Enumeration of Enumeration Algorithms

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Abstract

In this paper, we enumerate enumeration problems and algorithms1. Other useful catalogues for enumeration algorithms are provided by Komei Fukuda2 and Yasuko Matsui3. This survey is under construction. If you know some results not in this survey or there is anything wrong, please let me know.

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1 See also http://www-ikn.ist.hokudai.ac.jp/~wasa/enumeration_complexity.html
2 http://www-oldurls.inf.ethz.ch/personal/fukudak/publ/Enumeration/enumalgo95_update.pdf
3 http://www-oldurls.inf.ethz.ch/personal/fukudak/publ/Enumeration/enumalgo93.pdf
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1 Geometry

1.1 Arrangement

1.1.1 Enumeration of all cells in arrangements

Input An arrangement of distinct hyperplanes.

Output All cells in arrangements.

Complexity $O(nm\ell(n,m)N)$ total time and $O(nm)$ space.

Comment $n$ is the dimension, $m$ is the number of hyperplanes, and $\ell(n,m)$ is the time for solving an LP with $n$ variables and $m - 1$ inequalities. $N$ is the number of solutions.

Reference [7]

1.2 Face

1.2.1 Enumeration of all arrangements

Input An integer $n$ and $J \subseteq \{+,-\}^n$.

Output The set $\mathcal{F}$ of faces if $J$ is the set of maximal faces of an oriented matroid.

Complexity $O(\text{max}(n^2|J|^3, n^3|J|^2))$ total time.

Comment Their paper treats a reconstruction of the location vectors of all faces from the graph.

Reference [85]

1.3 Matching

1.3.1 Enumeration of all non-crossing perfect matchings (and convex partitions) in a given points

Input A point sets $P$ in a plane

Output All non-crossing perfect matchings (and convex partitions) in $P$.

Complexity After $O(2^n n^4)$ preprocessing time, polynomial delay.

Comment $n$ is the number of points in $P$

Reference [259]
1.4 Nearest neighbor

1.4.1 Enumeration of the $k$ smallest distances between pairs of points

Input \( n \) points in a plane.

Output The \( k \) smallest distances between pairs of points in non-decreasing order.

Complexity \( O(n \log n + k \log k) \) total time and \( O(n + k) \) space.

Reference [57]

1.5 Spanning tree

1.5.1 Enumeration of the Euclidean \( k \) best spanning trees in a plane with \( n \) points

Input \( n \) points in a plane

Output The Euclidean \( k \) best spanning trees of the given points.

Complexity \( O(k^2 n + n \log n) \) total time

Comment An Euclidean spanning tree in a plane is a spanning tree of the complete graph whose vertices are all given points and the weight of an edge equal to the Euclidean distance between the corresponding vertices.

Reference [64]

1.5.2 Enumeration of the orthogonal \( k \) best spanning trees in a plane with \( n \) points

Input \( n \) points in a plane

Output The orthogonal \( k \) best spanning trees of the given points.

Complexity \( O(k^2 + kn \log \log(n/k) + n \log n) \) total time.

Comment An orthogonal spanning tree in a plane is a spanning tree of the complete graph whose vertices are all given points and the weight of an edge equal to the \( L_1 \) distance between the corresponding vertices.

Reference [64]
1.5.3 Enumeration of all spanning trees of a plane

Input  A point set $P$.

Output  All spanning trees of $P$.

Complexity  $O(|P|^3N)$ total time and $O(|P|)$ space.

Comment  $N$ is the number of solutions.

Reference  [7]

1.5.4 Enumeration of the Euclidean $k$ best spanning trees in a plane with $n$ points

Input  $n$ points in a plane

Output  The Euclidean $k$ best spanning trees of the given points.

Complexity  $O(n \log n \log k + k \min(k, n)^{1/2})$ total time

Comment  An Euclidean spanning tree in a plane is a spanning tree of the complete graph whose vertices are all given points and the weight of an edge equal to the Euclidean distance between the corresponding vertices.

Reference  [68]

1.6 Triangulation

1.6.1 Enumeration of all regular triangulations

Input  $n$ points.

Output  All regular triangulations of given points in $(d - 1)$-dimensional space.

Complexity  $O(dsLP(r, ds)T)$ time and $O(ds)$ space.

Comment  $s$ is the upper bound of the number of simplices contained in one regular triangulation, $LP(r, ds)$ denotes the time complexity of solving linear programming problem with $ds$ strict inequality constraints in $r$ variables, and $T$ is the number of regular triangulations.

Reference  [152]
1.6.2 Enumeration of all spanning regular triangulations

**Input** $n$ points.

**Output** All spanning regular triangulations of given points in $(d - 1)$-dimensional space.

**Complexity** $O(dsLP(r, ds)T')$ time and $O(ds)$ space.

**Comment** $s$ is the upper bound of the number of simplices contained in one regular triangulation, $LP(r, ds)$ denotes the time complexity of solving linear programming problem with $ds$ strict inequality constraints in $r$ variables, and $T'$ is the number of regular triangulations.

**Reference** [152]

1.6.3 Enumeration of all triangulations of a point set

**Input** A point set $P$.

**Output** All triangulations of $P$.

**Complexity** $O(|P|N)$ total time and $O(|P|)$ space.

**Comment** $N$ is the number of solutions.

**Reference** [7]

1.6.4 Enumeration of all triangulations in general dimensions

**Input** Points.

**Output** All triangulations.

**Complexity** See the paper.

**Comment** This algorithm uses the enumeration algorithm for maximal independent sets.

**Reference** [233]
1.6.5 Enumeration of all regular triangulations in general dimensions

Input Points.

Output All regular triangulations.

Complexity See the paper.

Comment This algorithm uses the enumeration algorithm for maximal independent sets.

Reference [233]

1.6.6 Enumeration of all triangulation paths of a point set

Input A point set $P$.

Output All triangulation paths of $P$.

Complexity $O(N|P|^3 \log |P|)$ time and $O(|P|)$ space.

Comment $N$ is the number of solutions.

Reference [60]

1.6.7 Enumeration of all pseudotriangulations of a finite point set

Input A point set $S$ of size $n$.

Output All pointed pseudotriangulations of $S$.

Complexity $O(\log n)$ time per solution with linear space.

Reference [18]

1.6.8 Enumeration of all pseudotriangulations of a point set

Input A point set $P$.

Output All pseudotriangulations of $P$.

