

3. Branching Algorithms

COMP6741: Parameterized and Exact Computation

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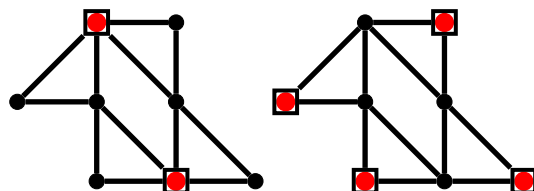
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1 Introduction

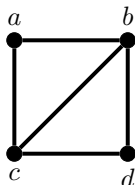
Recall: Maximal Independent Sets

- A vertex set $S \subseteq V$ of a graph $G = (V, E)$ is an *independent set* in G if there is no edge $uv \in E$ with $u, v \in S$.
- An independent set is *maximal* if it is not a subset of any other independent set.
- Examples:



Enumeration problem: Enumerate all maximal independent sets

ENUM-MIS
 Input: graph G
 Output: all maximal independent sets of G



Maximal independent sets: $\{a, d\}, \{b\}, \{c\}$

Note: Let v be a vertex of a graph G . Every maximal independent set contains a vertex from $N_G[v]$.

Branching Algorithm for Enum-MIS

Algorithm enum-mis(G, I)

Input : A graph $G = (V, E)$, an independent set I of G .

Output: All maximal independent sets of G that are supersets of I .

```

1  $G' \leftarrow G - N_G[I]$ 
2 if  $V(G') = \emptyset$  then                                     //  $G'$  has no vertex
3   Output  $I$ 
4 else
5   Select  $v \in V(G')$  such that  $d_{G'}(v) = \delta(G')$            //  $v$  has min degree in  $G'$ 
6   Run enum-mis( $G, I \cup \{u\}$ ) for each  $u \in N_{G'}[v]$ 

```

Running Time Analysis

Let us upper bound by $L(n) = 2^{\alpha n}$ the number of leaves in any search tree of **enum-mis** for an instance with $|V(G')| \leq n$.

We minimize α (or 2^α) subject to constraints obtained from the branching:

$$\begin{aligned}
 L(n) &\geq (d+1) \cdot L(n - (d+1)) && \text{for each integer } d \geq 0. \\
 \Leftrightarrow & 2^{\alpha n} \geq d' \cdot 2^{\alpha(n-d')} && \text{for each integer } d' \geq 1. \\
 \Leftrightarrow & 1 \geq d' \cdot 2^{\alpha(-d')} && \text{for each integer } d' \geq 1.
 \end{aligned}$$

For fixed d' , the smallest value for 2^α satisfying the constraint is $d'^{1/d'}$. The function $f(x) = x^{1/x}$ has its maximum value for $x = e$ and for integer x the maximum value of $f(x)$ is when $x = 3$.

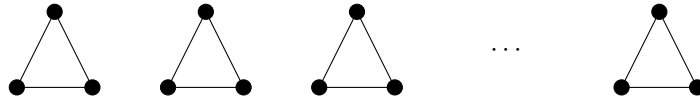
Therefore, the minimum value for 2^α for which all constraints hold is $3^{1/3}$. We can thus set $L(n) = 3^{n/3}$.

Since the height of the search trees is $\leq |V(G')|$, we obtain:

Theorem 1. *Algorithm enum-mis has running time $O^*(3^{n/3}) \subseteq O(1.4423^n)$, where $n = |V|$.*

Corollary 2. *A graph on n vertices has $O(3^{n/3})$ maximal independent sets.*

Running Time Lower Bound



Theorem 3. *There is an infinite family of graphs with $\Omega(3^{n/3})$ maximal independent sets.*

Branching Algorithm

- *Selection:* Select a local configuration of the problem instance
- *Recursion:* Recursively solve subinstances
- *Combination:* Compute an optimal solution of the instance based on the optimal solutions of the subinstances

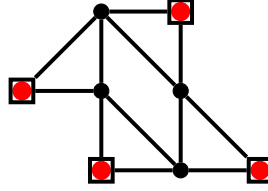
- *Simplification* rule: 1 recursive call
- *Branching* rule: ≥ 2 recursive calls

2 Maximum Independent Set

MAXIMUM INDEPENDENT SET

Input: graph G

Output: A largest independent set of G .



Branching Algorithm for Maximum Independent Set

Algorithm $\text{mis}(G)$

Input : A graph $G = (V, E)$.

