Linear-Time Counting Algorithms for Independent Sets in Chordal Graphs

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$\boxed{\text{Setup}}$ $G = (V, E)$ a graph (undirected, finite, simple)

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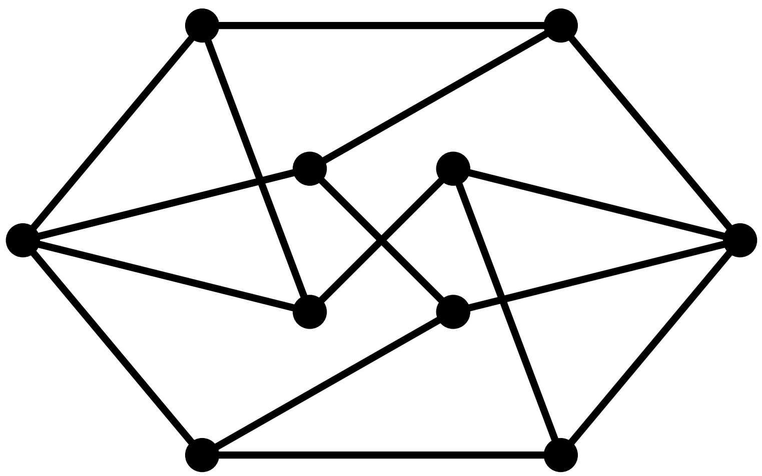
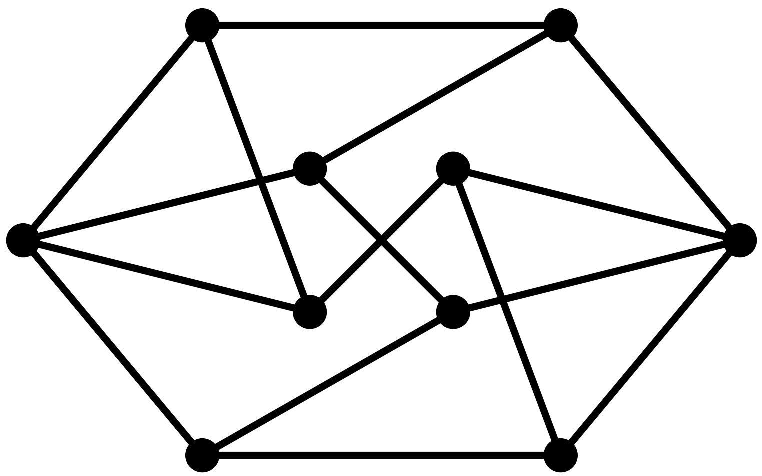


Setup $G = (V, E)$ a graph (undirected, finite, simple)

Def. A set $I \subseteq V$ is an **independent set** of G if no two vertices in I are adjacent.



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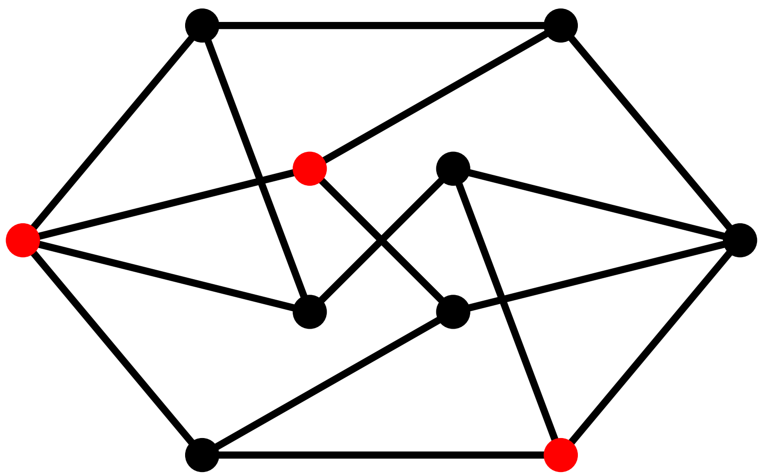

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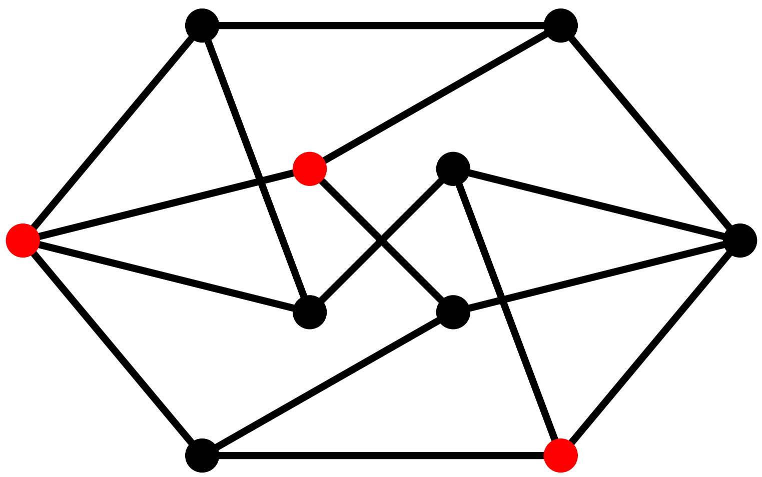

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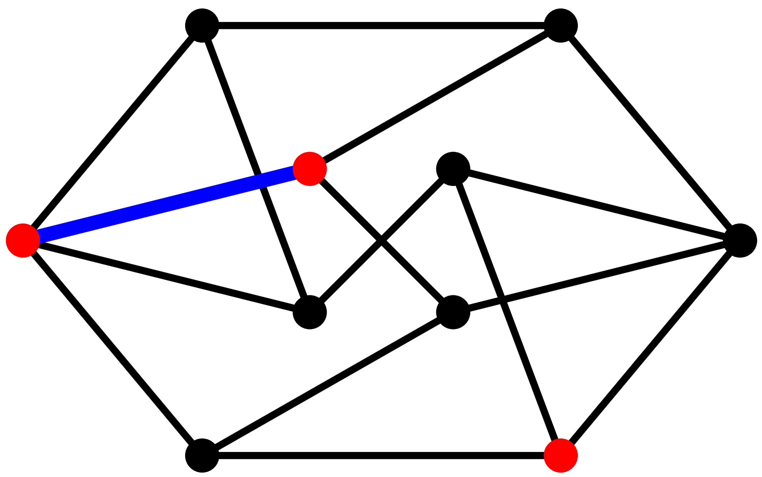

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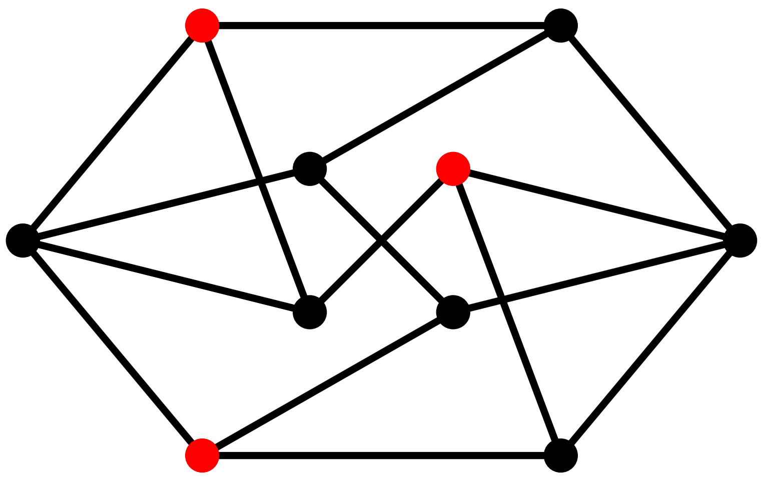

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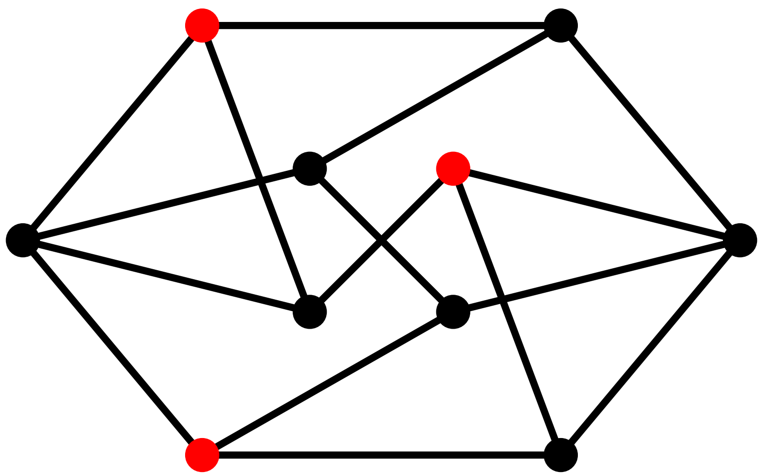

An independent set

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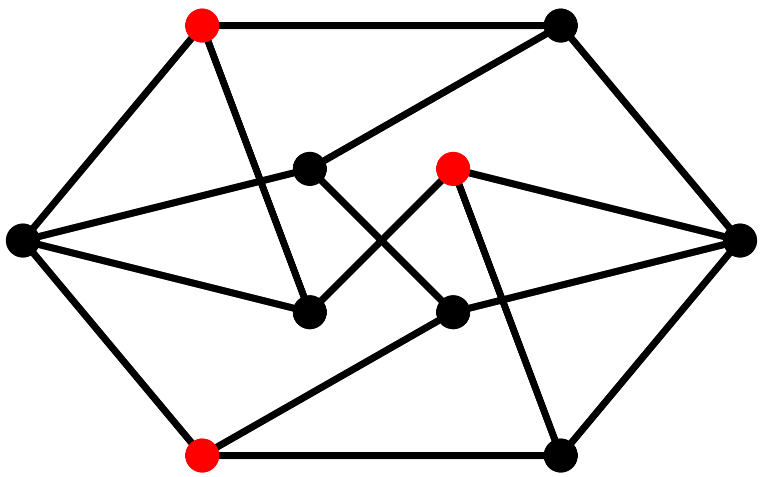
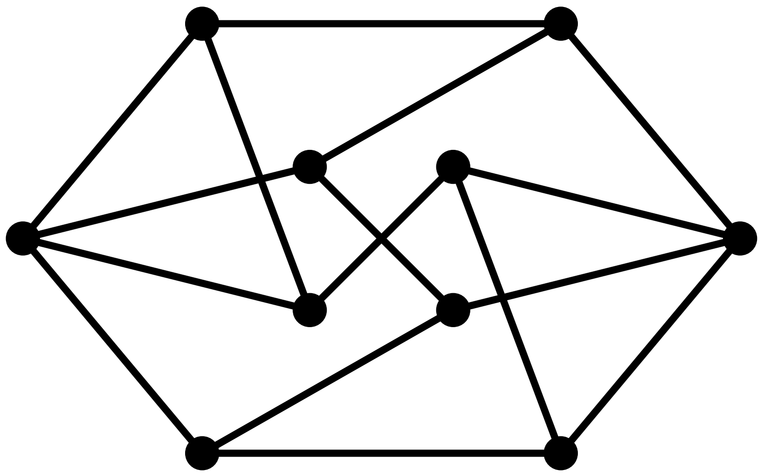


An independent set

Also called a stable set of G

$\boxed{\text{Input}}$ $G = (V, E)$ a graph

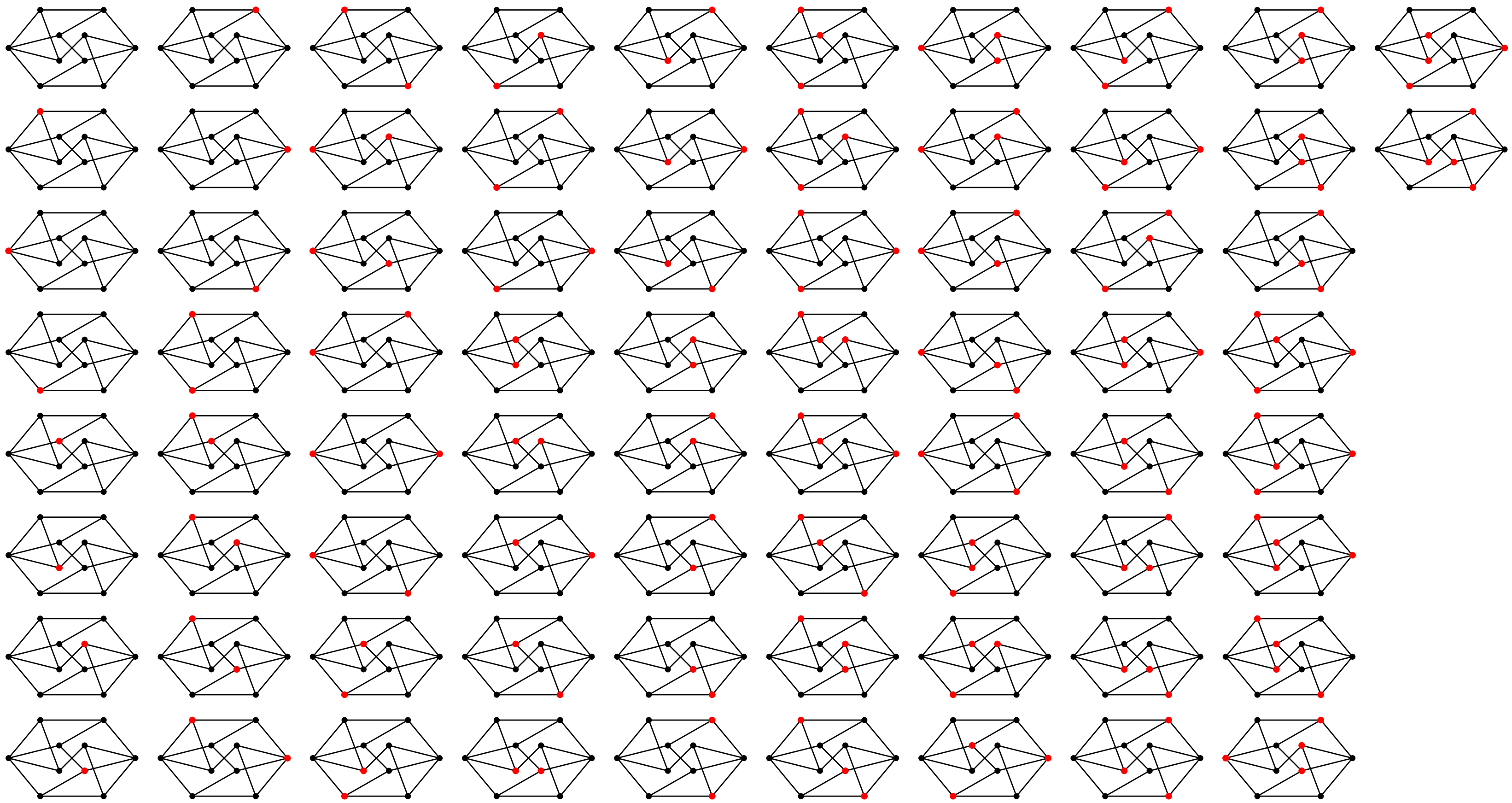
$\boxed{\text{Output}}$ All independent sets of G



An enumeration problem

Input $G = (V, E)$ a graph

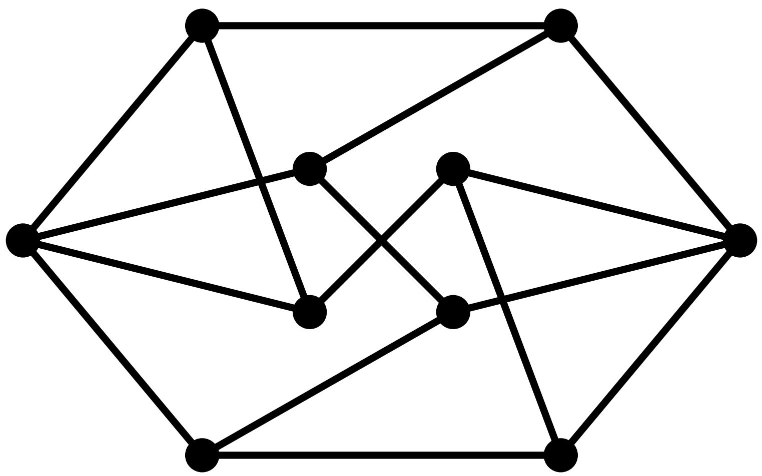
Output All independent sets of G



74 independent sets in total

Input $G = (V, E)$ a graph

Output $\#$ independent sets of G



$\boxed{\text{Input}}$ $G = (V, E)$ a graph

$\boxed{\text{Output}}$ # independent sets of G

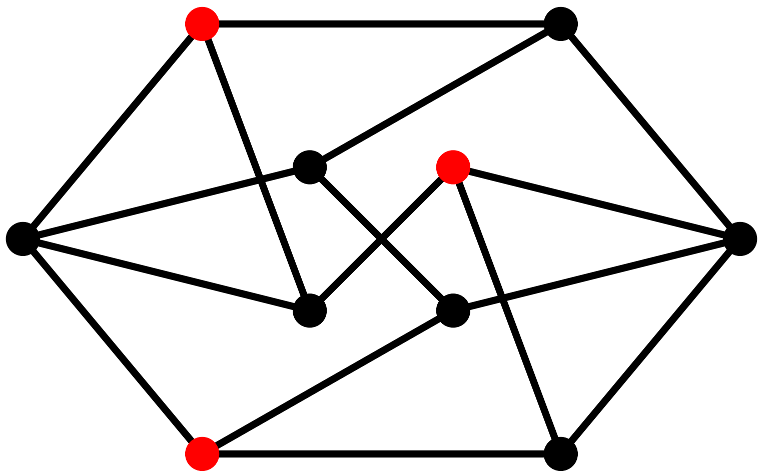
74

We study the following **counting problems**:

Input	$G = (V, E)$ a graph
Output	(1) # independent sets of G
	(2) # maximum independent sets of G
	(3) # independent sets of G of fixed size
	(4) # maximal independent sets of G
	(5) # minimum maximal independent sets of G

Setup $G = (V, E)$ a graph

Def. An independent set I of G is **maximum** if it has the largest size among all independent sets of G.



