

# Parameterization: basics classes and algorithms

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- 1 Parameterization
- 2 Bounded search tree
- 3 Kernelization

# Three NP complete problems

## VERTEX COLORING

Given a graph  $G$  and an integer  $k$ ,

$$\exists \sigma : V(G) \rightarrow \{1, \dots, k\} \mid \forall \{u, v\} \in E(G) \sigma(u) \neq \sigma(v)?$$

## INDEPENDENT SET

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$$\exists S \subseteq V(G) \mid |S| = k \text{ and } \forall \{u, v\} \in E(G) |\{u, v\} \cap S| \leq 1?$$

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Let's look to exact algorithms.

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- takes time  $O(n^{k+1})$  time.

A better algorithm?

# Vertex Cover

**function**  $\text{ALGVC}(G, k)$

**if**  $|E(G)| = 0$  **then**

**return** true

**if**  $k = 0$  **then**

**return** false

Select an edge  $e = \{u, v\} \in E(G)$

**return**  $\text{ALGVC}(G - u, k - 1)$  or  $\text{ALGVC}(G - v, k - 1)$

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  Select an edge  $e = \{u, v\} \in E(G)$   
  return ALGVC( $G - u, k - 1$ ) or ALGVC( $G - v, k - 1$ )
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Correctly solves the problem and takes time  $O(m2^k)$

# Algorithms cost

Given a graph  $G$  and an integer  $k$ :

- **VERTEX COLORING**:  $O(n^2 k^n)$
- **INDEPENDENT SET**:  $O(n^{k+1})$
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**Objective:** Find slices of the problem having efficient algorithms

**Slice:** The instances with a particular value of a parameter

# Natural small parameters

- VLSI design: the number of layers in a chip is below 10.
- Biology: DNA chains in many cases have **path width** below 11
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- Optimization problem: the measure of the optimal solution is small
- A problem might have more than one parameter of interest and the behavior with respect to different parameters might be different.

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- Parameterized problems are **decision problems** together with a parameterization.
- A problem can be analyzed under different parameterizations.

# Parameterized problem: An example

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Given a CNF formula  $F$ ,  
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- Consider  $\kappa : \Sigma^* \rightarrow \mathbb{N}$

$$\kappa(w) = \begin{cases} \# \text{ of variables in } F & \text{if } w \text{ codifies } F \\ -3 & \text{otherwise} \end{cases}$$

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## P#VAR-SAT

Input: A CNF formula  $F$ ,

Parameter: The number of variables in  $F$

Question: is there a satisfying assignment for  $F$ ?

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## PMAX#LIT-SAT

Input: A CNF formula  $F$

Parameter: The maximum number of literals in a clause in  $F$

Question: is there a satisfying assignment for  $F$ ?

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**P- $\Pi$**

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Parameter:  $k$

Question: Is there a solution  $y \in \text{sol}(x)$  such that  $m(x, y) \leq (\geq)k$ ?

# Graph problems and parameters

- Let  $G$  be a graph and  $k$  a natural number.
- The function  $\kappa(G, k) = k$  is used to define the parameterized problems
  - P-INDEPENDENT SET
  - P-VERTEX COLORING
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  - P-DOMINATING SET
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  - etc.

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  - etc.
- For problems on graphs we can use other graph properties to define **graph parameters** like max degree or diameter.  
Or any other graph parameter of interest.

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- We have show that there is an algorithm for VERTEX COVER requiring  $O(|E(G)|2^k)$  time  
**P-VERTEX COVER belongs to FPT!**

# Other classes (hard parameterized problems)

- **paraNP**

- $(L, \kappa)$  belongs to paraNP if there is a **non-deterministic** algorithm  $\mathcal{A}$  that decides  $x \in L$  in time  $f(\kappa(x))p(|x|)$ , for **computable** function  $f$  and **polynomial** function  $p$ .

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p-Clique, p-Vertex Cover, ... belong to paraNP.
- paraNP is the counterpart of NP in classic complexity.