Output: The size of a maximum i.s. of G .

```

1 if  $\Delta(G) \leq 2$  then                                     //  $G$  has max degree  $\leq 2$ 
2   return the size of a maximum i.s. of  $G$  in polynomial time
3 else if  $\exists v \in V : d(v) = 1$  then                       //  $v$  has degree 1
4   return  $1 + \text{mis}(G - N[v])$ 
5 else if  $G$  is not connected then
6   Let  $G_1$  be a connected component of  $G$ 
7   return  $\text{mis}(G_1) + \text{mis}(G - V(G_1))$ 
8 else
9   Select  $v \in V$  s.t.  $d(v) = \Delta(G)$                  //  $v$  has max degree
10  return  $\max(1 + \text{mis}(G - N[v]), \text{mis}(G - v))$ 

```

Correctness

Line 4:

Lemma 4. *If $v \in V$ has degree 1, then G has a maximum independent set I with $v \in I$.*

Proof. Let J be a maximum independent set of G . If $v \in J$ we are done because we can take $I = J$. If $v \notin J$, then $u \in J$, where u is the neighbor of v , otherwise J would not be maximum. Set $I = (J \setminus \{u\}) \cup \{v\}$. We have that I is an independent set, and, since $|I| = |J|$, I is a maximum independent set containing v . \square

2.1 Simple Analysis

Lemma 5 (Simple Analysis Lemma). *Let*

- A be a branching algorithm
- $\alpha > 0$, $c \geq 0$ be constants

such that on input I , A calls itself recursively on instances I_1, \dots, I_k , but, besides the recursive calls, uses time $O(|I|^c)$, such that

$$(\forall i : 1 \leq i \leq k) \quad |I_i| \leq |I| - 1, \text{ and} \quad (1)$$

$$2^{\alpha \cdot |I_1|} + \dots + 2^{\alpha \cdot |I_k|} \leq 2^{\alpha \cdot |I|}. \quad (2)$$

Then A solves any instance I in time $O(|I|^{c+1}) \cdot 2^{\alpha \cdot |I|}$.

Proof. By induction on $|I|$. W.l.o.g., suppose the hypotheses' O statements hide a constant factor $d \geq 0$, and for the base case assume that the algorithm returns the solution to an empty instance in time $d \leq d \cdot |I|^{c+1} 2^{\alpha \cdot |I|}$.

Suppose the lemma holds for all instances of size at most $|I| - 1 \geq 0$, then the running time of algorithm A on instance I is

$$\begin{aligned}
T_A(I) &\leq d \cdot |I|^c + \sum_{i=1}^k T_A(I_i) && \text{(by definition)} \\
&\leq d \cdot |I|^c + \sum d \cdot |I_i|^{c+1} 2^{\alpha \cdot |I_i|} && \text{(by the inductive hypothesis)} \\
&\leq d \cdot |I|^c + d \cdot (|I| - 1)^{c+1} \sum 2^{\alpha \cdot |I_i|} && \text{(by (1))} \\
&\leq d \cdot |I|^c + d \cdot (|I| - 1)^{c+1} 2^{\alpha \cdot |I|} && \text{(by (2))} \\
&\leq d \cdot |I|^{c+1} 2^{\alpha \cdot |I|}.
\end{aligned}$$

The final inequality uses that $\alpha \cdot |I| > 0$ and holds for any $c \geq 0$. □

Simple Analysis for mis

- At each node of the search tree: $O(n^2)$
- G disconnected: (1) If $\alpha \cdot s < 1$, then $s < 1/\alpha$, and the algorithm solves G_1 in constant time (provided that $\alpha > 0$). We can view this rule as a simplification rule, getting rid of G_1 and making one recursive call on $G - V(G_1)$. (2) If $\alpha \cdot (n - s) < 1$: similar as (1). (3) Otherwise,

$$(\forall s : 1/\alpha \leq s \leq n - 1/\alpha) \quad 2^{\alpha \cdot s} + 2^{\alpha \cdot (n-s)} \leq 2^{\alpha \cdot n}. \quad (3)$$

always satisfied since the function 2^x has slope ≥ 1 when $x \geq 1$.