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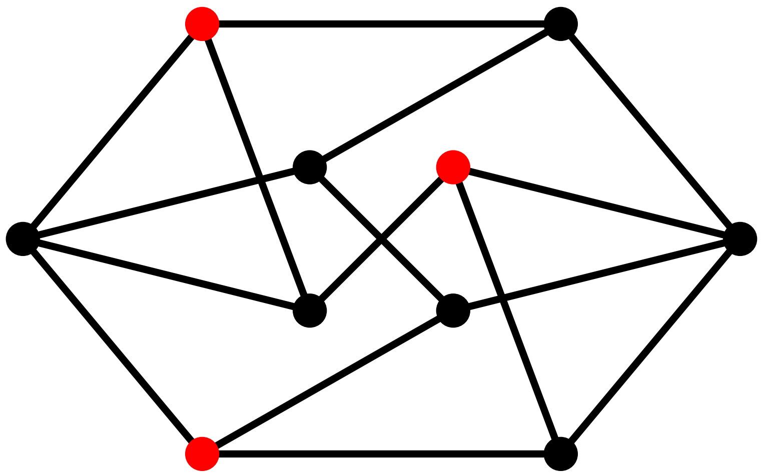

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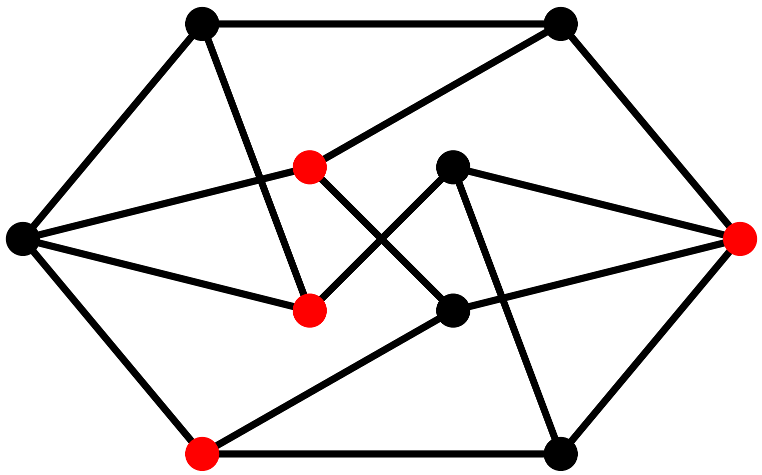

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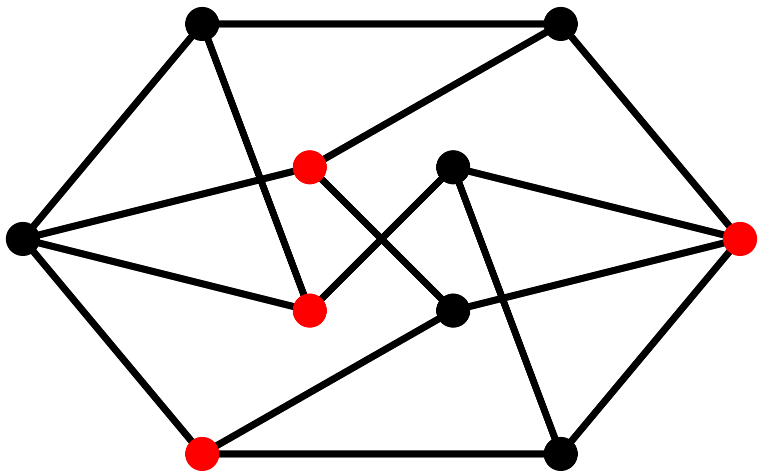
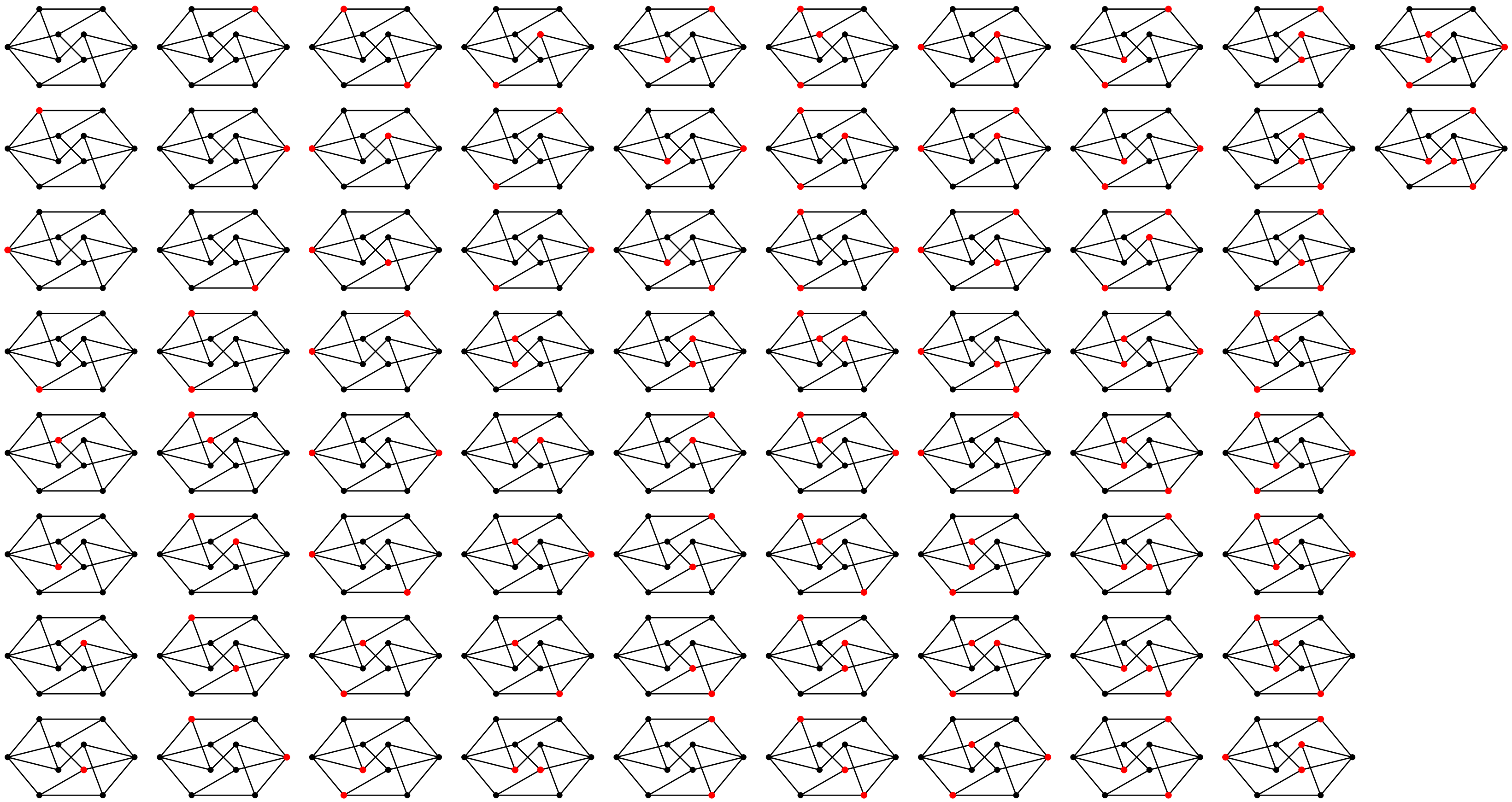


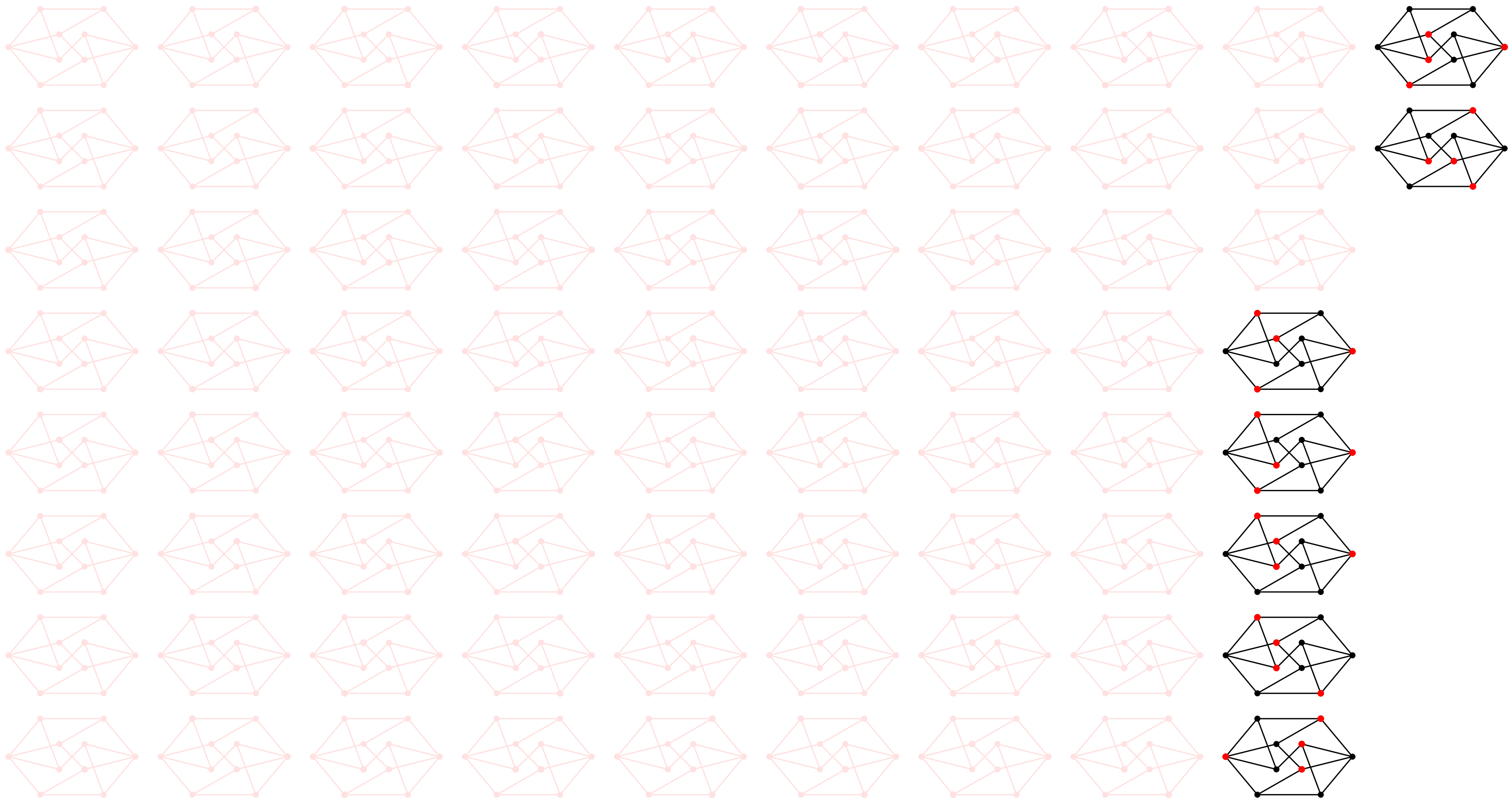
Maximum

Maximum independent sets



74 independent sets

Maximum independent sets

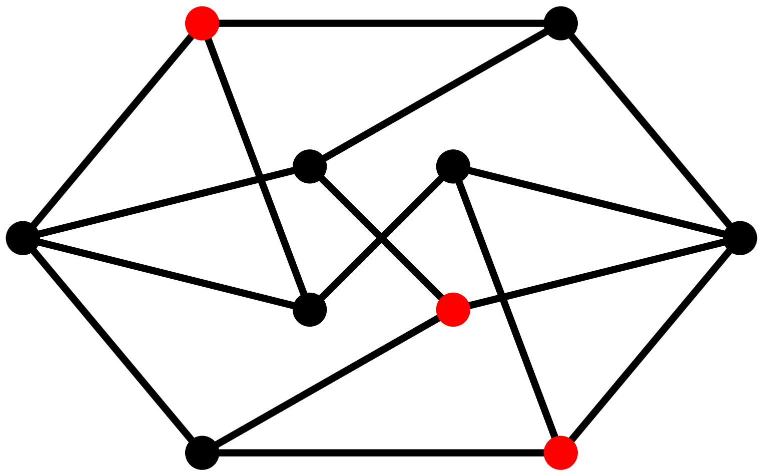


74 independent sets

7 maximum independent sets

Setup $G = (V, E)$ a graph

Def. An independent set I of G is **maximal** if no proper superset of I is independent.