Complexity $O(n)$ time per pseudotriangulation.

Comment $n$ is the number of points in $P$.

Reference [36]
1.6.9 Enumeration of all triangulations of a convex polygon of $n$ vertices with numbered

**Input** A convex polygon $P$ with $n$ vertices that are numbered.

**Output** All triangulations of $P$.

**Complexity** $O(1)$ time per triangulation and $O(n)$ space.

**Reference** [185]

1.6.10 Enumeration of all triangulations of a convex polygon of $n$ vertices

**Input** A convex polygon $P$ with $n$ vertices that are not numbered.

**Output** All triangulations of $P$.

**Complexity** $O(n^2)$ time per triangulation and $O(n)$ space.

**Reference** [185]

2 Graph

2.1 $k$-degenerate graph

2.1.1 Enumerate well-ordered (strongly) $k$-generate with $n$ vertices

**Input** $n$: the number of vertices.

**Output** All well-ordered (strongly) $k$-degenerate graphs with $n$ vertices.

**Complexity** $O(nm + m^2)$ time per enumerated and printed graph.

**Comment** $m$ is the number of edges of printed graphs.

**Reference** [16]

2.1.2 Enumerate well-ordered (strongly) $k$-generate with $n$ vertices and $m$ edges

**Input** $n$: the number of vertices, $m$: the number of edges.

**Output** All well-ordered (strongly) $k$-degenerate graphs with $n$ vertices and $m$ edges.
Complexity $O(n^{3/2}m^2)$ time per enumerated and printed graph.

Reference [16]

2.2 Bounded union

2.2.1 Enumeration of all bounded union

Input A graph with $h$ multiedges each with at most $d$ vertices.

Output All minimal subset $U$ of at most $k$ vertices that entirely includes at least one set from each multiedge.

Complexity $O(dc^{k+1}h + \min(kc^{2k}, hkc^k))$ time.

Reference [52]

2.3 Bridge

2.3.1 Enumeration of all bridge-avoiding extensions of a graph

Input A graph $G = (V, E)$ and an edge subset $B \subseteq E$.

Output All bridge-avoiding extensions of $G$.

Complexity $O(K^2 \log(K)|E|^2 + K^2(|V| + |E|)|E|^2)$ total time.

Comment $K$ is the number of bridge-avoiding extensions. $X$ is a bridge-avoiding extensions of $G$ if $X$ is a minimal edge set $X \subseteq E \setminus B$ such that no edge $b \in B$ is a bridge in $(V, B \cup X)$.

Reference [126]

2.4 Bubble

2.4.1 Enumeration of all bubbles in a directed graph

Input A directed graph $G = (V, E)$ and a source $s$.

Output All bubbles with a given source $s$.

Complexity $O(|V| + |E|)$ delay with $O(|V|(|V| + |E|))$ preprocessing time.

Comment An $(s, t)$-bubble is two disjoint $(s, t)$-paths that only share $s$ and $t$.

Reference [22]
2.4.2 Enumeration of all \((s, t, \alpha_1, \alpha_2)\)-bubble in a directed graph

**Input** A directed graph \(G = (V, E)\), source vertex \(s\), and two upper bounds \(\alpha_1\) and \(\alpha_2\).

**Output** All \((s, t, \alpha_1, \alpha_2)\)-bubble in \(G\).

**Complexity** \(O(|V||E| + |V| \log |V|)\) delay.

**Comment** A pair of two vertex-disjoint \((s, t)\)-paths \(p_1\) and \(p_2\) is \((s, t, \alpha_1, \alpha_2)\)-bubble in \(G\), if \(|p_1| \leq \alpha_1\) and \(|p_2| \leq \alpha_2\).

**Reference** [207]

2.5 Chord diagram

2.5.1 Enumeration of all non-isomorphic chord diagrams

**Input** An integer \(2n\).

**Output** All non-isomorphic chord diagrams with \(2n\) points.

**Comment** A chord diagram is a set of \(2n\) points on an oriented circle (counterclockwise) joined pairwise by \(n\) chords. In an experiment, their algorithm runs in almost CAT, but there is no Mathematical proof.

**Reference** [213]

2.6 Chordal graph

2.6.1 Enumeration of all chordal graphs in a graph

**Input** A graph \(G\).

**Output** All chordal graphs in \(G\).

**Complexity** \(O(1)\) delay with \(O(n^3)\) space.

**Comment** Using reverse search.

**Reference** [129]
### 2.6.2 Enumeration of all chordal supergraph that contains a given graph

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

**Output** All chordal supergraphs each of which contain $G$.

**Complexity** $O(|V|^3)$ time for each and $O(|V|^2)$ space.

**Reference** [128]

### 2.6.3 Enumeration of all chordal sandwiches in a graph

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

**Output** All chordal sandwiches in $G$.

**Complexity** Polynomial delay with polynomial space.

**Reference** [127]

### 2.7 Clique

#### 2.7.1 Enumeration of all cliques in a graph

**Input** A graph $G$.

**Output** All cliques in $G$.

**Comment** They pointed out Augustson and Minker’s algorithm has two errors.

**Reference** [167]

#### 2.7.2 Enumeration of all maximal clique in a graph

**Input** An undirected graph $G = (V, E)$.

**Output** All maximal clique.

**Reference** [3]
2.7.3 Enumeration of all cliques in a graph

Input  A graph $G$.

Output All cliques in $G$.

Reference [35]

2.7.4 Enumeration of all cliques in an undirected graph

Input  An undirected graph $G$.

Output All cliques in $G$.

Reference [112]

2.7.5 Enumeration of all maximal cliques in a given graph

Input  A graph $G$.

Output All maximal cliques in $G$.

Reference [92]

2.7.6 Enumeration of all maximum cliques in a circle graph

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

Output All maximum cliques in $G$.

Complexity $O(1)$ time per maximum clique.

Comment A graph is a circle graph if it is the intersection graph of chords in a circle. The definition of a circle graph can be found in Information System on Graph Classes and their Inclusions\(^4\).

Reference [195]

\(^4\)http://www.graphclasses.org/classes/gc_132.html
2.7.7 Enumeration of all cliques in a connected graph

Input  A connected graph $G = (V, E)$ and an order $l \geq 2$ of cliques.

Output  All cliques in $G$.

Complexity  $O(l\alpha(G)^{l-2}|E|)$ total time and linear space.

Comment  $\alpha(G)$ is the minimum number of edge-disjoint spanning forests into which $G$ can be decomposed.