- Branch on vertex of degree $d \geq 3$

$$(\forall d : 3 \leq d \leq n - 1) \quad 2^{\alpha \cdot (n-1)} + 2^{\alpha \cdot (n-1-d)} \leq 2^{\alpha n}. \quad (4)$$

Dividing all these terms by $2^{\alpha n}$, the constraints become

$$2^{-\alpha} + 2^{\alpha \cdot (-1-d)} \leq 1. \quad (5)$$

Compute optimum α

The minimum α satisfying the constraints is obtained by solving a convex mathematical program minimizing α subject to the constraints (the constraint for $d = 3$ is sufficient as all other constraints are weaker).

Alternatively, set $x := 2^\alpha$, compute the unique positive real root of each of the *characteristic polynomials*

$$c_d(x) := x^{-1} + x^{-1-d} - 1,$$

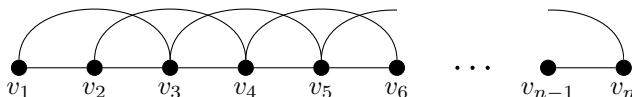
and take the maximum of these roots [Kullmann '99].

d	x	α
3	1.3803	0.4650
4	1.3248	0.4057
5	1.2852	0.3620
6	1.2555	0.3282
7	1.2321	0.3011

Simple Analysis: Result

- use the Simple Analysis Lemma with $c = 2$ and $\alpha = 0.464959$
- running time of Algorithm **mis** upper bounded by $O(n^3) \cdot 2^{0.464959 \cdot n} = O(2^{0.4650 \cdot n})$ or $O(1.3803^n)$

Lower bound



$$T(n) = T(n - 5) + T(n - 3)$$

- for this graph, P_n^2 , the worst case running time is $1.1938\dots^n \cdot \text{poly}(n)$
- Run time of algo **mis** is $\Omega(1.1938^n)$

Worst-case running time — a mystery

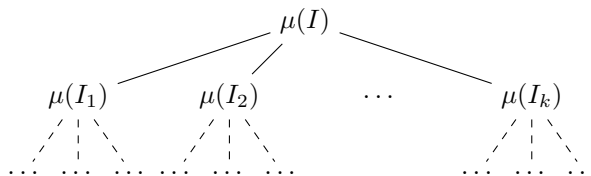
What is the worst-case running time of Algorithm **mis**?

- lower bound $\Omega(1.1938^n)$
- upper bound $O(1.3803^n)$

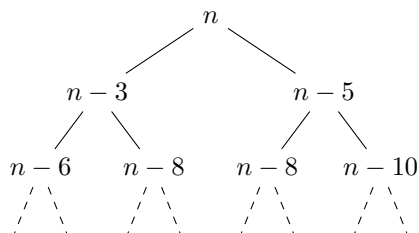
2.2 Search Trees and Branching Numbers

Search Trees

Denote $\mu(I) := \alpha \cdot |I|$.



Example: execution of **mis** on a P_n^2



Branching number: Definition

Consider a constraint

$$2^{\mu(I)-a_1} + \dots + 2^{\mu(I)-a_k} \leq 2^{\mu(I)}.$$

Its *branching number* is

$$2^{-a_1} + \dots + 2^{-a_k},$$

and is denoted by

$$(a_1, \dots, a_k).$$

Clearly, any constraint with branching number at most 1 is satisfied.

Branching numbers: Properties

Dominance For any a_i, b_i such that $a_i \geq b_i$ for all i , $1 \leq i \leq k$,

$$(a_1, \dots, a_k) \leq (b_1, \dots, b_k),$$

as $2^{-a_1} + \dots + 2^{-a_k} \leq 2^{-b_1} + \dots + 2^{-b_k}$.

In particular, for any $a, b > 0$,

$$\text{either } (a, a) \leq (a, b) \quad \text{or} \quad (b, b) \leq (a, b).$$

Balance If $0 < a \leq b$, then for any ε such that $0 \leq \varepsilon \leq a$,

$$(a, b) \leq (a - \varepsilon, b + \varepsilon)$$

by convexity of 2^x .

2.3 Measure Based Analysis

- Goal
 - capture more structural changes when branching into subinstances
- How?
 - potential-function method, a.k.a., *Measure & Conquer*
- Example: Algorithm **mis**
 - advantage when degrees of vertices decrease

Measure

Instead of using the number of vertices, n , to track the progress of **mis**, let us use a measure μ of G .

Definition 6. A *measure* μ for a problem P is a function from the set of all instances for P to the set of non negative reals.

Let us use the following measure for the analysis of **mis** on graphs of maximum degree at most 5:

$$\mu(G) = \sum_{i=0}^5 \omega_i n_i,$$

where $n_i := |\{v \in V : d(v) = i\}|$.