- **XP**

- $(L, \kappa)$  belongs to (uniform) XP if there is an algorithm  $\mathcal{A}$  that decides  $x \in L$  in time  $O(|x|^{f(\kappa(x))})$ , for a **computable** function  $f$ .

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# Other classes (hard parameterized problems)

- **paraNP**

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- 1 Parameterization
- 2 Bounded search tree**
- 3 Kernelization

# p-Vertex Cover

## P-VC

Input: a graph  $G$  and an integer  $k$ ,

Parameter:  $k$

Question:  $\exists S \subseteq V(G) \mid |S| = k$  and  $\forall \{u, v\} \in E(G) \mid \{u, v\} \cap S \geq 1$ ?

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**function**  $\text{ALGVC}(G, k)$

**if**  $|E(G)| = 0$  **then**

**return** true

**if**  $k = 0$  **then**

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  Select an edge  $e = \{u, v\} \in E(G)$

**return**  $\text{ALGVC}(G - u, k - 1)$  or  $\text{ALGVC}(G - v, k - 1)$

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- Such type of recursive algorithm is called a **bounded search tree algorithm**.
- If we have a constant bound on the number of recursive calls, depth bounded by the parameter, and polynomial cost per call, the resulting algorithm is an FPT algorithm.

# Hitting Set

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Input: a collection of subsets  $\mathcal{S} = (S_1, \dots, S_m)$  of  $U = \{1, \dots, n\}$  and an integer  $k$ .

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function ALGHS( $U, \mathcal{S}, k$ )  
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     $V = U - \{v\}$ ;  $\mathcal{S}_v = \{X \in \mathcal{S} \mid v \notin X\}$   
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Solves P-HITTING SET in time?

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- using the above inequalities it is easy to prove that

$$T(s, k, d) \leq (2d^k - 1)cs.$$

# p-Hitting Set

Lemma

P-HITTING SET *belongs to FPT*

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- When the parameter is unbounded the algorithms take exponential time.
- We get FPT algorithm because the **depth** and/or **branching** of the recursion are **function of the parameter**.
- This algorithmic technique is called **bounded search trees**.
- As a design tool we have to look for parameterizations allowing a recursive algorithm with those characteristics.

# A faster algorithm for p-VC

Recall some notation

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- For a graph  $G$  and  $v \in V(G)$ ,  $G - v$  denotes the graph obtained by deleting  $v$  (and all incident edges).
- For a set  $S$ ,  $S + v$  denotes  $S \cup \{v\}$ , and  $S - v$  denotes  $S \setminus \{v\}$ .
- For a vertex  $v \in V(G)$ ,  $N(v)$  denotes the set of neighbors of  $v$ .  
 $N[v] = N(v) + v$ .  $d(v) = |N(v)|$ .
- For a graph  $G = (V, E)$ ,  $\delta(G) = \min_{v \in V} d(v)$ , and  
 $\Delta(G) = \max_{v \in V} d(v)$ .

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- The recursion can skip a branching!

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- If  $\delta(G) \geq 2$ ,  $x \geq 2$ . The recursion can jump to a smaller problem in one step!

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- How to get a bound in the cost? **Guess and prove by induction!**

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- If  $k \geq 1$ , then there are 3 cases:

# A faster algorithm for p-VC

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- $G$  contains a degree 1 vertex, continue with the single instance  $(G - v, k - 1)$ , which by induction yields  $1.47^{k-1} < 1.47^k$  leaves.

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- $G$  contains a degree  $d \geq 3$  vertex, branch into two cases  $(G', k - 1)$  and  $(G'', k - d)$ . By induction, the total number of leaves is at most  $1.47^{k-1} + 1.47^{k-d} \leq 1.47^k$ .



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## Theorem

**FASTVC** has cost  $O(1.47^k p(n + m))$ , for some polynomial  $p$  besides the constant in  $O$  is also constant with respect to the parameter  $k$ .

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- We look for a polynomial time algorithm that transforms an instance  $x$  in another instance  $x'$  of the problem ([the kernel](#)). So that

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- We look for a polynomial time algorithm that transforms an instance  $x$  in another instance  $x'$  of the problem (the kernel). So that
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So, it is an FPT algorithm provided the problem is decidable.