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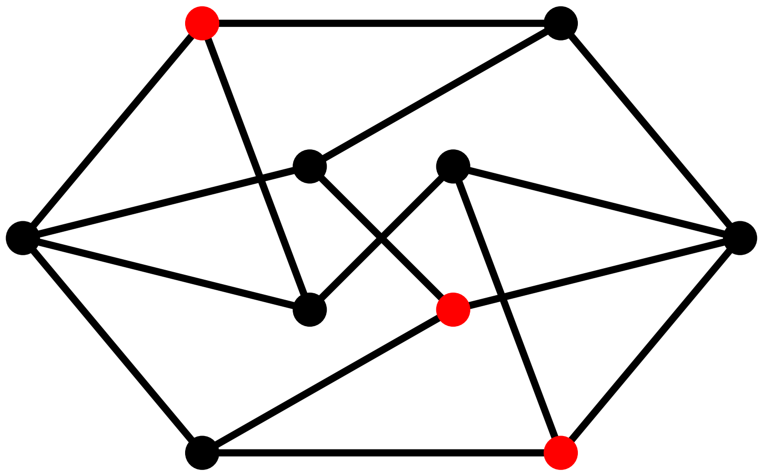

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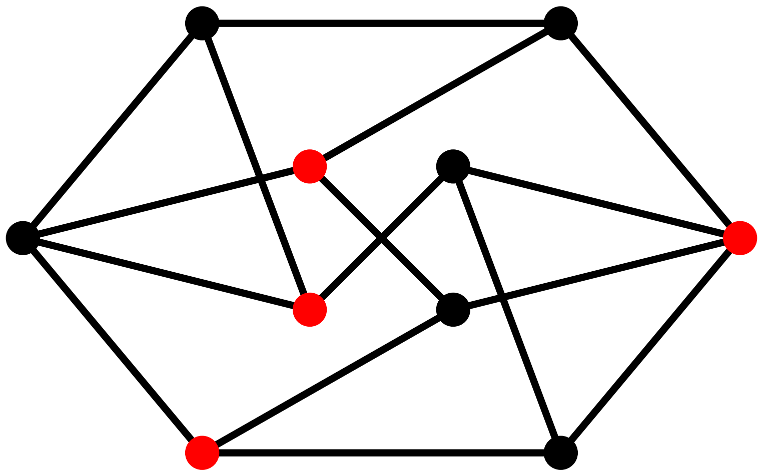

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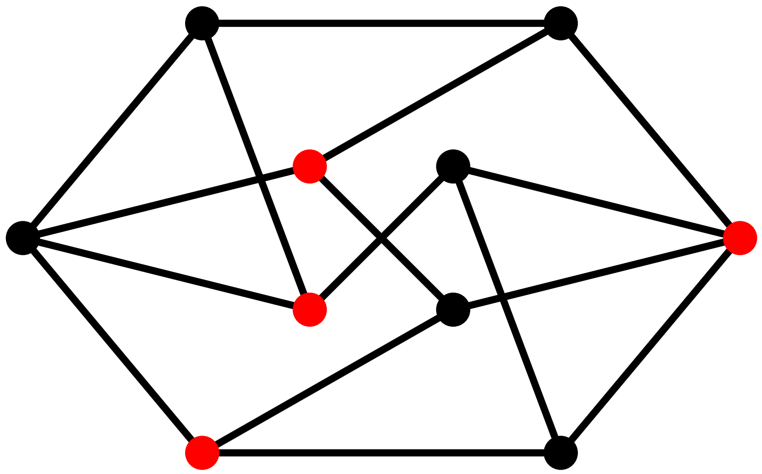

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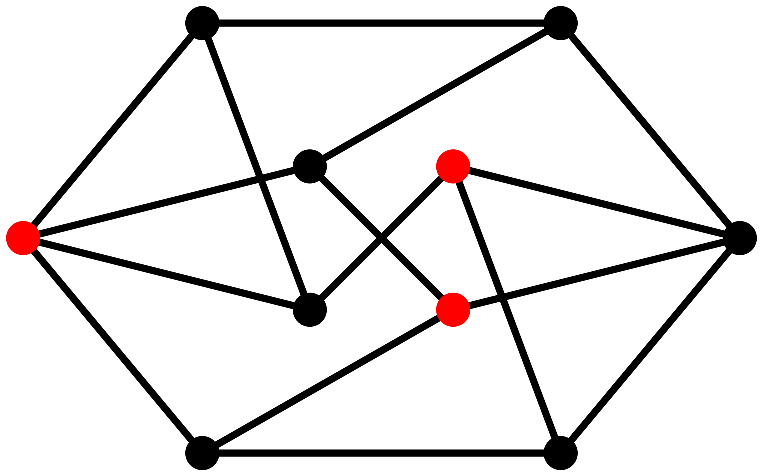

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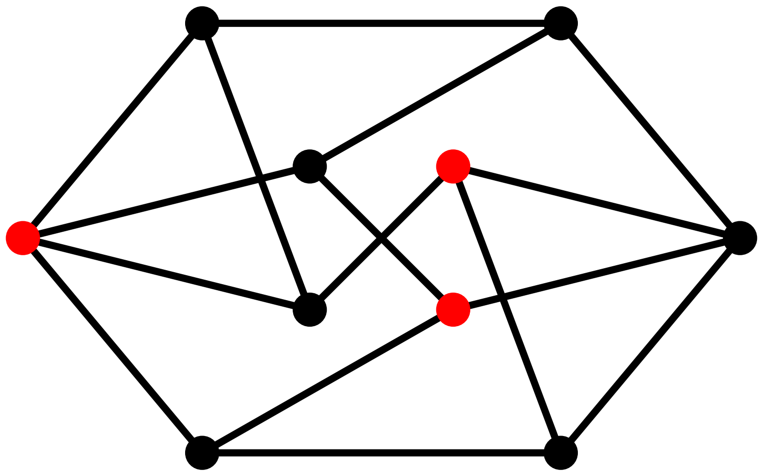

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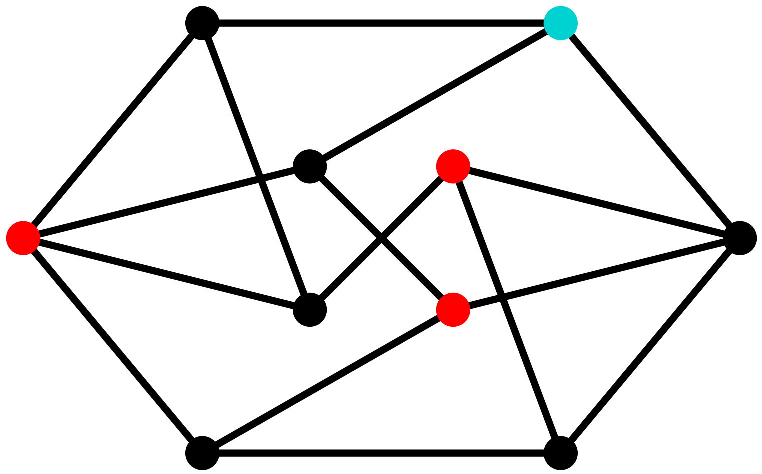

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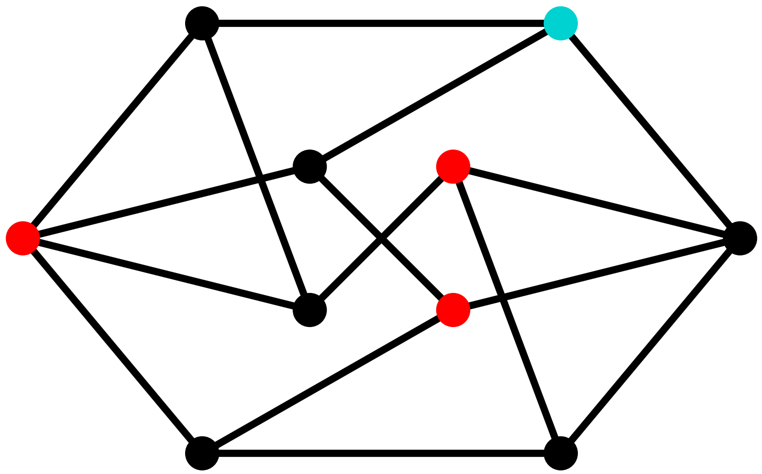
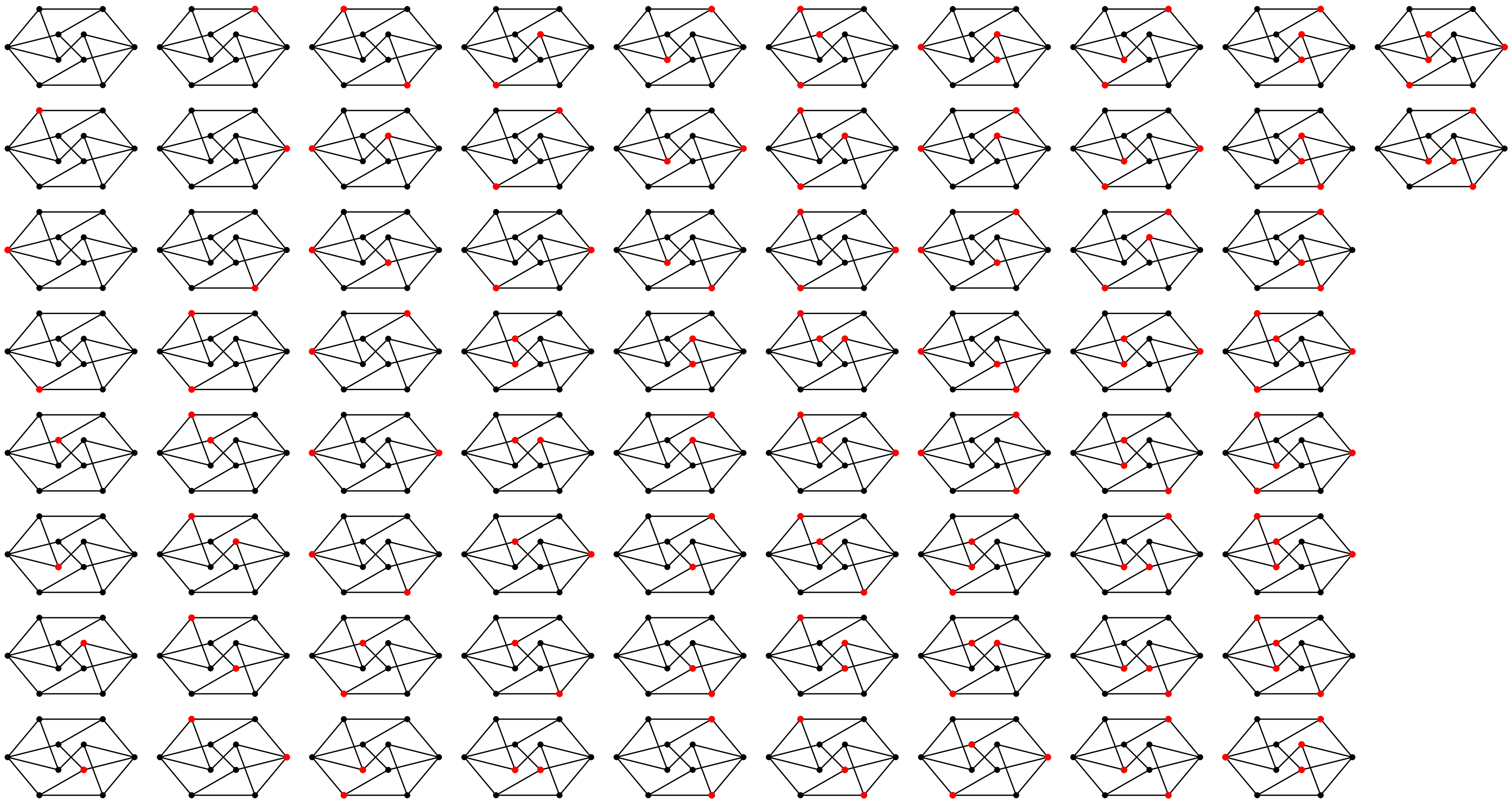


Not maximal

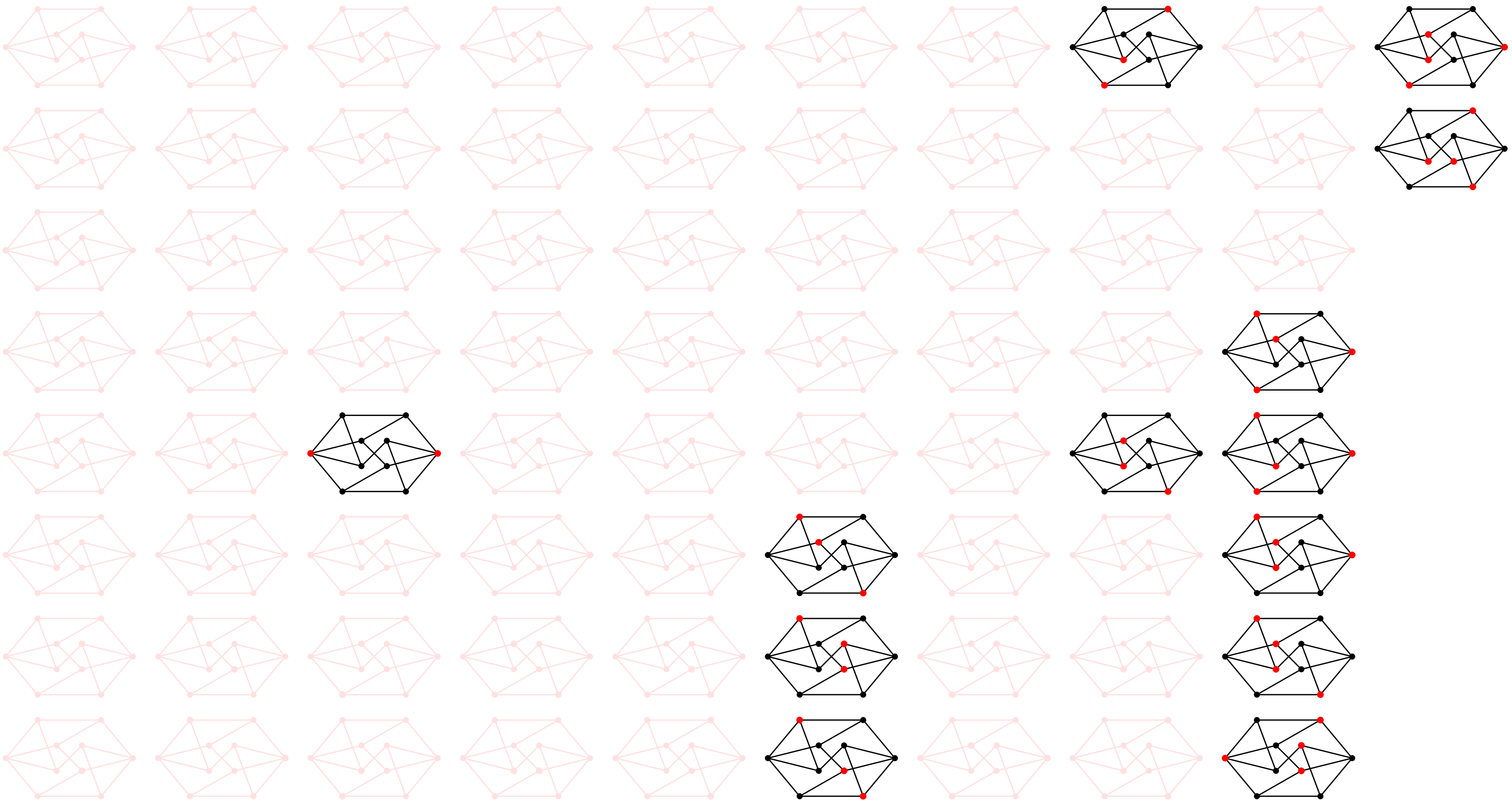
Also called an independent dominating set of G

Maximal independent sets



74 independent sets

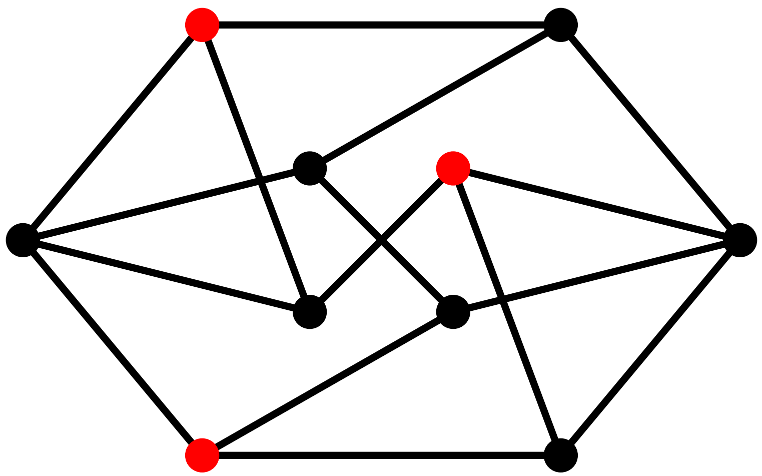
Maximal independent sets



74 independent sets 13 maximal independent sets

Setup $G = (V, E)$ a graph

Def. An independent set I of G is **minimum maximal** if it is maximal and has the smallest size among all maximal independent sets of G.