Measure Based Analysis

Lemma 7 (Measure Analysis Lemma). *Let*

- A be a branching algorithm
- $c \geq 0$ be a constant, and
- $\mu(\cdot), \eta(\cdot)$ be two measures for the instances of A ,

such that on input I , A calls itself recursively on instances I_1, \dots, I_k , but, besides the recursive calls, uses time $O(\eta(I)^c)$, such that

$$(\forall i) \quad \eta(I_i) \leq \eta(I) - 1, \text{ and} \tag{6}$$

$$2^{\mu(I_1)} + \dots + 2^{\mu(I_k)} \leq 2^{\mu(I)}. \tag{7}$$

Then A solves any instance I in time $O(\eta(I)^{c+1}) \cdot 2^{\mu(I)}$.

Analysis of **mis** for degree at most 5

For $\mu(G) = \sum_{i=0}^5 \omega_i n_i$ to be a valid measure, we constrain that

$$w_d \geq 0 \quad \text{for each } d \in \{0, \dots, 5\}$$

We also constrain that reducing the degree of a vertex does not increase the measure (useful for analysis of the degree-1 simplification rule and the branching rule):

$$-\omega_d + \omega_{d-1} \leq 0 \quad \text{for each } d \in \{1, \dots, 5\}$$

Lines 1–2 is a halting rule and we merely need that it takes polynomial time so that we can apply Lemma 7. Lines 3–4 of **mis** need to satisfy (7).

The simplification rule removes v and its neighbor u . We get a constraint for each possible degree of u :

$$\begin{aligned} & 2^{\mu(G) - \omega_1 - \omega_d} \leq 2^{\mu(G)} && \text{for each } d \in \{1, \dots, 5\} \\ \Leftrightarrow & 2^{-\omega_1 - \omega_d} \leq 2^0 && \text{for each } d \in \{1, \dots, 5\} \\ \Leftrightarrow & -\omega_1 - \omega_d \leq 0 && \text{for each } d \in \{1, \dots, 5\} \end{aligned}$$

These constraints are always satisfied since $\omega_d \geq 0$ for each $d \in \{0, \dots, 5\}$. **Note:** the degrees of u 's other neighbors (if any) decrease, but this degree change does not increase the measure.

For lines 5–7 of **mis** we consider two cases.

If $\mu(G_1) < 1$ (or $\mu(G - V(G_1)) < 1$, which is handled similarly), then we view this rule as a simplification rule, which takes polynomial time to compute **mis**(G_1), and then makes a recursive call **mis**($G - V(G_1)$). To ensure that instances with measure < 1 can be solved in polynomial time, we constrain that

$$w_d > 0 \quad \text{for each } d \in \{3, 4, 5\}$$

and this will be implied by other constraints.

Otherwise, $\mu(G_1) \geq 1$ and $\mu(G - V(G_1)) \geq 1$, and we need to satisfy (7). Since $\mu(G) = \mu(G_1) + \mu(G - V(G_1))$, the constraints

$$2^{\mu(G_1)} + 2^{\mu(G - V(G_1))} \leq 2^{\mu(G)}$$

are always satisfied since the slope of the function 2^x is at least 1 when $x \geq 1$. (I.e., we get no new constraints on $\omega_1, \dots, \omega_5$.)

Lines 8–10 of **mis** need to satisfy (7). We know that in $G - N[v]$, some vertex of $N^2[v]$ has its degree decreased (unless G has at most 6 vertices, which can be solved in constant time). Define

$$(\forall d : 2 \leq d \leq 5) \quad h_d := \min_{2 \leq i \leq d} \{w_i - w_{i-1}\}$$

We obtain the following constraints:

$$\begin{aligned} & 2^{\mu(G) - w_d - \sum_{i=2}^d p_i \cdot (w_i - w_{i-1})} + 2^{\mu(G) - w_d - \sum_{i=2}^d p_i \cdot w_i - h_d} \leq 2^{\mu(G)} \\ \Leftrightarrow & 2^{-w_d - \sum_{i=2}^d p_i \cdot (w_i - w_{i-1})} + 2^{-w_d - \sum_{i=2}^d p_i \cdot w_i - h_d} \leq 1 \end{aligned}$$

for all $d, 3 \leq d \leq 5$ (degree of v), and all $p_i, 2 \leq i \leq d$, such that $\sum_{i=2}^d p_i = d$ (number of neighbors of degree i).