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## $p$ -VERTEX COVER

Input: a graph  $G$  and an integer  $k$ ,

Parameter:  $k$

Question:  $\exists S \subseteq V(G) \mid |S| = k$  and  $\forall \{u, v\} \in E(G) \mid \{u, v\} \cap S \geq 1$ ?

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- Let  $(G, k)$  be a  $k$ -VC instance.
- recall: Two instances  $x_1$  and  $x_2$  of decision problem  $P$  are **equivalent** when " $x_1 \in P$  iff  $x_2 \in P$ ".

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- How big is  $(G', k')$ ?

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- So, we can filter as NO instances those leading to reduced instances with a high number of edges!
- By Obs 3, if  $|E(G')| > k^2$ , we replace  $(G', k')$  by a trivial small NO-instance, which is again equivalent.

# Kernel

## Theorem

Let  $(G, k)$  be an instance to **P-VC**. In polynomial time we can obtain an equivalent **P-VC** instance  $(G', k')$  with  $|V(G')|, |E(G')| \leq O(k^2)$ .

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# Kernelization algorithm

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- Assume that  $\text{KER-P}$  is a polynomial time algorithm computing a kernel for a given instance of problem  $\text{P}$  and that  $\text{ALG-P}$  is an exact (exponential time) algorithm for  $\text{P}$ .

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function ALGKERNEL-P( $x$ )  
   $z = \text{KER-P}(x)$   
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function ALGKER-P( $x$ )  
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- $\text{ALGKER-P-VC}$  is an FPT algorithm for  $P$ .

# A kernelization algorithm for p-VC

**function** ALGKERNEL-P-VC( $G, k$ )

$(G', k') =$  Iteratively remove isolated vertices and vertices with degree at least  $k + 1$ , decreasing the parameter by one in the second case.

**if**  $|E(G')| > k^2$  **then return** NO

**for** each  $S \subseteq V'$  with  $|S| = k'$  **do**

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ALGKERNEL-P-VC runs in  $O(n^c + k^{2k}k^2) = O(n^c) + O(k^{2k+2})$

# p-MaxSat

## P-MAXSAT

Input: a Boolean CNF formula  $F$  and an integer  $k$ .

Parameter:  $k$ .

Question: Is there a variable assignment satisfying at least  $k$  clauses?

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Question: Is there a variable assignment satisfying at least  $k$  clauses?

Recall that the size of a CNF formula is the sum of clause lengths (# literals); we ignore as usual log-factors.

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Let  $F'$  be obtained from formula  $F$  by removing all  $t$  trivial clauses.  $(F', k - t)$  and  $(F, k)$  are equivalent.

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## Obs 2

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If  $F$  contains at least  $2k$  clauses,  $(F, k)$  is a YES instance of **P-MAXSAT**.

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## Proof.

Take an arbitrary truth assignment  $x$  and its complement  $\bar{x}$  obtained by flipping all variables. Every clause of  $F$  is satisfied by  $x$  or by  $\overline{linex}$  (or by both). The one that satisfies most clauses satisfies at least  $k$  clauses.