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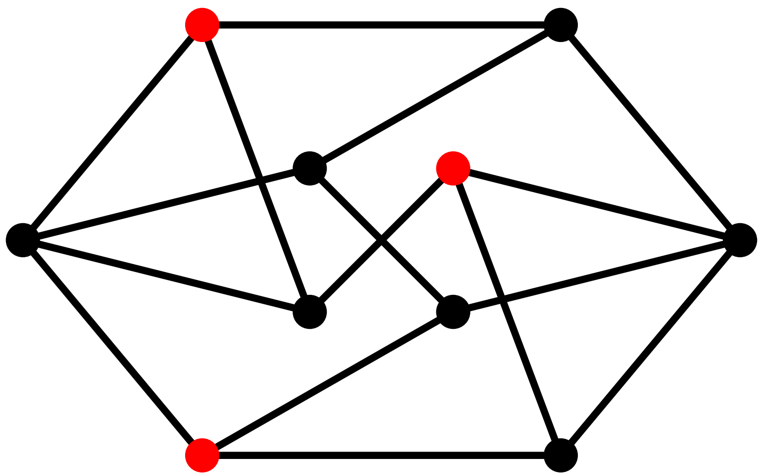

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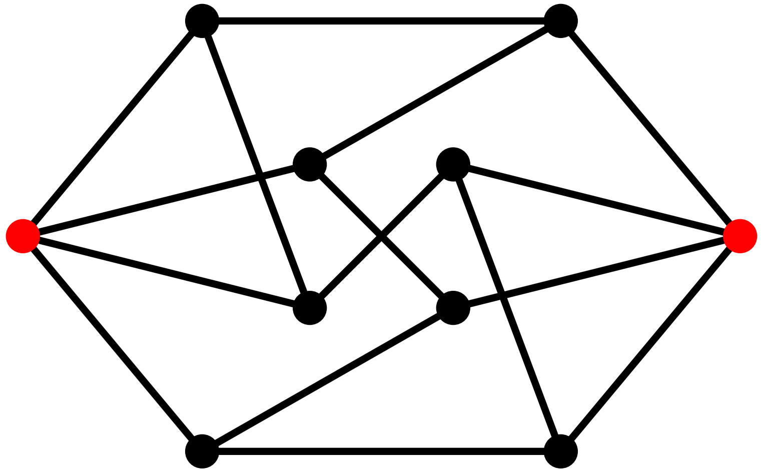

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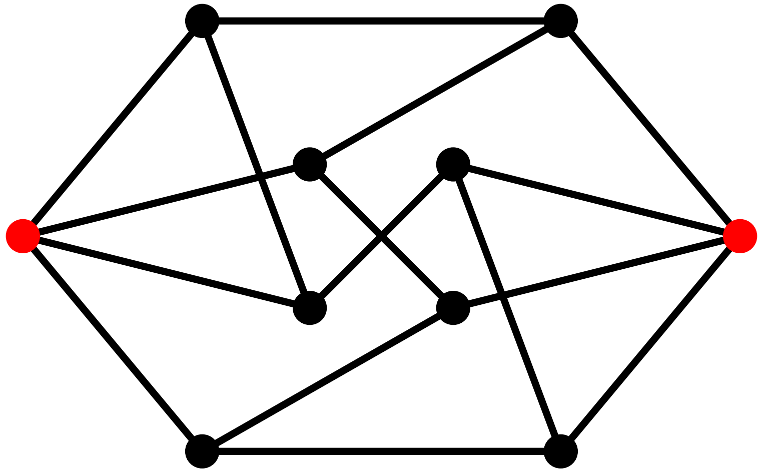

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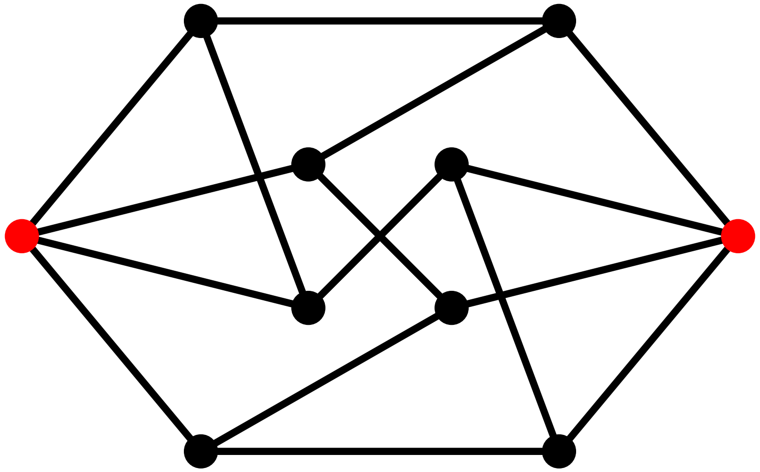
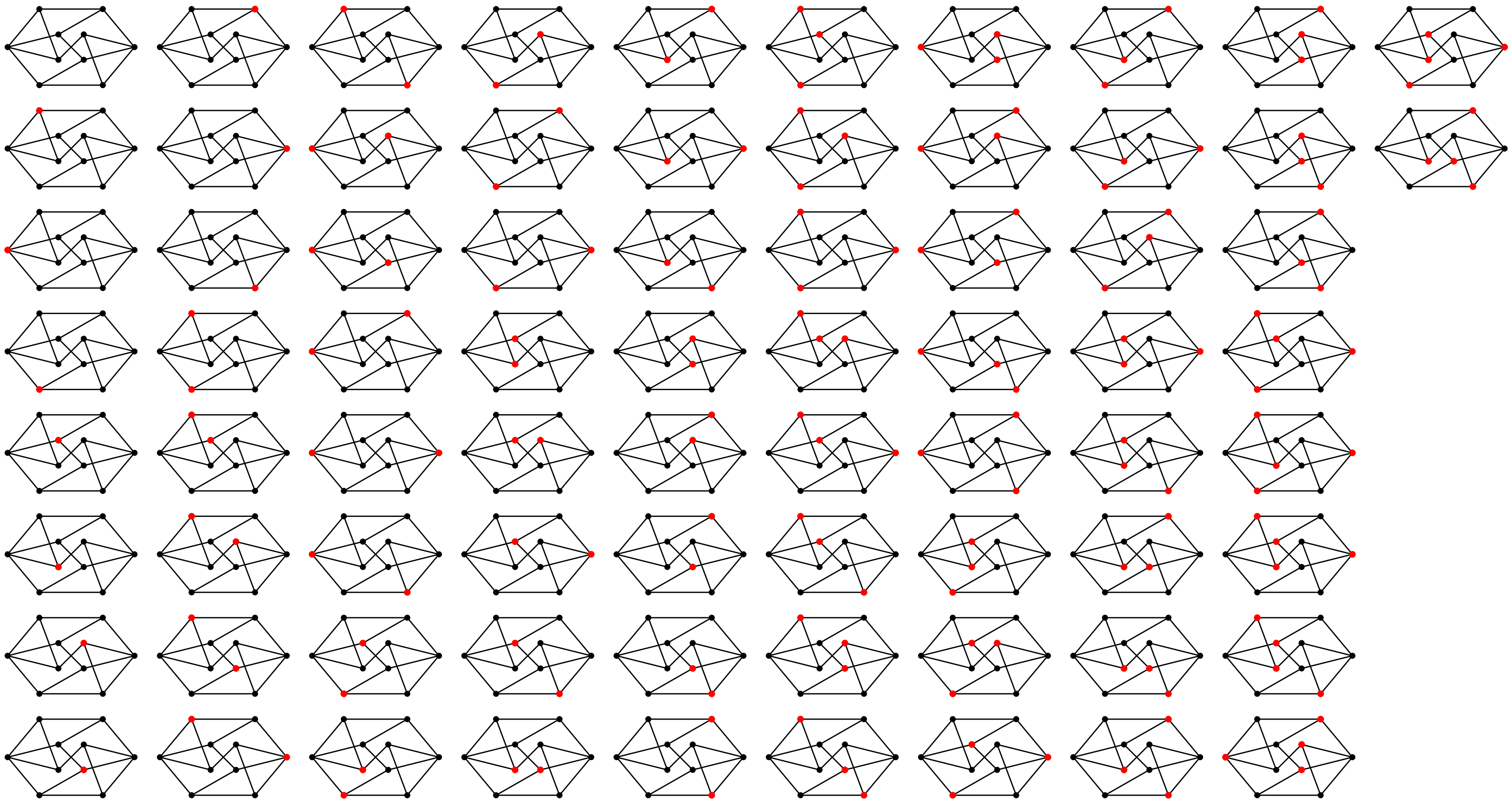


Minimum maximal

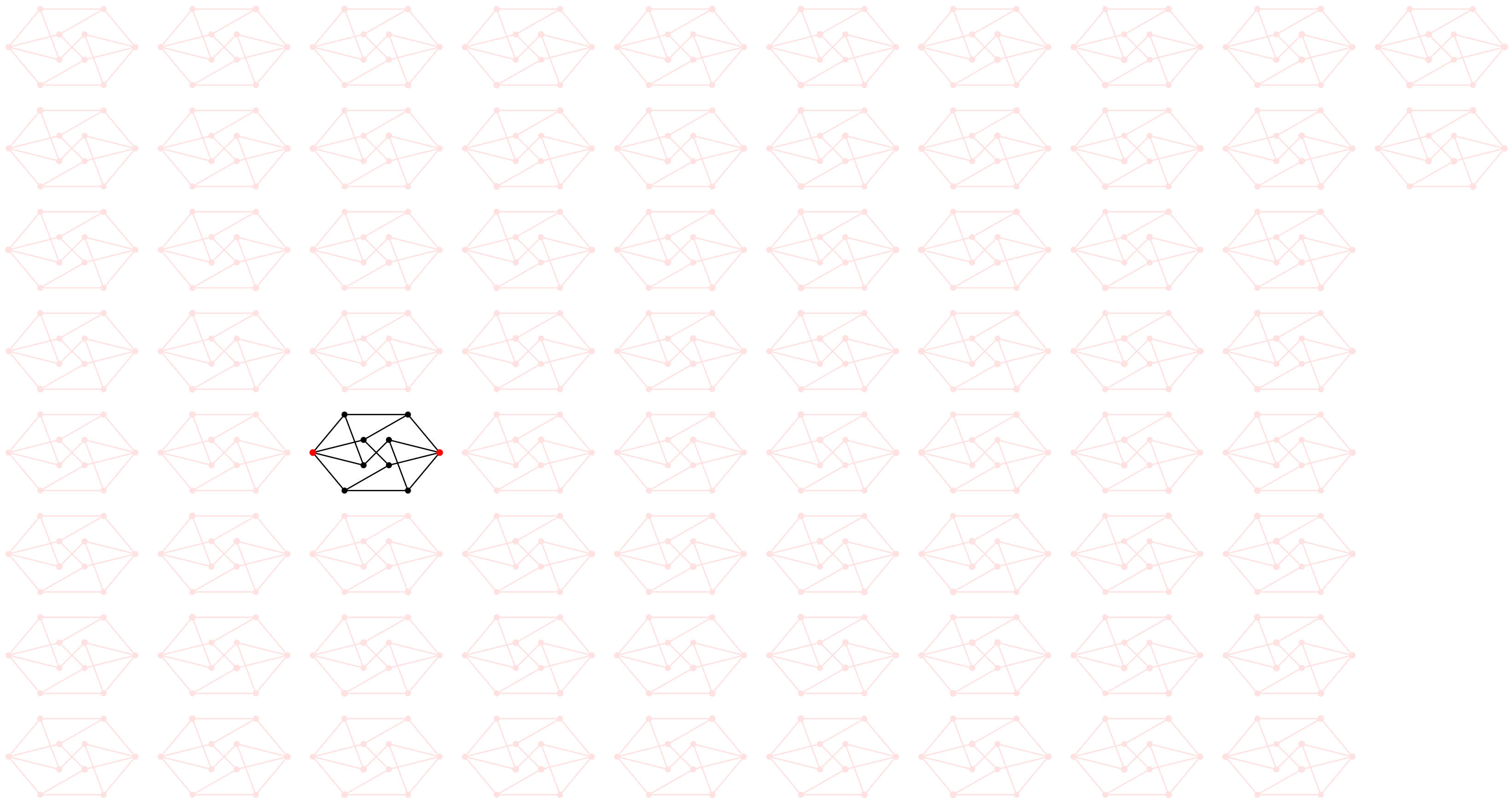
Also called a minimum independent dominating set of G

Minimum maximal independent sets



74 independent sets

Minimum maximal independent sets



74 independent sets

1 minimum maximal independent set

We study the following **counting problems**:

Input $\quad G = (V, E)$ a graph

Output
(1) # independent sets of G **74**

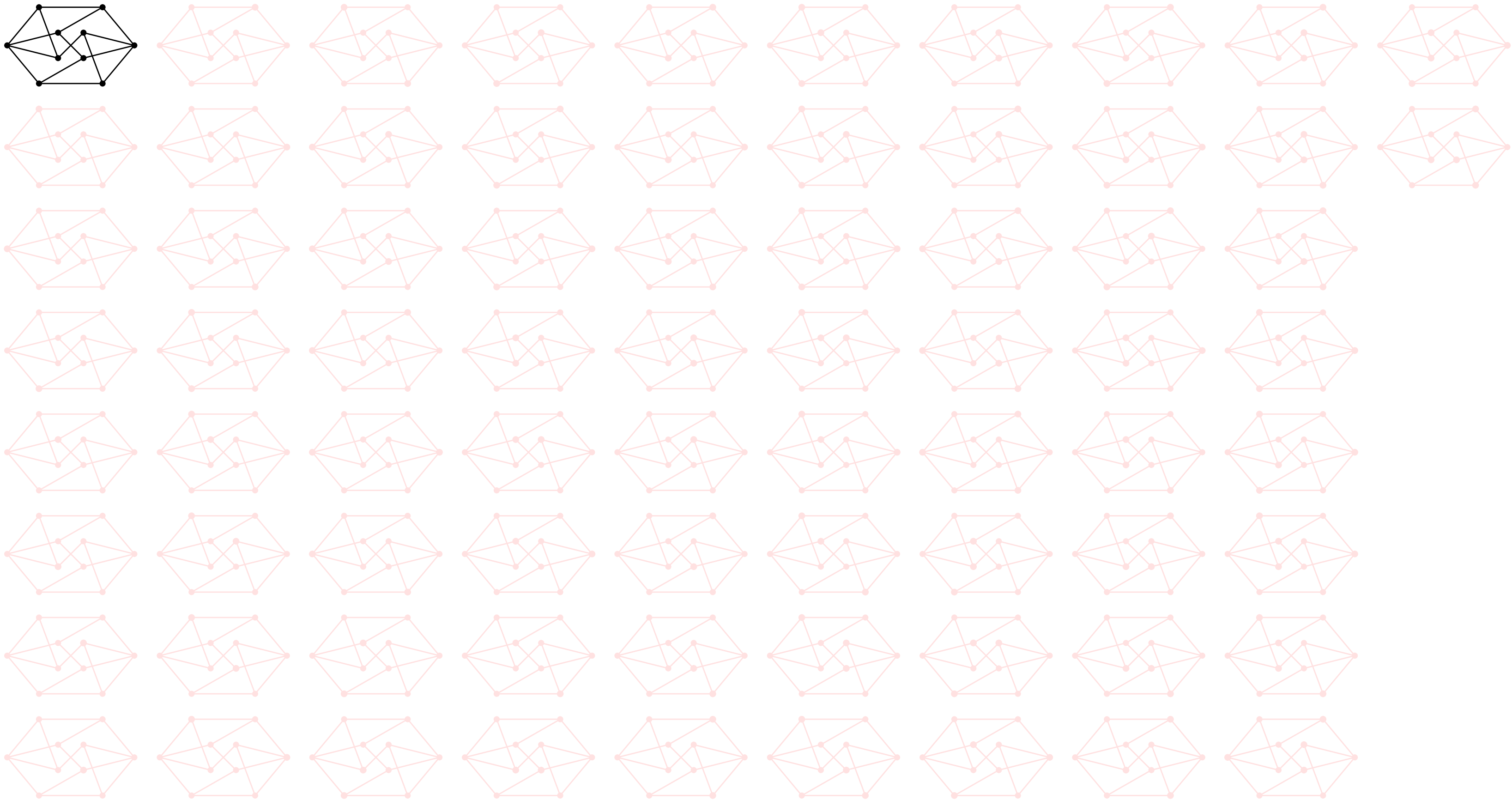
(2) # maximum independent sets of G **7**