Applying the lemma

Our constraints

$$\begin{aligned} & w_d \geq 0 \\ & -\omega_d + \omega_{d-1} \leq 0 \\ & 2^{-w_d - \sum_{i=2}^d p_i \cdot (w_i - w_{i-1})} + 2^{-w_d - \sum_{i=2}^d p_i \cdot w_i - h_d} \leq 1 \end{aligned}$$

are satisfied by the following values:

i	w_i	h_i
1	0	0
2	0.25	0.25
3	0.35	0.10
4	0.38	0.03
5	0.40	0.02

These values for w_i satisfy all the constraints and $\mu(G) \leq 2n/5$ for any graph of max degree ≤ 5 . Taking $c = 2$ and $\eta(G) = n$, the Measure Analysis Lemma shows that **mis** has run time $O(n^3)2^{2n/5} = O(1.3196^n)$ on graphs of max degree ≤ 5 .

2.4 Optimizing the measure

Compute optimal weights

- By convex programming [Gaspers, Sorkin 2009]

All constraints are already convex, except conditions for h_d

$$\begin{aligned}
 (\forall d : 2 \leq d \leq 5) \quad h_d &:= \min_{2 \leq i \leq d} \{w_i - w_{i-1}\} \\
 &\Downarrow \\
 (\forall i, d : 2 \leq i \leq d \leq 5) \quad h_d &\leq w_i - w_{i-1}.
 \end{aligned}$$

Use existing convex programming solvers to find optimum weights.

Convex program in AMPL

```

param maxd integer = 5;
set DEGREES := 0..maxd;
var W {DEGREES} >= 0; # weight for vertices according to their degrees
var g {DEGREES} >= 0; # weight for degree reductions from deg i
var h {DEGREES} >= 0; # weight for degree reductions from deg <= i
var Wmax; # maximum weight of W[d]

minimize Obj: Wmax; # minimize the maximum weight

subject to MaxWeight {d in DEGREES}:
  Wmax >= W[d];
subject to gNotation {d in DEGREES : 2 <= d}:
  g[d] <= W[d]-W[d-1];
subject to hNotation {d in DEGREES, i in DEGREES : 2 <= i <= d}:
  h[d] <= W[i]-W[i-1];
subject to Deg3 {p2 in 0..3, p3 in 0..3 : p2+p3=3}:
  2^(-W[3] -p2*g[2] -p3*g[3]) + 2^(-W[3] -p2*W[2] -p3*W[3] -h[3]) <=1;
subject to Deg4 {p2 in 0..4, p3 in 0..4, p4 in 0..4 : p2+p3+p4=4}:
  2^(-W[4] - p2*g[2] - p3*g[3] - p4*g[4])
+ 2^(-W[4] - p2*W[2] - p3*W[3] - p4*W[4] - h[4]) <=1;
subject to Deg5 {p2 in 0..5, p3 in 0..5, p4 in 0..5, p5 in 0..5 :
  p2+p3+p4+p5=5}:
  2^(-W[5] - p2*g[2] - p3*g[3] - p4*g[4] - p5*g[5])
+ 2^(-W[5] - p2*W[2] - p3*W[3] - p4*W[4] - p5*W[5] - h[5]) <=1;

```

Optimal weights

i	w_i	h_i
1	0	0
2	0.206018	0.206018
3	0.324109	0.118091
4	0.356007	0.031898
5	0.358044	0.002037

- use the Measure Analysis Lemma with $\mu(G) = \sum_{i=1}^5 w_i n_i \leq 0.358044 \cdot n$, $c = 2$, and $\eta(G) = n$
- **mis** has running time $O(n^3)2^{0.358044 \cdot n} = O(1.2817^n)$

2.5 Exponential Time Subroutines

Lemma 8 (Combine Analysis Lemma). *Let*

- *A be a branching algorithm and B be an algorithm,*
- *$c \geq 0$ be a constant, and*
- *$\mu(\cdot), \mu'(\cdot), \eta(\cdot)$ be three measures for the instances of A and B,*

such that $\mu'(I) \leq \mu(I)$ for all instances I, and on input I, A either solves I by invoking B with running time $O(\eta(I)^{c+1}) \cdot 2^{\mu'(I)}$, or calls itself recursively on instances I_1, \dots, I_k , but, besides the recursive calls, uses time $O(\eta(I)^c)$, such that

$$(\forall i) \quad \eta(I_i) \leq \eta(I) - 1, \text{ and} \tag{8}$$

$$2^{\mu(I_1)} + \dots + 2^{\mu(I_k)} \leq 2^{\mu(I)}. \tag{9}$$

Then A solves any instance I in time $O(\eta(I)^{c+1}) \cdot 2^{\mu(I)}$.