# A kernelization algorithm for p-MaxSat

```
1: function ALGKERNEL-P-MAXSAT( $F, k$ )
2:   Remove from  $F$  all  $t$  trivial clauses and set  $k = k - t$ 
3:   if  $F$  has at least  $k$  long clauses then return YES
4:   Remove from  $F$  all  $\ell$  long clauses and set  $k = k - \ell$ 
5:   if  $F$  has at least  $2k$  clauses then return YES
6:   for each set of  $k$  clauses do
7:     for each selection of one literal per clause in the set do
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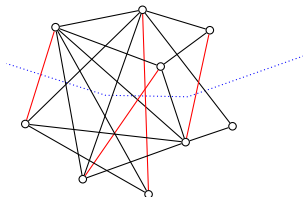
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ALGKERNEL-P-MAXSAT is an FPT algorithm for p-MAXSAT.

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- For disjoint vertex subsets  $U, W$  of a graph  $G$ ,  $M$  is a **matching of  $U$  into  $W$**  if every edge of  $M$  connects a vertex of  $U$  and a vertex of  $W$  and every vertex of  $U$  is an endpoint of some edge of  $M$ . We also say that  **$M$  saturates  $U$** .



If  $M$  saturates  $U$ ,  $|U| \leq |W|$

# Crown decomposition: Definition

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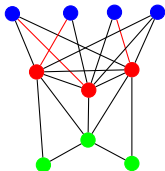
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# Computing a crown decomposition

## Theorem (König's theorem)

*In every undirected bipartite graph the size of a maximum matching is equal to the size of a minimum vertex cover.*

## Theorem (Hall's theorem)

*Let  $G = (V_1, V_2, E)$  be an undirected bipartite graph.  $G$  has a matching saturating  $V_1$  iff for all  $X \subseteq V_1$ , we have  $|N(X)| \geq |X|$ .*

Can you obtain a minimum vertex cover in a bipartite graph in polynomial time?

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# Computing a crown decomposition

Theorem ((Hopcroft-Karp, SIAM J. Computing 2, 225–231 (1973)))

*Let  $G = (V_1, V_2, E)$  be an undirected bipartite graph on  $n$  vertices and  $m$  edges. Then we can find a maximum matching as well as a minimum vertex cover of  $G$  in time  $O(m\sqrt{n})$ . Furthermore, in time  $O(m\sqrt{n})$  either we can find a matching saturating  $V_1$  or an inclusion-wise minimal set  $X \subseteq V_1$  such that  $|N(X)| < |X|$ .*

# Crown lemma

## Lemma

Let  $G = (V, E)$  be a graph without isolated vertices and with at least  $3k + 1$  vertices. There is a polynomial-time algorithm that either

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

## Proof

We compute a maximal matching  $M$  in  $G$ .

If  $|M| \geq k + 1$ , we are done.

Now,  $1 \leq |M| \leq k + 1$ .

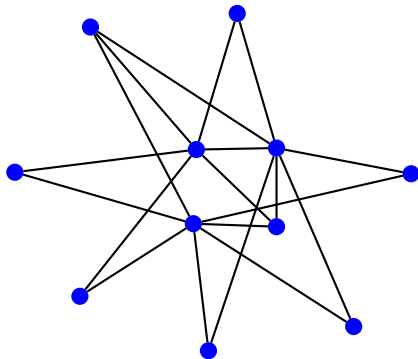
Let  $V_M$  be the end points of  $M$  and  $I = V - V_M$ .

- $M$  is a maximal matching, so  $I$  is an independent set.
- Let  $G_{I, V_M}$  be the bipartite subgraph induced in  $G$  by  $I$  and  $V_M$ .
- In polynomial time, we compute a minimum size vertex cover  $X$  and a maximum matching  $M'$  in  $G_{I, V_M}$ .
- If  $|M'| \geq k$ , we are done. From now on,  $|M'| \leq k$  and also  $|X| \leq k$ .
- If  $X \cap V_M = \emptyset$ ,  $X = I$ . Then,  $|I| = |X| \leq k$  and  $|V| = |I| + |X| \leq k + 2k \leq 3k!$