(3) # independent sets of G of fixed size

(4) # maximal independent sets of G **13**

(5) # minimum maximal independent sets of G **1**

Independent sets of fixed size

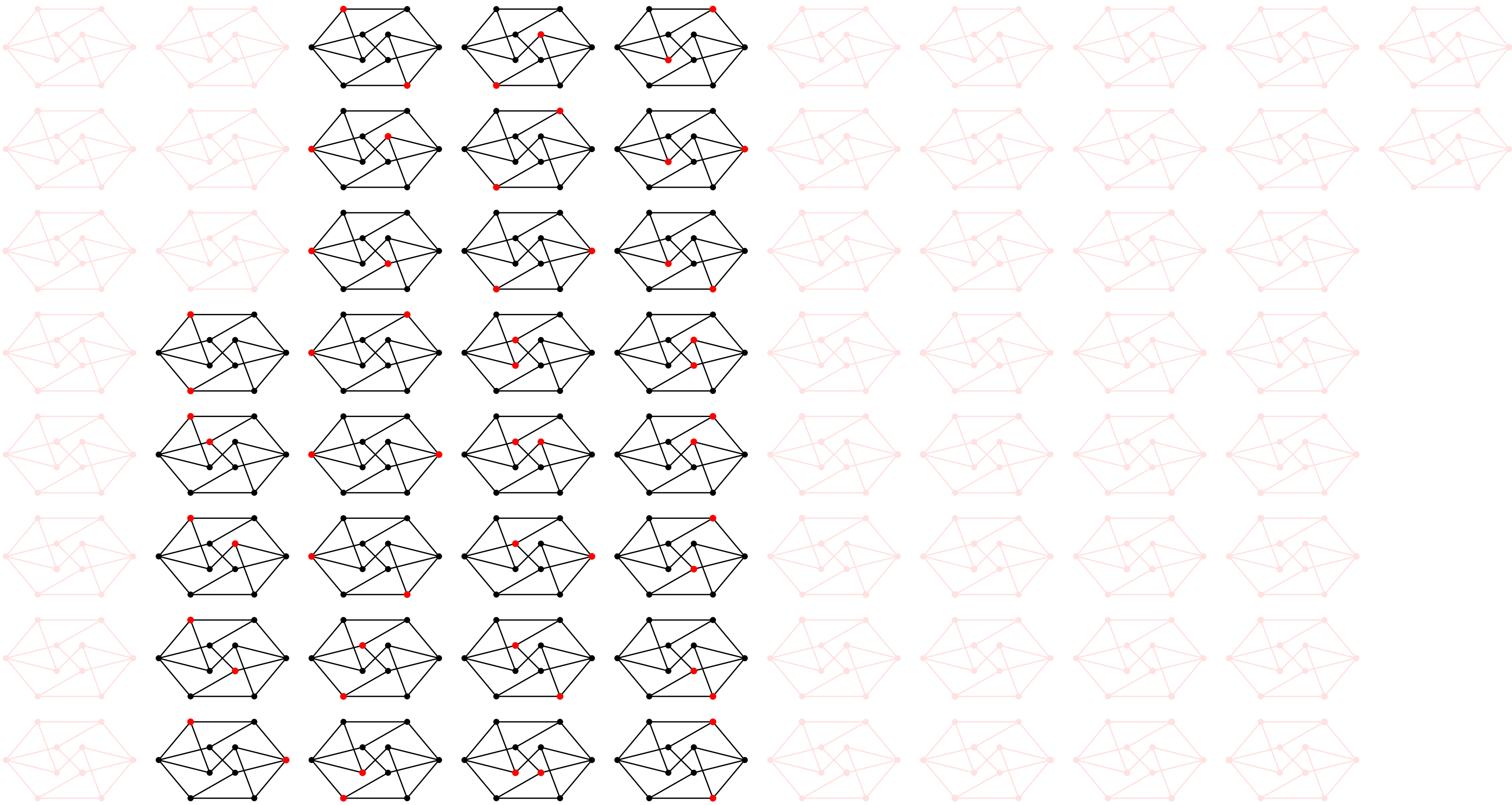


74 independent sets

1 independent set of size 0

74 independent sets

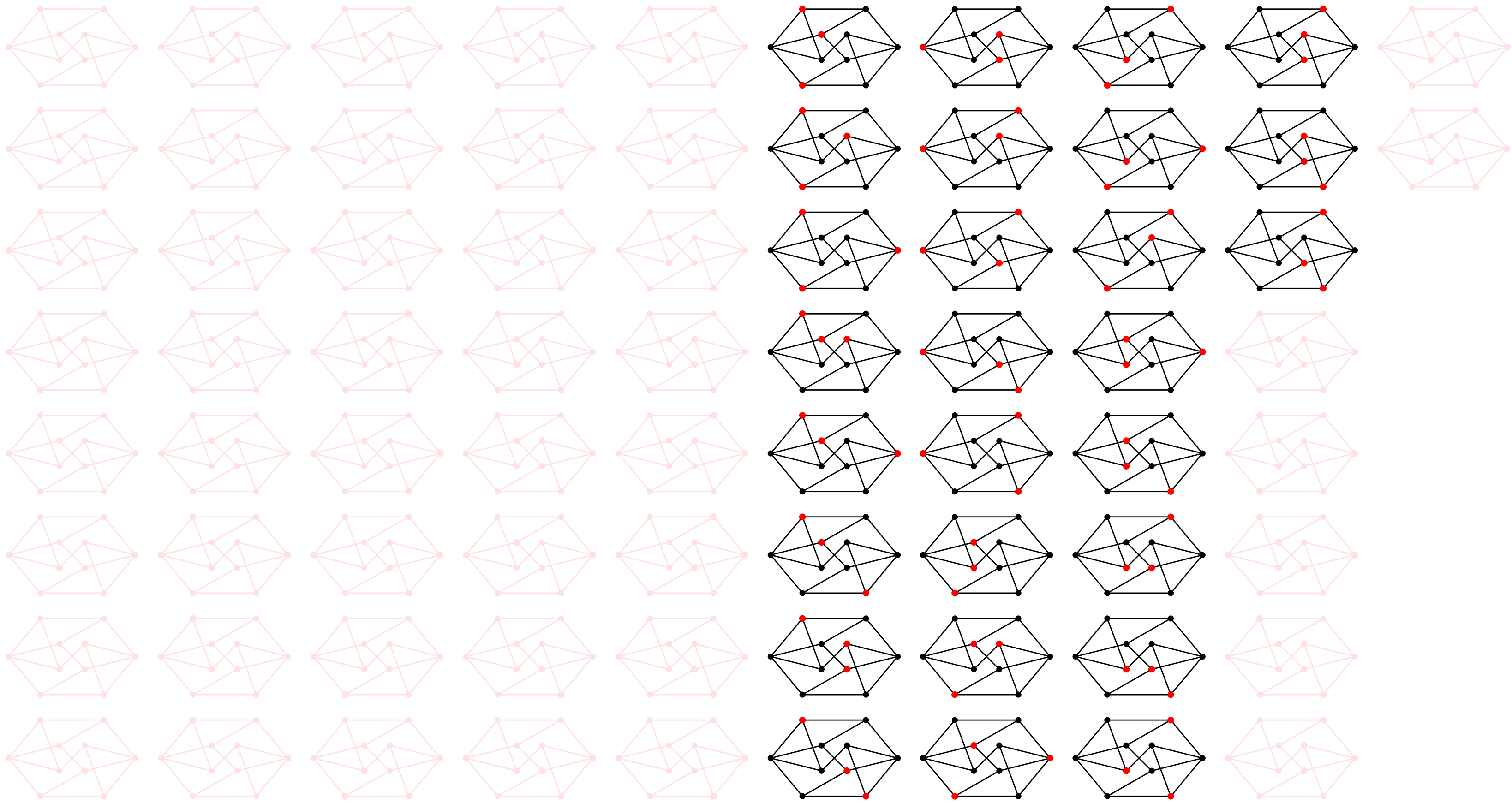
10 independent sets of size 1



74 independent sets

29 independent sets of size 2

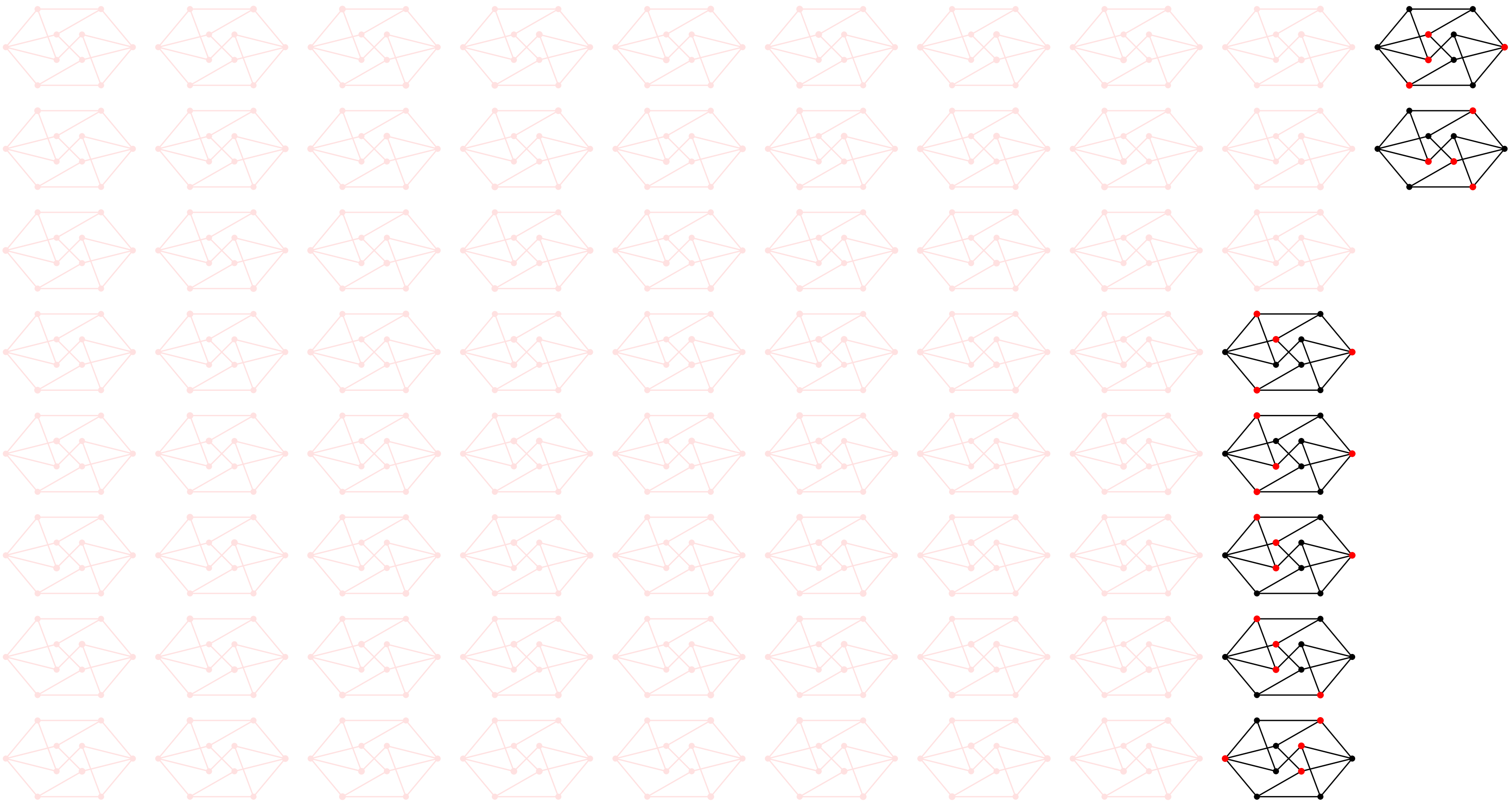
Independent sets of fixed size



74 independent sets

27 independent sets of size 3

Independent sets of fixed size



74 independent sets

7 independent sets of size 4

$\boxed{\text{Fact}}$ These counting problems are #P-complete (analoguous to NP-completeness).

$\Longrightarrow$ Cannot hope for a poly-time algorithms.

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$\Longrightarrow$ Cannot hope for a poly-time algorithms even for

- the line graphs of bipartite graphs (Valiant '79)
- bipartite graphs (Provan & Ball '83)
- planar bipartite graphs of max deg 4 (Vadhan '01).

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$\Longrightarrow$ Cannot hope for a poly-time algorithms even for

- the line graphs of bipartite graphs (Valiant '79)
- bipartite graphs (Provan & Ball '83)
- planar bipartite graphs of max deg 4 (Vadhan '01).

$\Longrightarrow$ Focus on another class of perfect graphs!!

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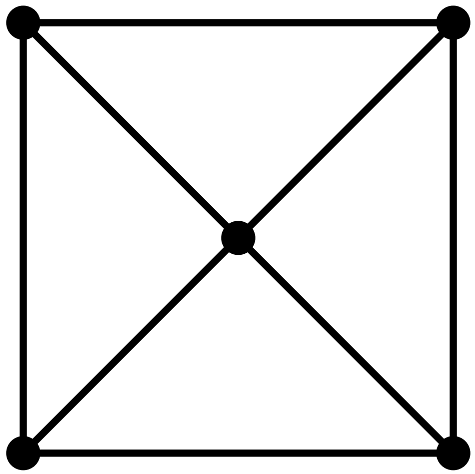

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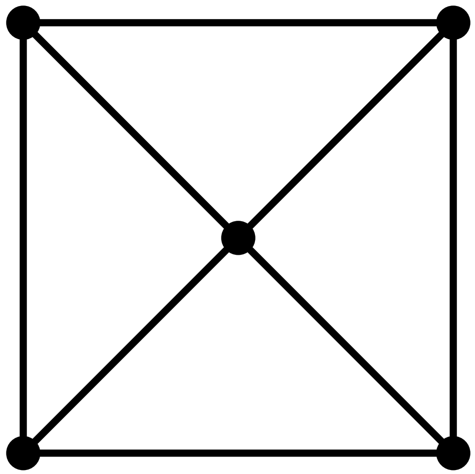

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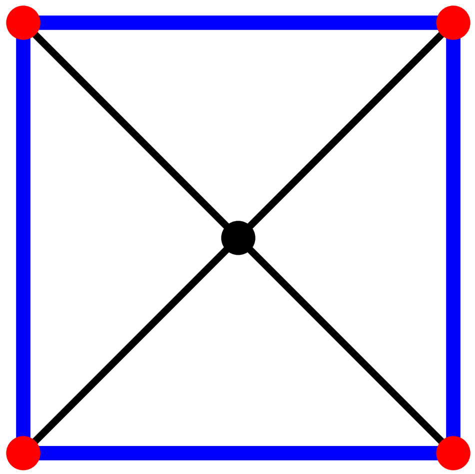

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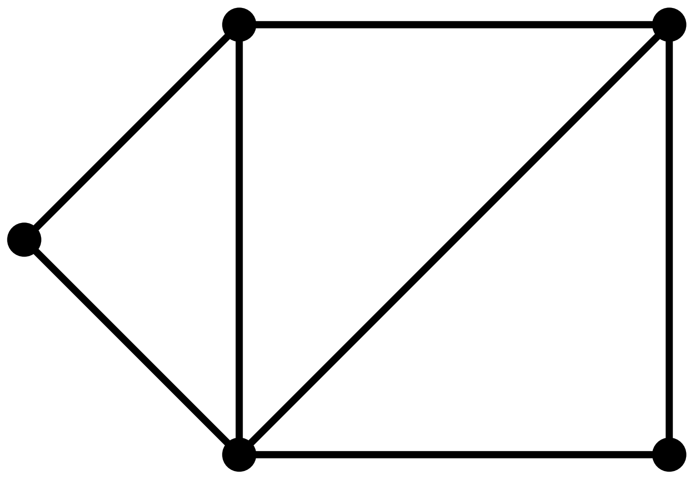

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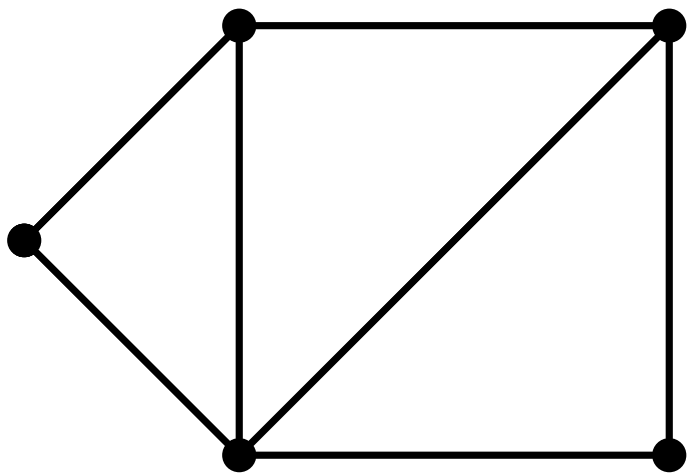

Chordal

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$\boxed{\text{Input}}$ $G = (V, E)$ a chordal graph

$\boxed{\text{Output}}$ (1) # independent sets of G

(2) # maximum independent sets of G

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We study the following **counting problems**:

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Rem "Finding one" is easy. (Gavril '72, Farber '82)

We obtain the following results for chordal graphs.