Algorithm **mis** on general graphs

- use the Combine Analysis Lemma with $A = B = \mathbf{mis}$, $c = 2$, $\mu(G) = 0.35805n$, $\mu'(G) = \sum_{i=1}^5 w_i n_i$, and $\eta(G) = n$
- for every instance G , $\mu'(G) \leq \mu(G)$ because $\forall i, w_i \leq 0.35805$
- for each $d \geq 6$,

$$(0.35805, (d+1) \cdot 0.35805) \leq 1$$

- Thus, Algorithm **mis** has running time $O(1.2817^n)$ for graphs of arbitrary degrees

2.6 Structures that arise rarely

Rare Configurations

- Branching on a local configuration C does not influence overall running time if C is selected only a constant number of times on the path from the root to a leaf of any search tree corresponding to the execution of the algorithm
- Can be proved formally by using measure

$$\mu'(I) := \begin{cases} \mu(I) + c & \text{if } C \text{ may be selected in the current subtree} \\ \mu(I) & \text{otherwise.} \end{cases}$$

Avoid branching on regular instances in **mis**

else

Select $v \in V$ such that

- (1) v has maximum degree, and
- (2) among all vertices satisfying (1), v has a neighbor of minimum degree

return $\max(1 + \mathbf{mis}(G - N[v]), \mathbf{mis}(G - v))$

New measure:

$$\mu'(G) = \mu(G) + \sum_{d=3}^5 [G \text{ has a } d\text{-regular subgraph}] \cdot C_d$$

where $C_d, 3 \leq d \leq 5$, are constants. The Iverson bracket $[F] = \begin{cases} 1 & \text{if } F \text{ true} \\ 0 & \text{otherwise} \end{cases}$

Resulting Branching numbers

For each $d, 3 \leq d \leq 5$ and all $p_i, 2 \leq i \leq d$ such that $\sum_{i=2}^d p_i = d$ and $p_d \neq d$,

$$\left(w_d + \sum_{i=2}^d p_i \cdot (w_i - w_{i-1}), w_d + \sum_{i=2}^d p_i \cdot w_i + h_d \right).$$

All these branching numbers are at most 1 with the optimal set of weights

Result

i	w_i	h_i
1	0	0
2	0.207137	0.207137
3	0.322203	0.115066
4	0.343587	0.021384
5	0.347974	0.004387

Thus, the modified Algorithm **mis** has running time $O(2^{0.3480 \cdot n}) = O(1.2728^n)$.

Current best algorithm for MIS: $O(1.1996^n)$ [Xiao, Nagamochi '13]

3 Max 2-CSP

Max 2-CSP generalizes Maximum Independent Set

MAX 2-CSP

Input: A graph $G = (V, E)$ and a set S of *score functions* containing

- a score function $s_e : \{0, 1\}^2 \rightarrow \mathbb{N}_0$ for each edge $e \in E$,
- a score function $s_v : \{0, 1\} \rightarrow \mathbb{N}_0$ for each vertex $v \in V$, and
- a score “function” $s_\emptyset : \{0, 1\}^0 \rightarrow \mathbb{N}_0$ (which takes no arguments and is just a constant convenient for bookkeeping).

Output: The maximum score $s(\phi)$ of an assignment $\phi : V \rightarrow \{0, 1\}$:

$$s(\phi) := s_\emptyset + \sum_{v \in V} s_v(\phi(v)) + \sum_{uv \in E} s_{uv}(\phi(u), \phi(v)).$$

4 Further Reading

- Chapter 2, *Branching* in Fedor V. Fomin and Dieter Kratsch. Exact Exponential Algorithms. Springer, 2010.
- Chapter 6, *Measure & Conquer* in Fedor V. Fomin and Dieter Kratsch. Exact Exponential Algorithms. Springer, 2010.
- Chapter 2, *Branching Algorithms* in Serge Gaspers. Exponential Time Algorithms: Structures, Measures, and Bounds. VDM Verlag Dr. Mueller, 2010.