Reference  [47]

2.7.8 Enumeration of all maximal cliques in a connected graph

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

Output  All maximal cliques in $G$.

Complexity  $O(\alpha(G)|E|)$ total time and linear space.

Comment  $\alpha(G)$ is the minimum number of edge-disjoint spanning forests into which $G$ can be decomposed.

Reference  [47]

2.7.9 Enumeration of all maximum cliques of a circular-arc graph

Input  A circular-arc graph $G = (V, E)$.

Output  All maximum cliques of $G$.

Complexity  $O(|V|^{3.5} + N)$.

Comment  $N$ is the number of maximum cliques of $G$. For a family $A$ of arcs on a circle, a graph $G = (V, E)$ is called the circular-arc graph for $A$ if there exists a one-to-one correspondence between $V$ and $A$ such that two vertices in $V$ are adjacent if and only if their corresponding arcs in $A$ intersect.

Reference  [119]
2.7.10  Enumeration of all maximal cliques in a graph

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

Output  All maximal cliques included in $G$.

Complexity  $O(M(n))$ time delay and $O(n^2)$ space, or $O(\delta^4)$ time delay and $O(n + m)$ space, after $O(nm)$ preprocessing.

Comment  $M(n)$: the time needed to multiply two $n \times n$ matrices, $\delta$: maximum degree of $G = (V, E)$, $n$: total number of vertices, and $m$: total number of edges.

Reference  [149]

2.7.11  Enumeration of all maximal cliques in a bipartite graph

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

Output  All maximal bicliques included in $G$.

Complexity  $O(M(n))$ time delay and $O(n^2)$ space, or $O(\delta^4)$ time delay and $O(n + m)$ space, after $O(nm)$ preprocessing.

Comment  $M(n)$: the time needed to multiply two $n \times n$ matrices, $\delta$: maximum degree of $G = (V, E)$, $n$: total number of vertices, and $m$: total number of edges.

Reference  [149]

2.7.12  Enumeration of all maximal cliques in a dynamic graph

Input  A graph $G_t = (V, E_t)$.

Output  All maximal cliques in $G_t$.

Reference  [228]

2.7.13  Enumeration of all maximal cliques in a dynamic graph

Input  A dynamic graph $G$.

Output  All maximal cliques in $G$.

Reference  [228]
2.7.14  Enumeration of all bicliques in a graph in lexicographical order

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

Output All bicliques in $G$.

Complexity $O(|V|^3)$ delay and $O(2^{|V|})$ space.

Comment There is no polynomial-delay enumeration algorithm for all bicliques in reverse lexicographical order unless $P = NP$.

Reference [56]

2.7.15  Enumeration of all maximal cliques in a graph

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

Output All maximal Cliques in $G$.

Complexity $O(\frac{\Delta M_c T r i^2}{p})$ delay and $O(|V| + |E|)$ space.

Comment $\Delta$ is the maximum degree in $G$, $M_c$ is the size of the maximum clique in $G$, and $T r i$ is the number of triangles in $G$. This algorithm runs on the computer with $P$ processors.

Reference [59]

2.7.16  Enumeration of all cliques in a chordal graph

Input  A chordal graph $G$.

Output All cliques in $G$.

Complexity $O(1)$ time per solution on average.

Reference [129]

2.7.17  Enumeration of all maximal cliques in a graph

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

Output All maximal cliques in $G$.

Complexity $O(3^{n/3})$ total time.

Reference [237]
2.7.18 Enumeration of $K$-largest maximal cliques in a graph

**Input** A graph $G$.

**Output** $K$-largest maximal cliques in $G$.

**Reference** [37]

2.7.19 Enumeration of all maximal cliques in a graph

**Input** A graph $G$.

**Output** All maximal cliques in $G$.

**Reference** [183]

2.7.20 Enumeration of all maximal bicliques in a bipartite graph

**Input** A bipartite graph $G = (U, V, E)$.

**Output** All maximal bicliques in $G$ in lexicographical order on $U$.

**Complexity** $O((|U| + |V|)^2)$ delay with exponential space.

**Reference** [90]

2.7.21 Enumeration of all maximal cliques in a comparability graph

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

**Output** All maximal cliques in $G$ in lexicographical order.

**Complexity** $O(|V|)$ delay and $O(|V| + |E|)$ space.

**Reference** [90]

2.7.22 Enumeration of all maximal cliques in a graph

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

**Output** All maximal cliques in $G$ in lexicographical order.

**Complexity** $O(|V||E|)$ delay with exponential space.

**Reference** [90]
2.7.23 Enumeration of all maximal cliques in a graph

**Input** A graph $G$.

**Output** All maximal cliques in $G$.

**Comment** This algorithm can be paralleled.

**Reference** [218]

2.7.24 Enumeration of all $c$-isolated maximal clique in a graph

**Input** A graph $G = (V, E)$ and a positive real number $c$.

**Output** All $c$-isolated maximal clique in $G$.

**Complexity** $O(c^42^{2c}|E|)$ total time.

**Reference** [107]

2.7.25 Enumeration of all $c$-isolated pseudo-clique in a graph

**Input** A graph $G = (V, E)$ and a positive real number $c$.

**Output** All $c$-isolated $PC(k - \log k, \frac{k}{\log k})$ in $G$.

**Complexity** $O(c^42^{2c}|E|)$ total time.

**Comment** $PC(\alpha, \beta)$ is a induced subgraph of $G$ with an average degree at least $\alpha$ and the minimum degree at least $\beta$.

**Reference** [107]

2.7.26 Enumeration of all $c$-isolated maximal cliques in a graph

**Input** A graph $G = (V, E)$ and an integer $c$.

**Output** All avg-$c$-isolated maximal cliques in $G$.

**Complexity** $O(2^c c^5|E|)$ total time.

**Comment** A vertex set $S \subseteq V$ with $k$ vertices is $c$-isolated if it has less than $ck$ outgoing edges, where an outgoing edge is an edge between a vertex in $S$ and a vertex in $V \setminus S$.

**Reference** [105]
2.7.27 Enumeration of all max-$c$-isolated maximal cliques in a graph

**Input** A graph $G = (V, E)$ and an integer $c$.

**Output** All max-$c$-isolated maximal cliques in $G$.

**Complexity** $O(2^c c^5 |E|)$ total time.

**Comment** A vertex set $S \subseteq V$ with $k$ vertices is max-$c$-isolated if every vertex in $S$ has less than $c$ neighbors in $V \setminus S$.

