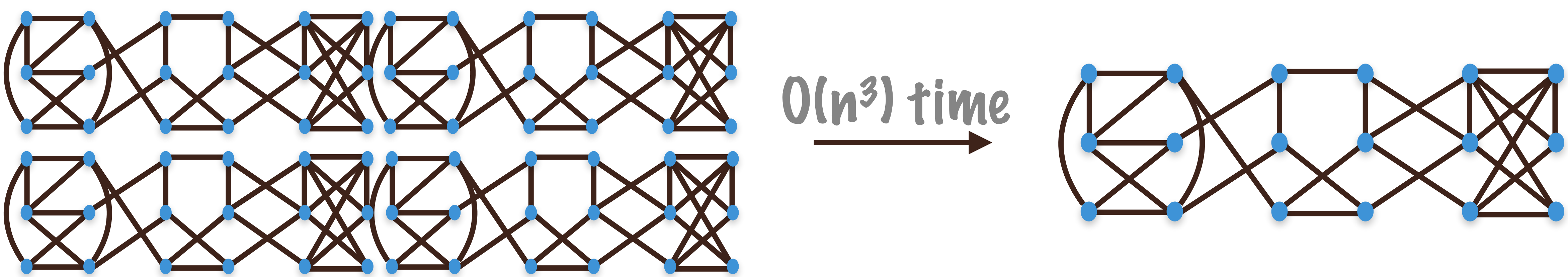
Independent Set

Can H have more than r^2 edges?

Vertex Cover Parameterized by Solution Size

If H has more than r^2 edges then (H,r) is no yes-instance

Otherwise, H has at most r^2 edges and at most $r+r^2$ vertices



G on n vertices and m edges
Does G have a VC of size <= k?
Parameter: k

H on $r+r^2$ vertices and r^2 edges
Does H have a VC of size <= r?
Parameter: r

$|(H,r)| = f(k)$ Kernel

(G,k) is an yes-instance iff (H,r) is an yes-instance

Kernel => FPT