- Then,  $X \cap V_M \neq \emptyset$

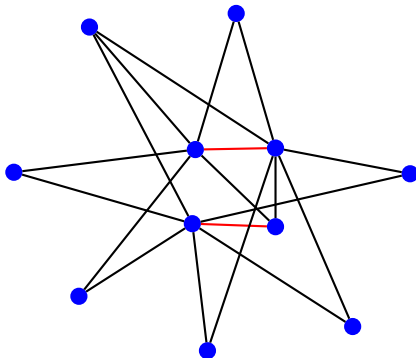
- We obtain a crown decomposition  $(C, H, R)$  as follows.
- Since  $|X| = |M'|$ , every edge of the matching  $M'$  has exactly one endpoint in  $X$ .
- Let  $M^*$  be the subset of  $M'$  such that every edge from  $M^*$  has exactly one endpoint in  $X \cap V_M$  and let  $V_{M^*}$  denote the set of endpoints of edges in  $M^*$ .
- Set head  $H = X \cap V_M = X \cap V_{M^*}$ , crown  $C = V_{M^*} \cap I$ , and the remaining part is  $R$ .
- $C$  is an independent set and, by construction,  $M^*$  is a matching of  $H$  into  $C$ .
- Since  $X$  is a vertex cover of  $G_{I, V_M}$ , every vertex of  $C$  can be adjacent only to vertices of  $H$ .

End proof

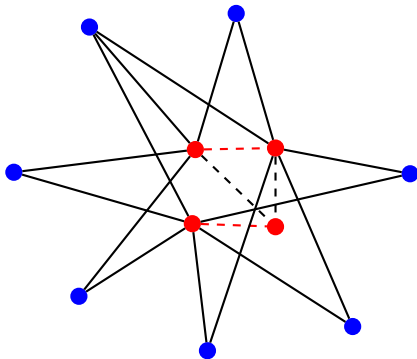
# An example with $k = 3$



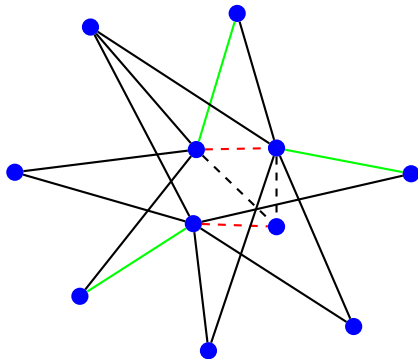
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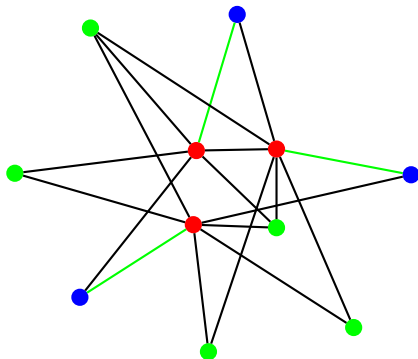
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# Crown decomposition: Vertex cover

Consider a Vertex Cover instance  $(G, k)$ .

- By an exhaustive application of the isolated vertex reduction rule, we may assume that  $G$  has no isolated vertices.
- If  $|V(G)| > 3k$ , we use the crown lemma to get either
- a matching of size  $k + 1$ , (so  $(G, k)$  is a no-instance) or a crown decomposition  $C, H, R$ .

# Crown decomposition: Vertex cover

From the crown decomposition  $C, H, R$  of  $G$ , let  $M$  be a matching of  $H$  into  $C$ .

- The matching  $M$  witnesses that, for every vertex cover  $X$  of  $G$ ,  $X$  contains at least  $|M| = |H|$  vertices of  $H \cap C$  to cover the edges of  $M$ .
- $H$  covers all edges of  $G$  that are incident to  $H \cup C$ .
- So, there exists a minimum vertex cover of  $G$  that contains  $H$ , and we may reduce  $(G, k)$  to  $(G - H, k - |H|)$ .
- Further, in  $(G - H, k - |H|)$ ,  $c \in C$  is isolated and can be eliminated.

# Crown decomposition: Vertex cover

As the crown lemma promises that  $H \neq \emptyset$ , we can always reduce the graph as long as  $|V(G)| > 3k$ .

## Lemma

*Vertex Cover admits a kernel with at most  $3k$  vertices.*

# Crown decomposition: Max SAT

## Lemma

*Max SAT admits a kernel with at most  $k$  variables and  $2k$  clauses.*

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- Kernelization algorithms usually consist of reduction rules, which reduce simple local structures (degree 1 vertices / high degree vertices / long clauses, etc), and a bound  $f(k)$  for irreducible instances  $(X, k)$  that allows us to
  - return NO if  $|X| > f(k)$ , for minimization problems, or
  - return YES if  $|X| > f(k)$ , for maximization problems.

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- **Any problem in FPT admits a kernelization.**
- Hardness notion?
- We would like to get a kernel as small as possible.
- Statements like:  $(L, \kappa)$  does not admit a linear (quadratic) kernel unless **some complexity assumption fails** are the kind of results showing kernelization hardness.