**Reference** [105]

2.7.28 Enumeration of all maximal $c$-isolated cliques in a graph

**Input** A graph $G = (V, E)$ and an integer $c$.

**Output** All maximal $c$-isolated cliques in $G$.

**Complexity** $O(2.89^c c^2 |E|)$ total time.

**Comment** A vertex set $S \subseteq V$ with $k$ vertices is $c$-isolated if it has less than $ck$ outgoing edges, where an outgoing edge is an edge between a vertex in $S$ and a vertex in $V \setminus S$.

**Reference** [136]

2.7.29 Enumeration of all cliques in a graph with degeneracy $d$

**Input** A graph $G = (V, E)$ with degeneracy $d$.

**Output** All cliques in $G$.

**Complexity** $O(d|V|^{3d/3})$ time.

**Comment** They also show the largest possible number of maximal cliques in $G$. The number is $(|V| - d)^{3d/3}$.

**Reference** [67]
2.7.30  Enumeration of all pseudo-cliques in a graph

Input  A graph $G = (V, E)$ and a threshold $\theta$.

Output  All pseudo-cliques in $G$, whose densities are no less than $\theta$.

Complexity  $O(\Delta |V| + \min\{\Delta^2, |V| + |E|\})$ delay with $O(|V| + |E|)$ space.

Comment  $\Delta$ is the maximum degree of $G$. The density of a subgraph $G[S]$ induced by $S \subseteq V$ is given by the number of edges over the number of all its vertex pairs.

Reference  [245]

2.7.31  Enumeration of all maximal cliques in a graph with limited memory

Input  A graph $G$.

Output  All maximal graphs in $G$.

Complexity  See the paper.

Reference  [46]

2.7.32  Enumeration of all maximal cliques in a graph

Input  An undirected graph $G = (V, E)$.

Output  All maximal clique.

Complexity  $O(\delta \cdot H^3)$ time delay and $O(n + m)$ space.

Comment  $H$ satisfies $|\{v \in V | \sigma(v) \geq H\}| \leq H$.

Reference  [42]

2.7.33  Enumeration of all maximal cliques in a graph

Input  A graph $G$.

Output  All maximal cliques in $G$.

Reference  [102]
2.8 Coloring

2.8.1 Enumeration of all the edge colorings in a bipartite graph

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

Output All edge colorings in $G$.

Complexity $O(\Delta |E|)$ time per solution and space.

Comment $\Delta$ is the maximum degree in $G$.

Reference [271]

2.8.2 Enumeration of all the edge colorings of a bipartite graph

Input A bipartite graph $B = (V, E)$.

Output All the edge colorings of $B$.

Complexity $O(T(|V| + |E| + \Delta) + K \min\{|V|^2 + |E|, T(|V|, |E|, \Delta)\})$ total time and $O(|E|\Delta)$ space.

Comment $\Delta$ is the number of maximum degree and $T(|V|, |E|, \Delta)$ is the time complexity of an edge coloring algorithm.

Reference [156]

2.8.3 Enumeration of all the edge colorings of a bipartite graph

Input A bipartite graph $B = (V, E)$.

Output All the edge colorings of $B$.

Complexity $O(|V|)$ time per solution and $O(|E|)$ space.

Reference [159]

2.9 Connected

2.9.1 Enumeration of all minimal strongly connected subgraphs in a strongly connected subgraph

Input A strongly connected subgraph $G$.

Output All minimal strongly connected subgraph.
Complexity Incremental polynomial time.
Reference [27]

2.9.2 Enumeration of all minimal 2-vertex connected spanning subgraphs in a graph

Input A graph $G$.
Output All minimal 2-vertex connected spanning subgraphs of $G$.
Complexity Incremental polynomial time.
Reference [124]

2.10 Cut

2.10.1 Enumeration of all cuts between all pair of vertices in a given graph

Input A graph $G$.
Output All cuts between all pair of vertices in $G$.
Reference [150]

2.10.2 Enumeration of all cutsets in a graph

Input A graph $G = (V, E)$.
Output All cutsets in $G$.
Complexity $O((|V| + |E|)(\mu + 1))$ total time and $O(|V| + |E|)$ or $O(|V|^2)$ space.
Comment $\mu$ is the number of solutions.
Reference [239]

2.10.3 Enumeration of $k$ best cuts in a directed graph

Input A directed graph $G = (V, E)$.
Output $k$ best cuts in $G$.
Complexity $O(k|V|^4)$ total time.
Reference [100]
2.10.4 Enumeration of $K$-best cuts in a network

Input A graph $G = (V,E)$.
Output $K$-best cuts in $G$.
Complexity $O(K \cdot |V|^4)$ time.
Reference [100]

2.10.5 Enumeration of all articulation pairs in a planar graph

Input An undirected graph $G = (V,E)$.
Output All articulation pairs in $G$.
Complexity $O(|V|^2)$ total time.
Reference [141]

2.10.6 Enumeration of all minimum-size separating vertex sets in a graph

Input A graph $G = (V,E)$.
Output All minimum-size separating vertex sets.
Complexity $\Theta(M|V| + C) = O(2^k n^3)$ total time.
Comment $M$ is the number of solutions, $k$ is the connectivity of $G$, and $C = k|V| \min(k(|V| + |E|), A)$, where $A$ is the time complexity of the best maximum network flow algorithm for unit network.
Reference [114]

2.10.7 Enumeration of all minimal separators in a graph

Input A graph $G = (V,E)$.
Output All minimal separators in $G$.
Complexity $O(|V|^6 R)$ total time.
Comment $R$ is the number of solutions.
Reference [130]
2.10.8 Enumeration of all \((s,t)\)-cuts in a graph

**Input** A graph \(G = (V,E)\) and two vertices \(s,t\) in \(G\).

**Output** All \((s,t)\)-cuts in \(G\).

**Complexity** \(O(|E|)\) time per cut.

**Reference** [189]

2.10.9 Enumeration of all \((s,t)\)-cuts in a directed graph

**Input** A directed graph \(G = (V,E)\) and two vertices \(s,t\) in \(G\).

**Output** All \((s,t)\)-cuts in \(G\).

**Complexity** \(O(|E|)\) time per cut.

**Reference** [189]

2.10.10 Enumeration of all \((s,t)\)-uniformly directed cuts in a directed graph

**Input** A directed graph \(G = (V,E)\) and two vertices \(s,t\) in \(G\).

**Output** All \((s,t)\)-uniformly directed cuts in \(G\).

**Complexity** \(O(|V|)\) time per cut.

**Comment** An undirected directed cut is also called a UDC. An \((s,t)\)-DUC is an \((s,t)\)-cut \((X,Y)\) such that \((X,Y) = \emptyset\), where \((X,Y) = \{(u,v) \in E : u \in X, v \in Y\}\).