(1) # independent sets of G
(2) # maximum independent sets of G
(3) # independent sets of G of fixed size

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We obtain the following results for chordal graphs.

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$O(|V| + |E|)$ alg.

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#P-complete

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$O(|V| + |E|)$ alg.

(4) # maximal independent sets of G
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#P-complete

Given $G = (V, E)$ a (connected) chordal graph

Def A **clique tree** of G is a tree T st

(1) the nodes of T = the maximal cliques of G,

(2) $\forall\, v \in V$,

the nodes of T containing v induce a tree.

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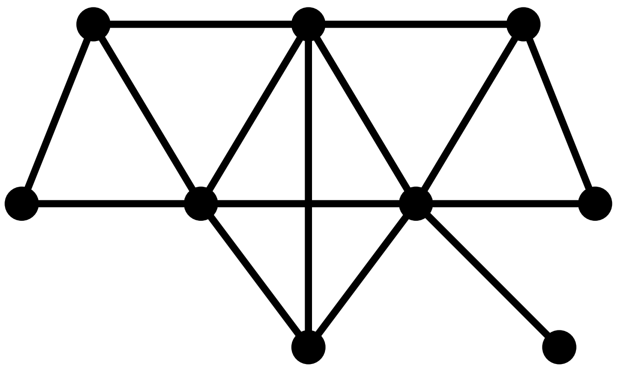

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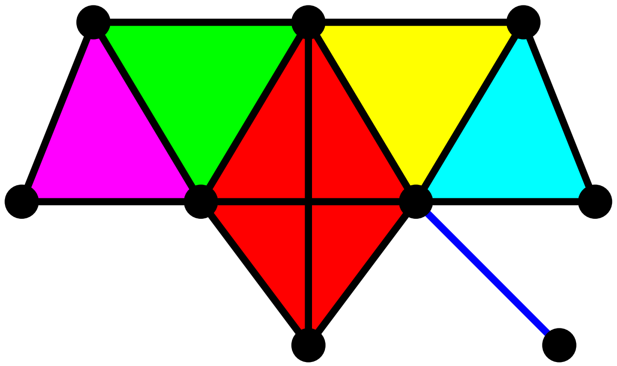

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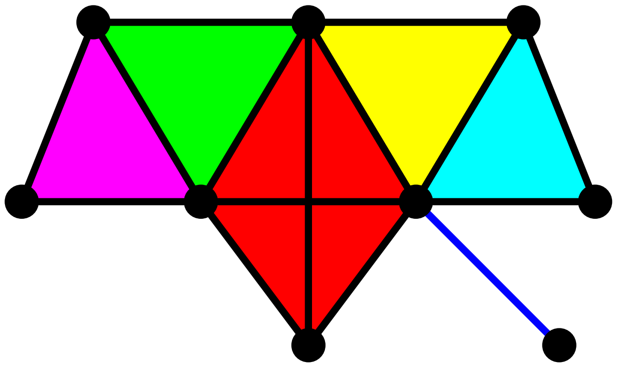

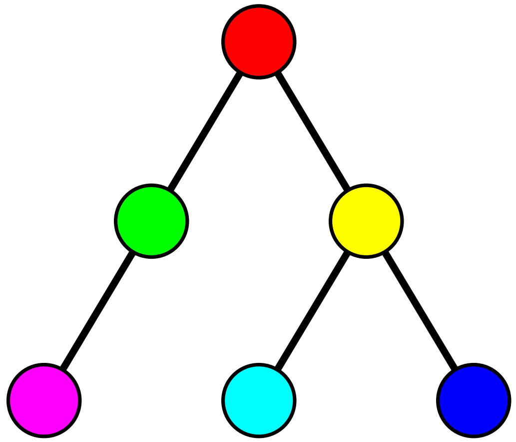

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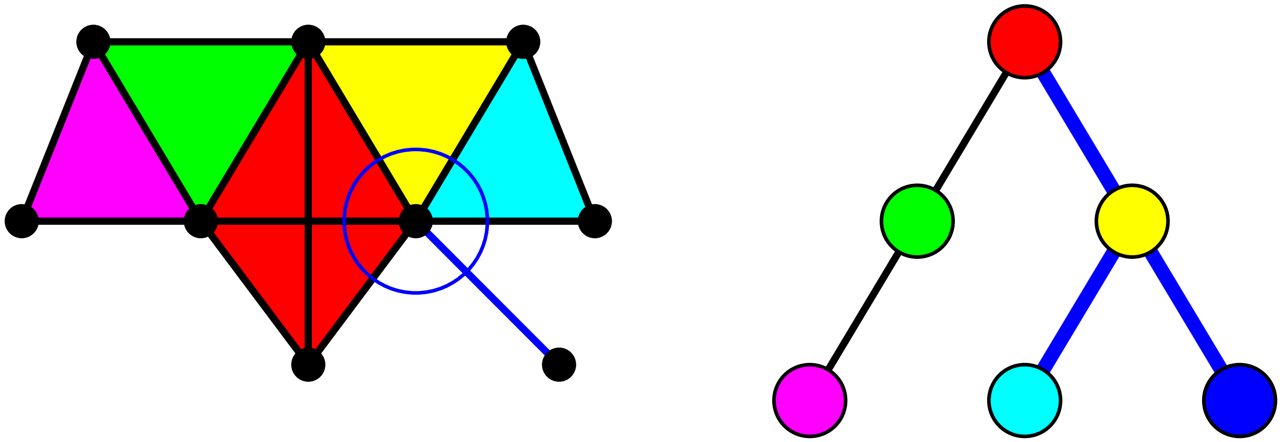

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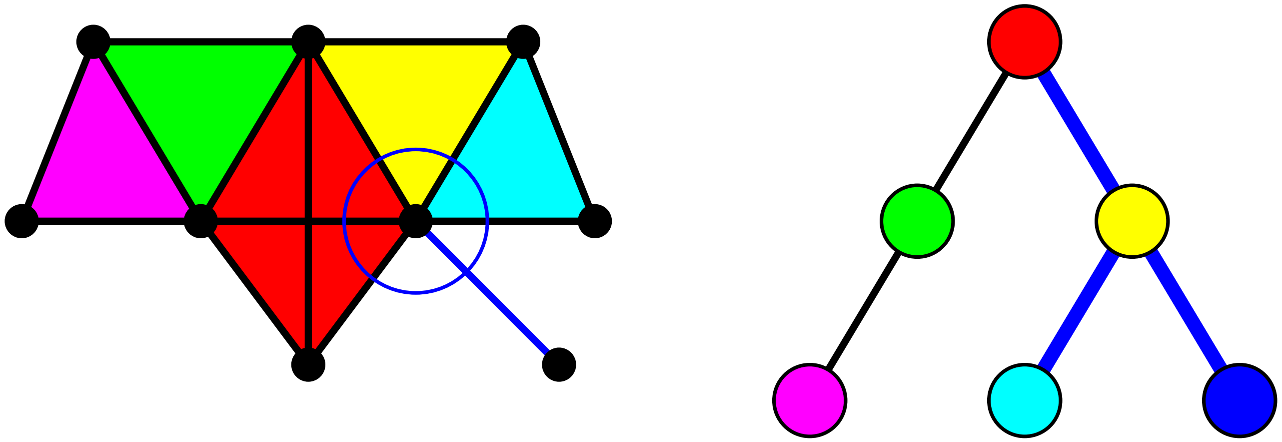
the nodes of T containing v induce a tree.



A clique tree can be computed in linear time.

$\boxed{\text{Given}}$ $G = (V, E)$ a (connected) chordal graph,

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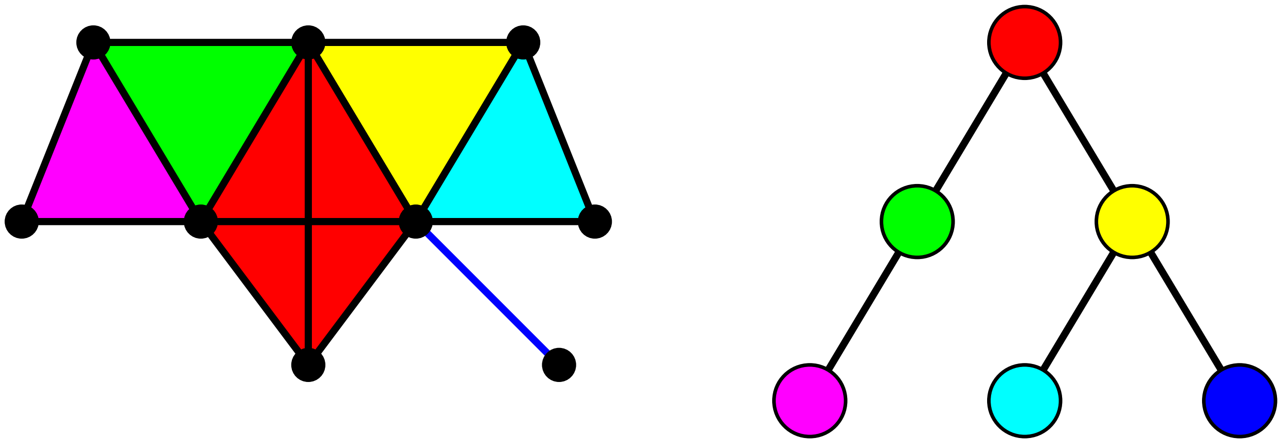

Given $G = (V, E)$ a (connected) chordal graph,
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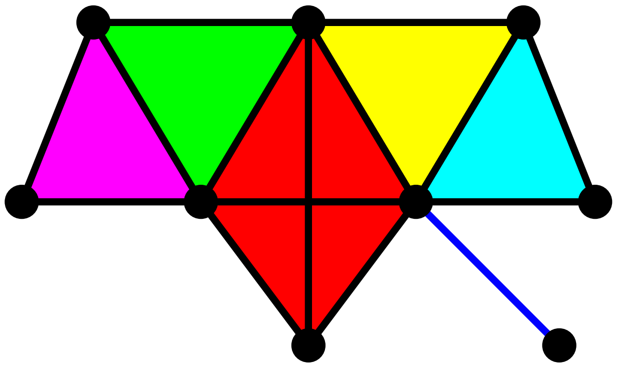
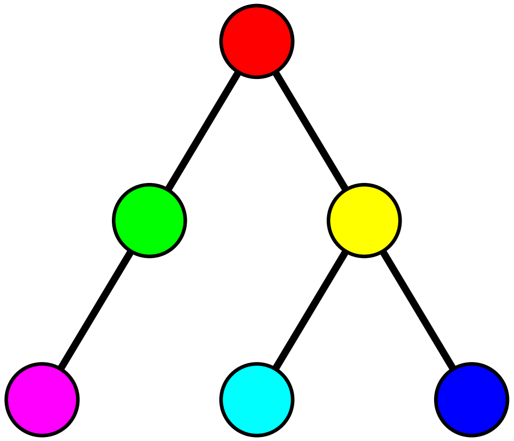
Property Every independent set of G either

contains exactly one vertex in K or not.





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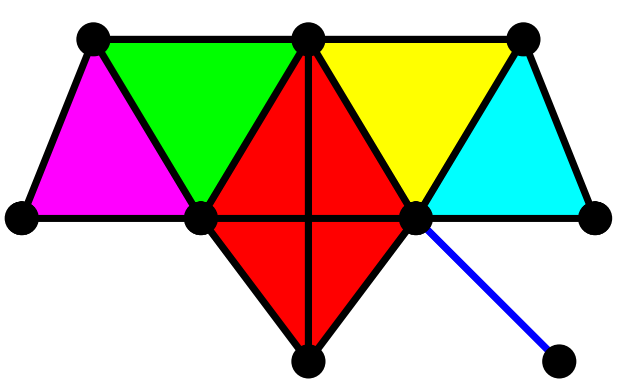
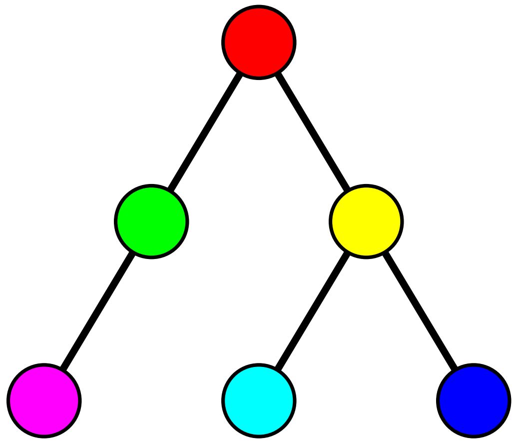
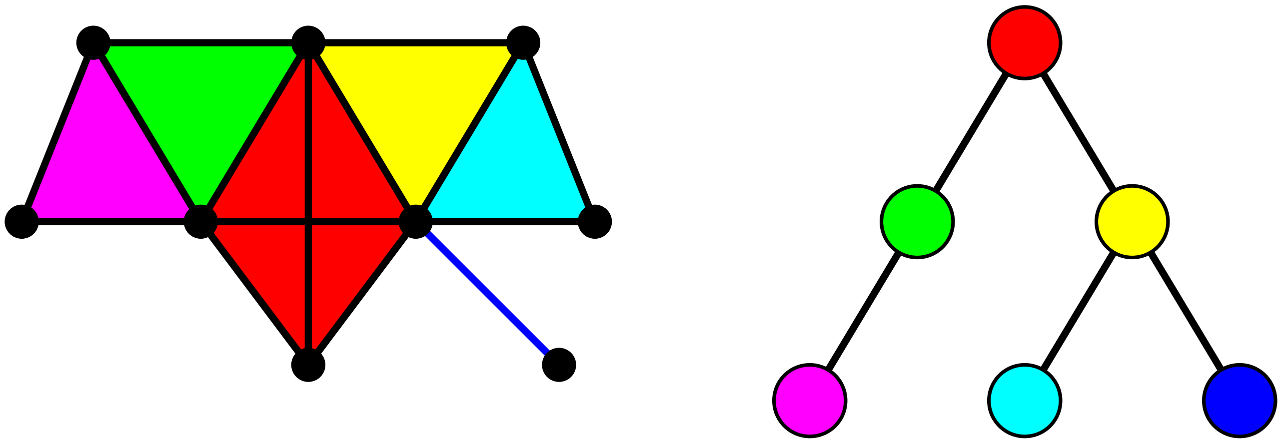




Leads to a recursive formula...