**Reference** [189]

2.10.11 Enumeration of all minimum weighted \((s,t)\) cuts in an weighted graph

**Input** An weighted graph \(G = (V,E)\) and two vertices \(s,t\) in \(G\).

**Output** All minimum weighted \((s,t)\) cuts in \(G\).

**Complexity** \(O(|V|)\) time per cut.

**Reference** [189]
2.10.12 Enumeration of all semidirected \((s, t)\) cuts in a directed graph

**Input** A directed graph \(G = (V, E)\) and two vertices \(s, t\) in \(G\).

**Output** All semidirected \((s, t)\) cuts in \(G\).

**Complexity** \(O(|V||E|)\) time per cut.

**Comment** For a subset \(D\) of directed edges, a semidirected \((s, t)\) cut with respect to \(D\) is an \((s, t)\) cut \((X, Y)\) such that \((X, Y) \cup (Y, X)\) defines an undirected \((s, t)\) cutset and such that \((X, Y) \cap D = \emptyset\), where a cutset is an minimal cut set.

**Reference** [189]

2.10.13 Enumeration of all strong \((s, K)\) cutsets in a graph

**Input** A graph \(G = (V, E)\), \(s \in V\) and \(K \subseteq V \setminus \{s\}\).

**Output** All strong \((s, K)\) cutsets in \(G\).

**Complexity** \(O(|E|)\) time per cut.

**Comment** An \((s, K)\)-cut is defined to be any cut \((X, Y)\) for which \(s \in X\) and \(K \cap Y \neq \emptyset\). A strong \((s, K)\) cutset is minimal cuts of the form \((X, Y)\) where \(s \in X\) and \(K \subseteq Y\).

**Reference** [189]

2.10.14 Enumeration of all strong \((s, K)\) cutsets in a directed graph

**Input** A directed graph \(G = (V, E)\), \(s \in V\) and \(K \subseteq V \setminus \{s\}\).

**Output** All strong \((s, K)\) cutsets in \(G\).

**Complexity** \(O(|E|)\) time per cut.

**Comment** An \((s, K)\)-cut is defined to be any cut \((X, Y)\) for which \(s \in X\) and \(K \cap Y \neq \emptyset\). A strong \((s, K)\) cutset is minimal cuts of the form \((X, Y)\) where \(s \in X\) and \(K \subseteq Y\).

**Reference** [189]
2.10.15 Enumeration of all quasi \((s, K)\) cuts in a graph

**Input** A graph \(G = (V, E)\), \(s \in V\) and \(K \subseteq V \setminus \{s\}\).

**Output** All quasi \((s, K)\) cutsets in \(G\).

**Complexity** \(O(|E|)\) time per cut.

**Comment** An \((s, K)\)-cut is defined to be any cut \((X, Y)\) for which \(s \in X\) and \(K \cap Y \neq \emptyset\). A Quasi \((s, K)\) cut is an edge set that is strong \((s, A)\)-cutsets for some \(A \subseteq K\) and \(A \neq \emptyset\).

**Reference** [189]

2.10.16 Enumeration of all quasi \((s, K)\) cuts in a directed graph

**Input** A directed graph \(G = (V, E)\), \(s \in V\) and \(K \subseteq V \setminus \{s\}\).

**Output** All quasi \((s, K)\) cutsets in \(G\).

**Complexity** \(O(|E|)\) time per cut.

**Comment** An \((s, K)\)-cut is defined to be any cut \((X, Y)\) for which \(s \in X\) and \(K \cap Y \neq \emptyset\). A Quasi \((s, K)\) cut is an edge set that is strong \((s, A)\)-cutsets for some \(A \subseteq K\) and \(A \neq \emptyset\).

**Reference** [189]

2.10.17 Enumeration of all \((s, K)\) cutsets in a graph

**Input** A graph \(G = (V, E)\), \(s \in V\) and \(K \subseteq V \setminus \{s\}\).

**Output** All \((s, K)\) cutsets in \(G\).

**Complexity** \(O(|E|)\) time per cut.

**Comment** An \((s, K)\)-cut is defined to be any cut \((X, Y)\) for which \(s \in X\) and \(K \cap Y \neq \emptyset\). A \((s, K)\) cutset is minimal \((s, K)\) cuts.

**Reference** [189]
2.10.18 Enumeration of all minimal $a$-$b$ separators in a graph

Input An undirected connected simple graph $G = (V, E)$, non-adjacent vertices $a$ and $b$ in $G$.

Output All minimal $a$-$b$ separator of $G$.

Complexity $O(R_{ab}|V|^3)$ total time.

Comment $R_{ab}$ is the number of minimal $a$-$b$ separators.

Reference [223]

2.10.19 Enumeration of all minimal $a$-$b$ separators in a graph

Input An undirected connected simple graph $G = (V, E)$, non-adjacent vertices $a$ and $b$ in $G$.

Output All minimal $a$-$b$ separator of $G$.

Complexity $O(R_{ab}|V|/\log |V|)$ total time.

Comment $R_{ab}$ is the number of minimal $a$-$b$ separators. This algorithm needs $O(|V|^3)$ processors on a CREW PRAM.

Reference [223]

2.10.20 Enumeration of all minimal separators of a graph

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

Output All minimal separators of $G$.

Complexity $O(|V|^5R)$ total time.

Comment $R$ is the number of solutions.

Reference [131]

2.10.21 Enumeration of all minimal separator of a graph

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

Output All minimal separator of $G$.

Complexity $O(|V|^3)$ time per solution.

Reference [19]
2.10.22 Enumeration of all minimal separator of a chordal graph

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

**Output**  All minimal separator of $G$.

**Complexity**  $O(|V| + |E|)$ total time.

**Reference**  [40]

2.10.23 Enumeration of all cut conjunctions for a given set of vertex pairs in a graph

**Input**  A graph $G = (V, E)$, and a collection $B = \{(s_1, t_1), \ldots, (s_k, t_k)\}$ of $k$ vertex pairs $s_i, t_i \in V$.

**Output**  All cut conjunctions for $B$ in $G$.

**Complexity**  Incremental polynomial time.

**Comment**  A minimal edge sets $X \subseteq E$ is a cut conjunction if, for all $i = 1, \ldots, k$, vertices $s_i$ and $t_i$ is disconnected in $G' = (V, E \setminus X)$. A cut conjunction is a generalization of an $s - t$ cut.

**Reference**  [125]

2.10.24 Enumeration of all minimal separators of a 3-connected planar graph

**Input**  A 3-connected planar graph $G = (V, E)$.

**Output**  All minimal separators of $G$.

**Complexity**  $O(|V|)$ time per solution.

**Reference**  [162]

2.10.25 Enumeration of all cut conjunctions of a graph

**Input**  A graph $G = (V, E)$ and a collection $B = \{(s_1, t_1), \ldots, (s_k, t_k)\}$.

**Output**  All cut conjunctions of $G$.

**Complexity**  $O(K^2 \log(K)|V||E|^2 + K^2|B|(|V| + |E|)|E|^2)$ total time.
Comment  $K$ is the number of cut conjunctions. $X$ is a cut conjunctions of $G$ if $X$ is a minimal edge set such that for all $i = 1, \ldots, k$, a pair of vertices $s_i$ and $t_i$ is disconnected in $(V, E \setminus X)$.

Reference [126]

2.10.26  Enumeration of all $(s, t)$-cuts in an weighted directed graph

Input  An weighted directed graph $G = (V, E)$.

Output  All cuts in $G$ by non-decreasing weights ordering.

Complexity $O(|V||E| \log(|V|^2/|E|))$ delay.

Reference [273]

2.10.27  Enumeration of all $(s, t)$-cuts in an weighted undirected graph

Input  An weighted undirected graph $G = (V, E)$.

Output  All cuts in $G$ by non-decreasing weights ordering.

Complexity $O(|V||E| \log(|V|^2/|E|))$ delay.

Reference [273]

2.11  Cycle

2.11.1  Enumeration of all cycles in an $n$-cube, where $n \leq 4$

Input  An integer $n$.

Output  All cycles (closed paths) in an $n$-cube.

Reference [93]

2.11.2  Enumeration of all cycles in a graph

Input  A graph $G$.

Output  All cycles in $G$.

Reference [256]
2.11.3 Enumeration of all simple cycles in a graph

Input A graph $G$.

Output All simple cycles in $G$.

Complexity

Reference [186]

2.11.4 Enumeration of all circuits in a graph

Input A graph $G$.

Output All circuits in $G$.

Reference [257]

2.11.5 Enumeration of all Hamiltonian circuits in a graph

Input A graph $G$.

Output All Hamiltonian circuits in $G$.

Reference [272]

2.11.6 Enumeration of all directed circuits in a directed graph

Input A directed graph $G$.

Output All directed circuits in $G$.

Reference [113]

2.11.7 Enumeration of all cycles in a graph

Input A graph $G$.

Output All cycles in $G$.

Reference [53]
2.11.8 Enumeration of all cycles in a graph
Input  A graph \( G \).
Output  All cycles in \( G \).
Reference  [10]

2.11.9 Enumeration of all elementary circuit in a graph
Input  A graph \( G \).
Output  All elementary circuit in \( G \).
Complexity
Reference  [236]

2.11.10 Enumeration of all cycles in a graph
Input  A graph \( G \).
Output  All cycles in \( G \).
Reference  [44]

2.11.11 Enumeration of all cycles in an undirected graph
Input  An undirected graph \( G \).
Output  All cycles in \( G \).
Reference  [255]

2.11.12 Enumeration of all cycles in a finite undirected graph
Input  A finite undirected graph \( G \).
Output  All cycles in \( G \).
Comment  He claimed that J. T. Welch, Jr.’s algorithm is wrong.
Reference  [255]
2.11.13 Enumeration of all cycles in a directed graph

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

Output All cycles in $G$.

Complexity $O((|V| \cdot |E|)(C + 1))$ total time and $O(|V| + |E|)$ space.

Comment $C$ is the number of cycles included in $G$.

Reference [235]

2.11.14 Enumeration of all cycles in a directed graph

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

Output All cycles in $G$.

Complexity $O(|E| + c(|V| \times |E|))$ total, where $c$ is the number of circuits in $G$.

Reference [61]

2.11.15 Enumeration of all cycles in a directed graph

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

Output All cycles in $G$.

Complexity $O((|V| + |E|)(C + 1))$ total time and $O(|V| + |E|)$ space.

Comment $C$ is the number of cycles included in $G$.

Reference [110]

2.11.16 Enumeration of all cycles in a graph

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

Output All cycles in $G$.

Complexity $O(|E|)$ time per cycle with $O(|E|)$ space.

Reference [193]
2.11.17 Enumeration of all cycles in a directed graph

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

Output All cycles in $G$.

Complexity $O(|E|)$ time per cycle with $O(|E|)$ space.

Reference [193]

2.11.18 Enumeration of all cycles in a planar graph

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

Output All cycles in $G$.

Complexity $O(|V|(C + 1))$ total time and $O(|V|)$ space.

Comment $C$ is the number of cycles included in $G$.

Reference [230]

2.11.19 Enumeration of all cycles of a given length in a graph

Input A graph $G$ and an integer $k$.

Output All cycles of length $k$ in $G$.

Complexity See paper.

Reference [4]

2.11.20 Enumeration of all cycles in a graph

Input A graph $G$.

Output All cycles in $G$.

Reference [261]

2.11.21 Enumeration of all small cycles in a graph

Input A graph $G$.

Output All cycles with length at most 5 in $G$.

Reference [261]
2.11.22 Enumeration of all chordless cycles in a graph

Input  A graph $G$.

Output  All chordless cycles in $G$.

Reference [261]

2.11.23 Enumeration of all Hamiltonian cycles in a graph

Input  A graph $G$.

Output  All Hamiltonian cycles in $G$.

Reference [261]

2.11.24 Enumeration of all cycles in a graph

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

Output  All cycles in $G$.

Complexity  $O(|E| + \sum_{c \in \mathcal{C}(G)} |c|)$ total time.

Comment  $\mathcal{C}(G)$ is the set of all cycles in $G$.

Reference [23]

2.11.25 Enumeration of all chordless cycles in a graph

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

Output  All chordless cycles in $G$.