Given $G = (V, E)$ a (connected) chordal graph,
T a clique tree of G, with root K

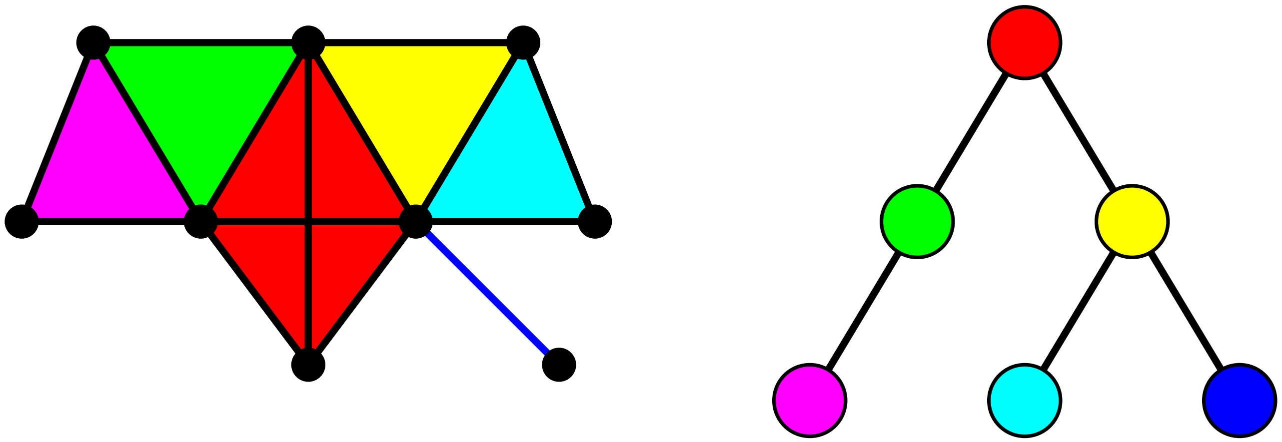
Lem # of independent sets of G =
# of independent sets of G excluding K +
$\sum_{v \in K}$(# of indepedent sets of G containing v)



Chordal graph from a subtree

Given $G = (V, E)$ a (connected) chordal graph,
T a clique tree of G with root K
K' a node of T

Notation $T(K')$ the subtree of G rooted at K'



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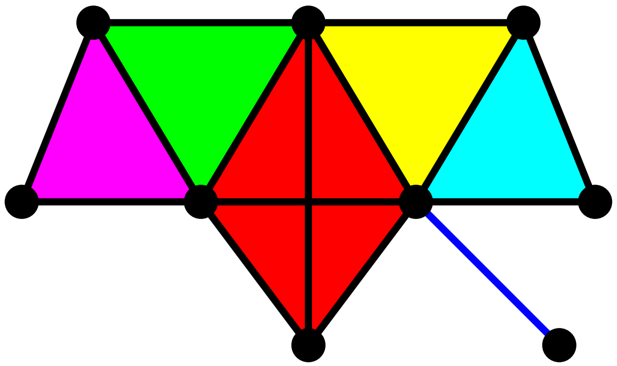
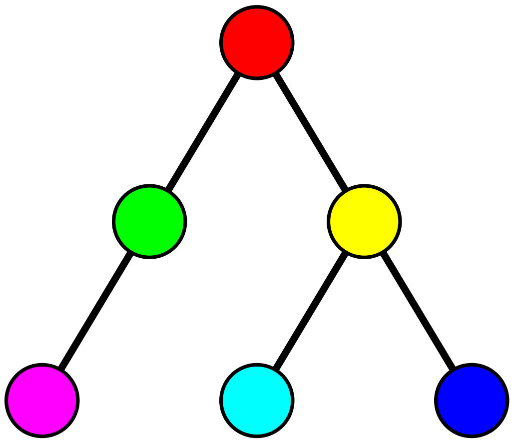
Property $T(K')$ is a clique tree of some chordal graph.





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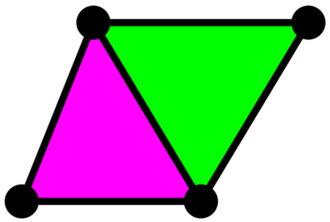

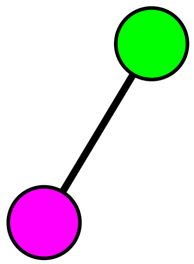

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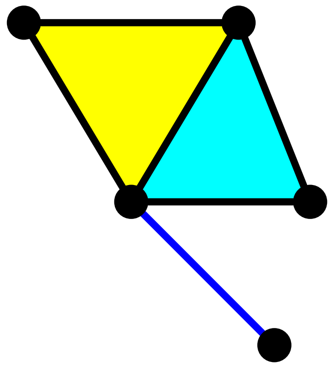
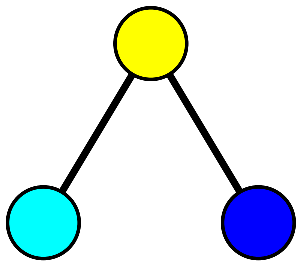
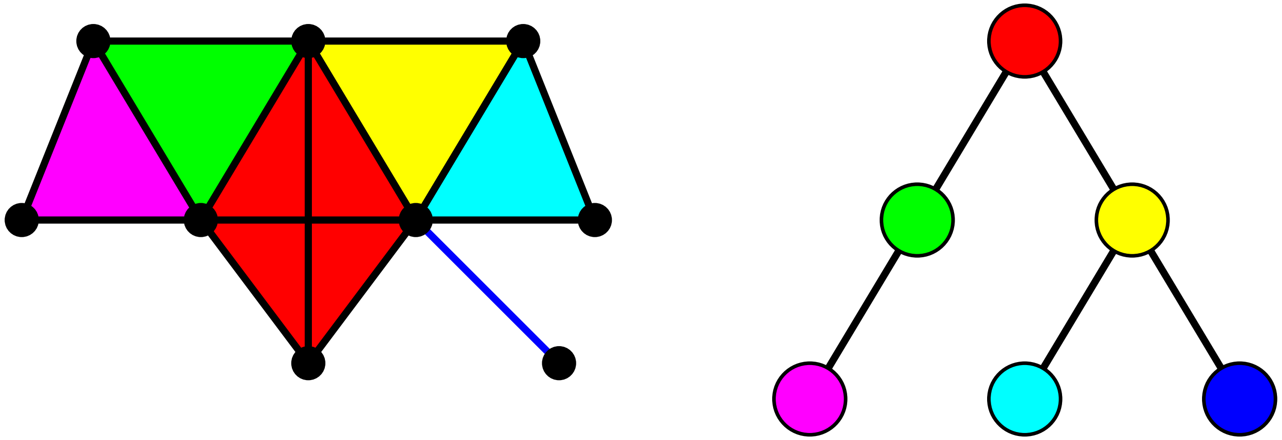




Given $G = (V, E)$ a (connected) chordal graph,
T a clique tree of G, with root K,
$K_1, \ldots, K_r$ the children of K in T

Lem # of independent sets of G excluding K =
$$\prod_i (\text{\# of independent sets of } G \text{ excluding } K \cap K_i)$$



Recursive formula

Let G be a chordal graph and T be a rooted clique tree of G. For a maximal clique K of G which is not a leaf of the clique tree, let $K_1, \dots, K_\ell$ be the children of K in T. Furthermore, let $v \in K$. Then, the following identities hold.

$$\mathcal{IS}(G(K)) = \overline{\mathcal{IS}}(G(K), K) \,\dot\cup \dot{\bigcup_{v \in K}} \mathcal{IS}(G(K), v);$$

$$\mathcal{IS}(G(K), v) = \{S \cup \{v\} \mid S = \bigcup_{i=1}^{\ell} S_i, S_i \in \left\{ \begin{array}{ll} \mathcal{IS}(G(K_i), v) & \text{if } v \in K_i \\ \overline{\mathcal{IS}}(G(K_i), K \cap K_i) & \text{otherwise} \end{array} \right\}\};$$

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where $\mathcal{IS}(G)$ denotes the family of independent sets in G, $\mathcal{IS}(G, v)$ denotes for a vertex v the family of independent sets in G including v, $\overline{\mathcal{IS}}(G, U)$ denotes the family of independent sets in G including no vertex of U for a vertex set U.

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A detailed analysis yields a linear-time algorithm to count the independent sets in a chordal graph!

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Thm The independent sets in a chordal graph $G = (V, E)$ can be counted in $O(|V| + |E|)$ time.

We obtain the following results for chordal graphs.

(1) # independent sets of G
(2) # maximum independent sets of G
(3) # independent sets of G of fixed size

$O(|V| + |E|)$ alg.

(4) # maximal independent sets of G
(5) # minimum maximal independent sets of G

#P-complete

We use the following counting problem
(a counting version of the set cover problem).

Given X a finite set, $\mathcal{S} \subseteq 2^X$ a family

Output The number of subfamilies $\mathcal{S}' \subseteq \mathcal{S}$ st $\bigcup_{Y \in \mathcal{S}'} Y = X$.

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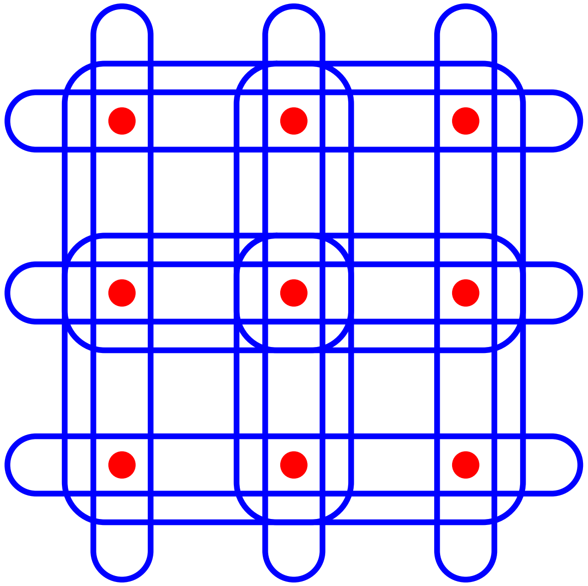

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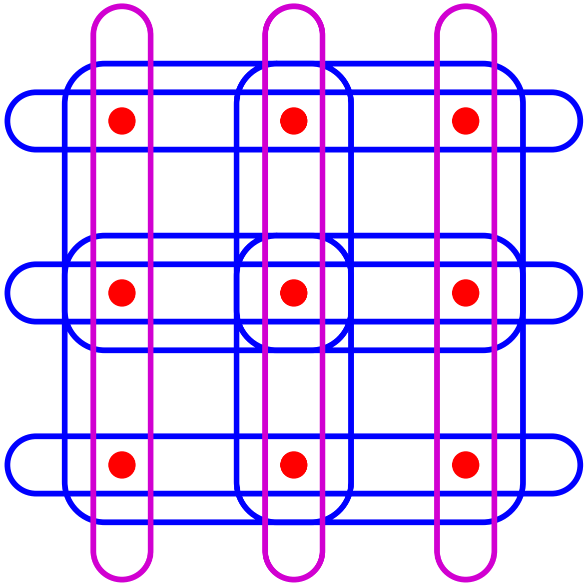

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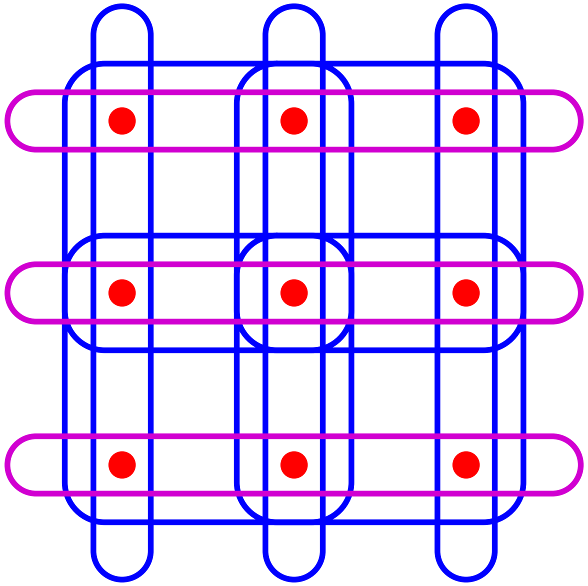

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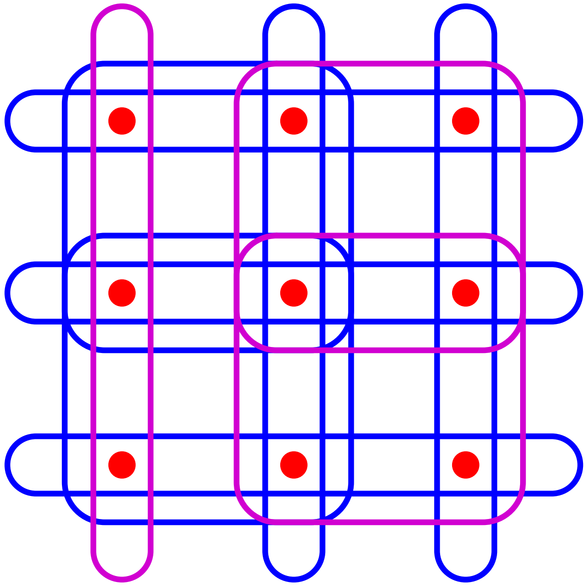

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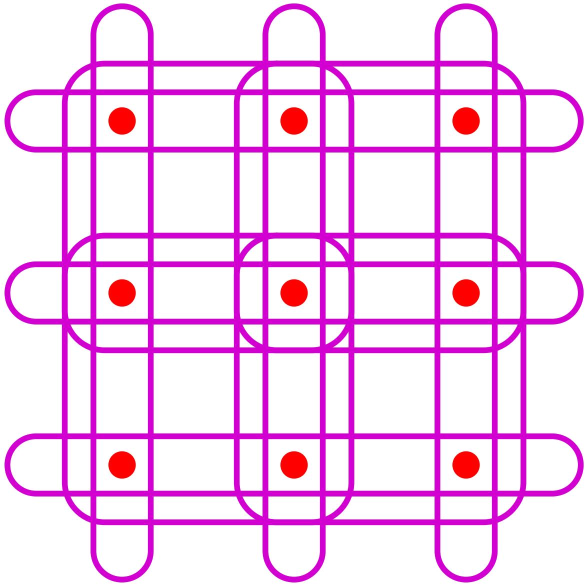