Complexity  $\tilde{O}(|E| + |V| \cdot C)$ total time.

Comment  $C$ is the number of chordless cycles in $G$.

Reference [76]

2.11.26 Enumeration of all chordless cycles in a graph

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

Output  All chordless cycles in $G$.

Complexity  $O(|V| + |E|)$ time per chordless cycle.

Reference [247]
2.12 Dominating set

2.12.1 Enumeration of all minimal dominating sets in a graph

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

Output All minimal dominating sets in $G$.

Complexity $O(1.7159|V|)$ total time.

Reference [78]

2.12.2 Enumeration of $z$ smallest weighted edge dominating sets in a graph

Input An weighted graph $G = (V, E)$, and positive integers $k$ and $z$. Each edge of $G$ has a positive weight.

Output $z$ smallest weighted edge dominating sets in $G$.

Complexity $O(5.6^{2k}k^4z^2 + 4^{2k}k^3z|V|)$ total time.

Reference [250]

2.12.3 Enumeration of all minimal dominating sets in a line graph

Input A line graph $G$.

Output All minimal dominating sets in $G$.

Complexity $O(||G||^5N^6)$ total time.

Comment $||G||$ is the size of $G$ and $N$ is the number of minimal dominating sets in $G$.

Reference [117]

2.12.4 Enumeration of all minimal dominating sets in a path graph or $(C_4, C_5, craw)$-free graph

Input A line graph or $(C_4, C_5, craw)$-free graph $G$.

Output All minimal dominating sets in $G$.

Complexity $O(||G||^2N^3)$ total time.
Comment \(|G|\) is the size of \(G\) and \(N\) is the number of minimal dominating sets in \(G\).

Reference [117]

2.12.5 Enumeration of all minimal edge-dominating sets in a graph

Input A graph \(G\).

Output All minimal edge-dominating sets in \(G\).

Complexity \(O(|L(G)|^5N^6)\) total time.

Comment \(L(G)\) is the line graph of \(G\), \(|L(G)|\) is the size of \(L(G)\), and \(N\) is the number of minimal edge-dominating sets in \(G\).

Reference [117]

2.12.6 Enumeration of all minimal dominating sets in an undirected permutation graph

Input An undirected permutation graph \(G = (V, E)\).

Output All minimal dominating sets.

Complexity \(O(|V|)\) delay with \(O(|V|^8)\) pre-processing.

Reference [116]

2.12.7 Enumeration of all minimal dominating sets in an undirected interval graph

Input An undirected interval graph \(G = (V, E)\).

Output All minimal dominating sets.

Complexity \(O(|V|)\) delay with \(O(|V|^3)\) pre-processing.

Reference [116]
2.12.8 Enumeration of all minimal edge dominating sets in a graph

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

Output All minimal edge dominating sets in $G$.

Complexity $O(|V|^6|\mathcal{L}|)$ delay.

Comment $\mathcal{L}$ is the set of already generated solutions.

Reference [95]

2.12.9 Enumeration of all minimal dominating sets in a line graph

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

Output All minimal dominating sets in $G$.

Complexity $O(|V|^2|E|^2|\mathcal{L}|)$ delay.

Comment $\mathcal{L}$ is the set of already generated solutions.

Reference [95]

2.12.10 Enumeration of all minimal edge dominating sets in a bipartite graph

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

Output All minimal edge dominating sets in $G$.

Complexity $O(|V|^4|\mathcal{L}|)$ delay.

Comment $\mathcal{L}$ is the set of already generated solutions.

Reference [95]

2.12.11 Enumeration of all minimal dominating sets in the line graph of a bipartite graph

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

Output All minimal dominating sets in $G$.

Complexity $O(|V|^2|E||\mathcal{L}|)$ delay.
Comment: $\mathcal{L}$ is the set of already generated solutions.

Reference [95]

2.12.12 Enumeration of all minimal dominating sets in a graph of girth at least 7

Input: A graph $G = (V, E)$ of girth at least 7.

Output: All minimal dominating sets in $G$.

Complexity: $O(|V|^2|E||\mathcal{L}|^2)$ delay.

Comment: $\mathcal{L}$ is the set of already generated solutions.

Reference [95]

2.12.13 Enumeration of all 2-dominating sets in a tree

Input: A tree $T = (V, E)$.

Output: All 2-dominating sets of $T$.

Complexity: $O(1.3248^n)$ total time.

Comment: If a subset $U \subseteq V$ is a 2-dominating set if every vertex $v \in V \setminus U$ has at least two neighbors in $U$.

Reference [140]

2.12.14 Enumeration of all minimal dominating sets in a $P_6$-free chordal graph

Input: A $P_6$-free chordal graph $G = (V, E)$.

Output: All minimal dominating sets in $G$.

Complexity: Linear delay with $O(|V|^2)$ space.

Reference [115]
2.12.15 Enumeration of all minimal dominating sets in a chordal bipartite graph

**Input**  A chordal bipartite graph $G$.

**Output**  All minimal dominating sets in $G$.

**Complexity**  $O(n^3 m |\mathcal{L}|^2)$ delay and the total running time is $O(n^3 m |\mathcal{L}^*|^2)$.

**Comment**  $n$ is the number vertices in $G$, $m$ is the number of edges in $G$, $\mathcal{L}$ is the family of already generated minimal dominating sets, and $\mathcal{L}^*$ is the family of all minimal dominating sets.

**Reference**  [96]

2.13 Drawing

2.13.1 Enumeration of all rectangle drawings with $n$ faces

**Input**  An integer $n$.

**Output**  All rectangle drawings with $n$ faces.

**Complexity**  $O(n)$ time per drawing and space.

**Reference**  [232]

2.14 Feedback arc set

2.14.1 Enumeration of all minimal feedback arc sets in a graph

**Input**  A graph $G$.

**Output**  All minimal feedback arc sets in $G$.

**Reference**  [272]

2.14.2 Enumeration of all minimal feedback arc sets in a directed graph

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

**Output**  All minimal feedback arc sets in $G$.

**Complexity**  $O(|V||E|(|V| + |E|))$ time delay.

**Reference**  [219]
2.15 Feedback vertex set

2.15.1 Enumeration of all minimal feedback vertex sets in a graph

**Input** A graph $G$.

**Output** All minimal feedback vertex sets in $G$.

**Reference** [272]

2.15.2 Enumeration of all feedback vertex sets in a strongly connected directed graph

**Input** A strongly connected directed graph $G = (V,E)$ and an integer $k$.

**Output** All feedback vertex sets of size $k$ in $G$.

**Complexity** $O(|V|^k - |E|)$ total time and $O(|E|)$ space.

**Reference** [89]

2.15.3 Enumeration of all minimal feedback vertex sets in a graph

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

**Output** All minimal feedback vertex sets in $G$.

**Complexity** $O(|V||E|(|V| + |E|))$ time delay.

**Reference** [219]

2.15.4 Enumeration of all minimal feedback vertex sets in a directed graph

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

**Output** All minimal feedback vertex sets in $G$.

**Complexity** $O(|V|^2(|V| + |E|))$ time delay.

**Reference** [219]
2.16 General

2.16.1 Enumeration of all graphs in an almost sure first order fimiles

Input  A first order language \( \theta \).