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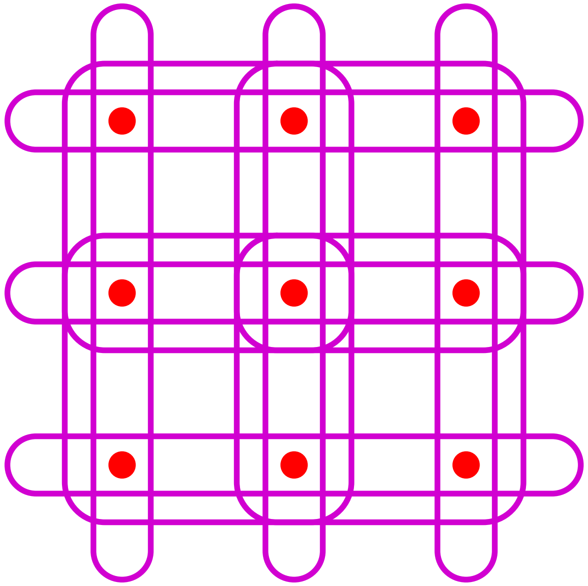
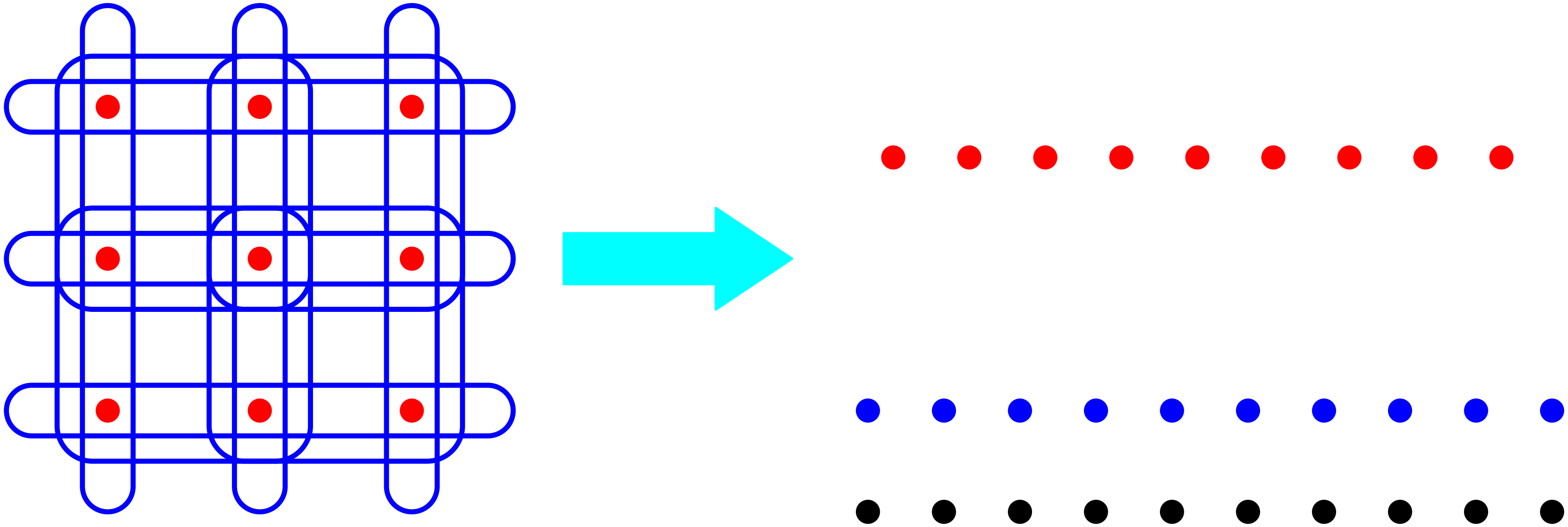


Actual reduction



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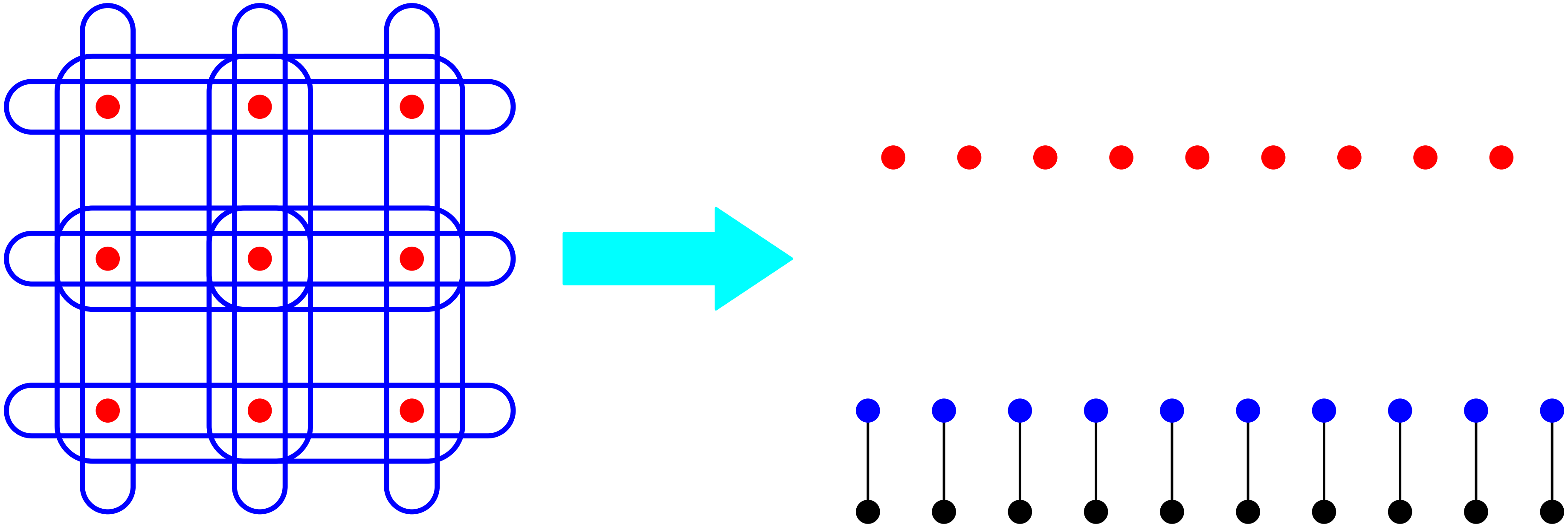

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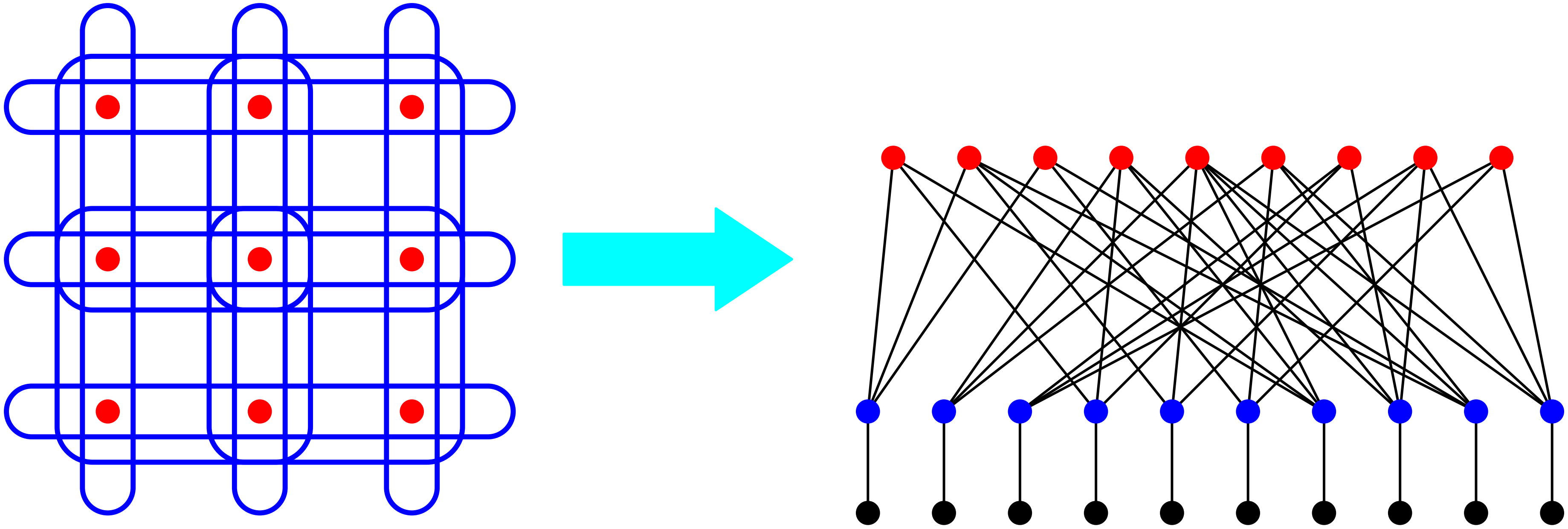

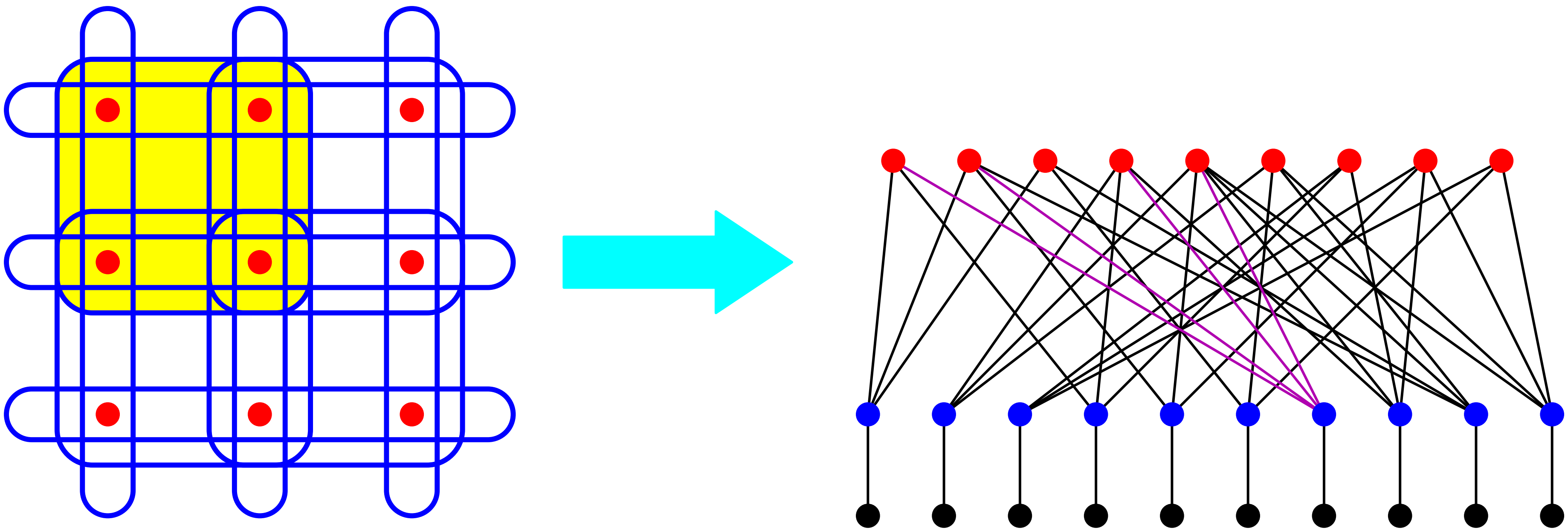

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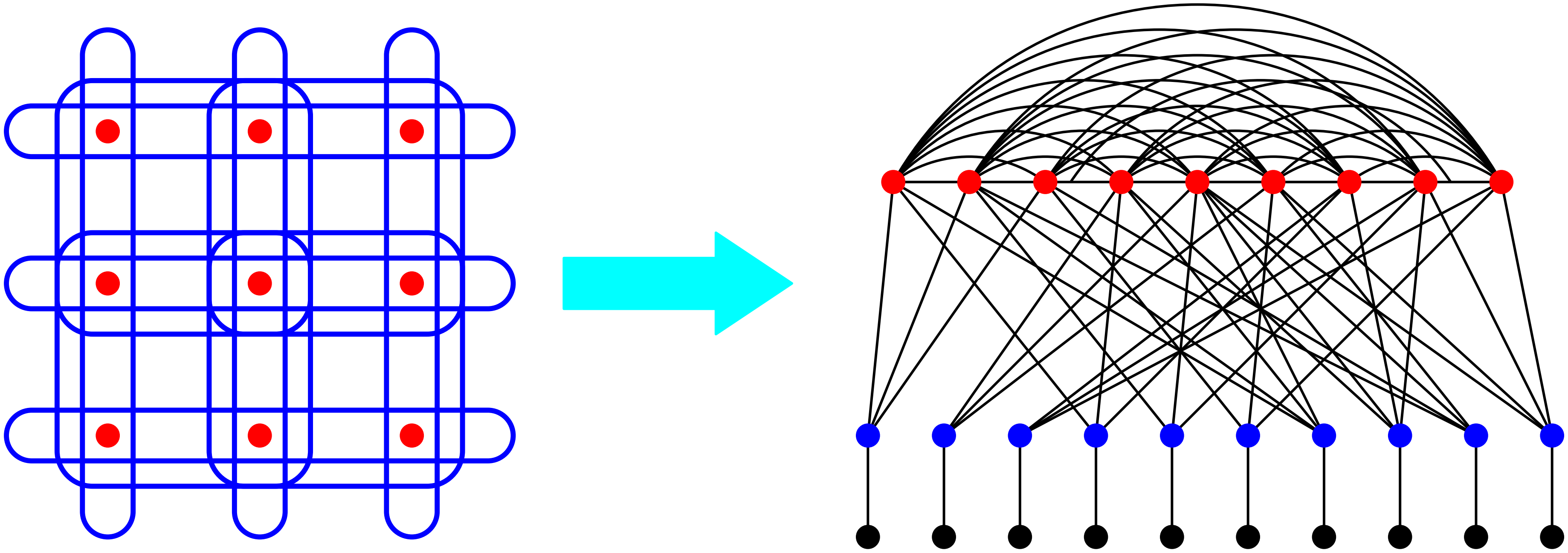

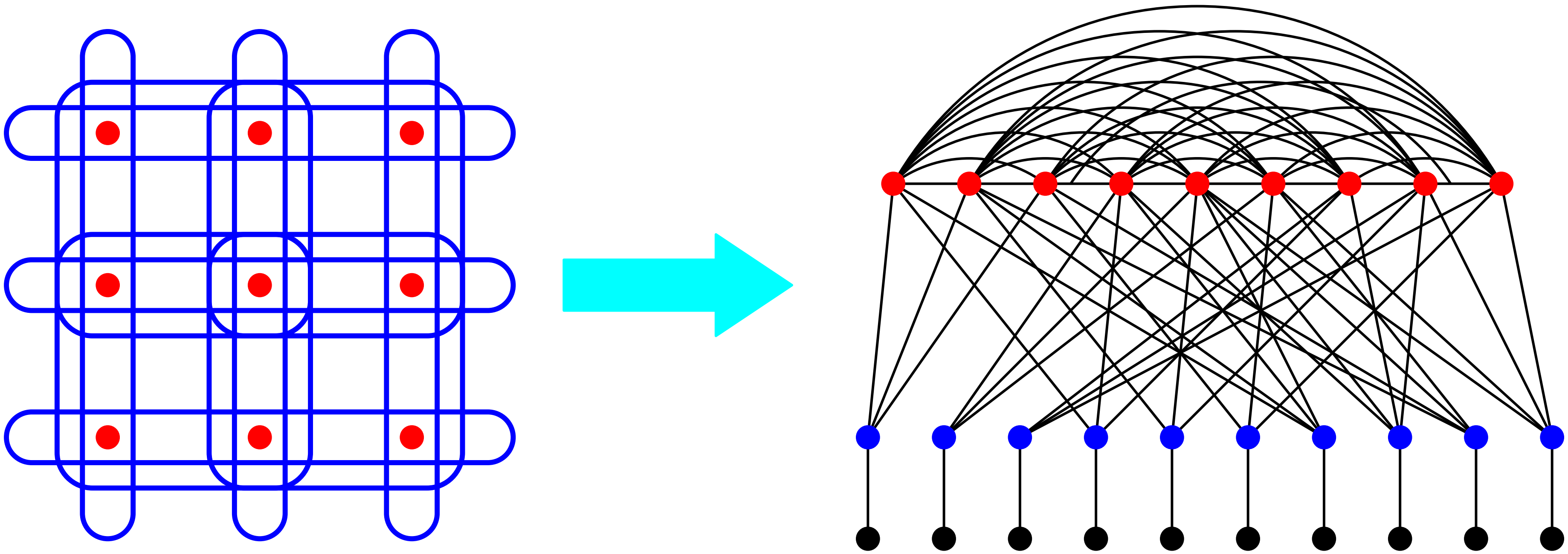

$$\#\ \text{set covers} + \sum_{x\in X} 2^{\#\ \text{sets not containing } x}$$

$$\|$$

$$\#\ \text{maximal independent sets}$$

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[End of my talk]

Merci beaucoup.