Output  All graphs in \( G_\theta \).

Complexity  Polynomial space and delay.

Reference  [94]

2.17 Independent set

2.17.1 Enumeration of all maximal independent sets in a chordal graph

Input  A chordal graph \( G = (V, E) \).

Output  All maximal independent sets in \( G \).

Complexity  \( O(|V||E|\mu) \) total time.

Comment  \( \mu \) is the number of maximal independent sets of \( G \). This algorithm can also enumerate all the maximal cliques.

Reference  [240]

2.17.2 Enumeration of all maximal independent sets in a claw-free graph

Input  A claw-free graph \( G \).

Output  All maximal independent sets in \( G \).

Reference  [166]

2.17.3 Enumeration of all maximal independent sets in an undirected graph

Input  A graph \( G \).

Output  All maximal independent sets in \( G \) in lexicographically.

Reference  [146]
2.17.4 Enumeration of all maximal independent sets in an interval graph

**Input** An interval graph \( G = (V, E) \).

**Output** All maximal independent sets in \( G \).

**Complexity** \( O(|V|^2 + \beta) \) total time.

**Comment** \( \beta \) is the sum of the vertices in all maximal independent sets of \( G \).

**Reference** [143]

2.17.5 Enumeration of all maximal independent sets in a circular-arc graph

**Input** A circular-arc graph \( G = (V, E) \).

**Output** All maximal independent sets in \( G \).

**Complexity** \( O(|V|^2 + \beta) \) total time.

**Comment** \( \beta \) is the sum of the vertices in all maximal independent sets of \( G \).

**Reference** [143]

2.17.6 Enumeration of all maximal independent sets in a chordal graph

**Input** A chordal graph \( G = (V, E) \).

**Output** All maximal independent sets in \( G \).

**Complexity** \( O((|V| + |E|)N) \) total time.

**Comment** \( N \) is the number of solutions.

**Reference** [143]
2.17.7 Enumeration of all maximal independent sets in a graph

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

**Output** All maximal independent sets included in $G$.

**Complexity** $O(n(m + n \log C)) = O(n^3)$ delay and exponential space.

**Comment** $C$: total number of maximal independent sets, $n$: total number of vertices, and $m$: total number of edges. Is there no polynomial space and delay algorithm?

**Reference** [109]

2.17.8 Enumeration of all maximum independent sets of a bipartite graph

**Input** A bipartite graph $B = (V, E)$.

**Output** All maximum independent sets of $B$.

**Complexity** $O(|V|^{2.5} + N)$.

**Comment** $N$ is the number of maximum independent sets of $B$.

**Reference** [119]

2.17.9 Enumeration of all maximal independent sets on a tree in lexicographic order

**Input** Tree $T = (V, E)$.

**Output** All maximal independent sets on $T$ in lexicographic order.

**Complexity** $O(|V|^2)$ delay with $O(|V|)$ space.

**Reference** [43]

2.17.10 Enumeration of all maximum independent set of a graph

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

**Output** All maximum independent set of $G$.

**Complexity** $O(2^{0.114|E|})$ total time and polynomial space.

**Reference** [17]
2.17.11 Enumeration of all maximum independent set of a graph

Input A graph $G = (V, E)$ with maximum degree 3.

Output All maximum independent set of $G$.

Complexity $O(2^{0.171|V|})$ total time and polynomial space.

Reference [17]

2.17.12 Enumeration of all maximum independent set of a graph

Input A graph $G = (V, E)$ with maximum degree 4.

Output All maximum independent set of $G$.

Complexity $O(2^{0.228|V|})$ total time and polynomial space.

Reference [17]

2.17.13 Enumeration of all maximum independent set of a graph

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

Output All maximum independent set of $G$.

Complexity $O(2^{0.290|V|})$ total time and polynomial space.

Reference [17]

2.17.14 Enumeration of all maximal independent sets of a graph

Input A graph $G = (V, E)$ and a position integer $k$.

Output Enumeration of all maximal independent sets with at most size $k$ of $G$.

Complexity $O(3^{4k-|V|}4^{|V|-3k})$ total time.

Reference [66]
2.17.15 Enumeration of all independent sets in a chordal graph

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

**Output** All independent sets in $G$.

**Complexity** Constant time per solution on average after $O(|V| + |E|)$ time for preprocessing.

**Reference** [179]

2.17.16 Enumeration of all independent sets of size $k$ in a chordal graph

**Input** A chordal graph $G = (V, E)$ and a positive integer $k$.

**Output** All independent sets of size $k$ in $G$.

**Complexity** Constant time per solution on average after $O((|V| + |E|)|V|^2)$ time for preprocessing.

**Reference** [179]

2.17.17 Enumeration of all maximum independent sets in a chordal graph

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

**Output** All maximum independent sets in $G$.

**Complexity** Constant time per solution on average after $O((|V| + |E|)|V|^2)$ time for preprocessing.

**Reference** [179]

2.17.18 Enumeration of all independent sets in an input chordal graph

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

**Output** All independent sets in $G$.

**Complexity** $O(1)$ delay and $O(|V|(|V| + |E|))$ time and space for preprocessing.
Comment Counting all independent sets in an input chordal graph needs $O(n + m)$ time.

Reference [180]

2.17.19 Enumeration of all maximum independent sets in an input chordal graph

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

Output All maximum independent sets in $G$.

Complexity $O(1)$ delay and $O(|V|(|V| + |E|))$ time and space for preprocessing.

Comment Counting all maximum independent sets in an input chordal graph needs $O(n + m)$ time.

Reference [180]

2.17.20 Enumeration of all independent sets with $k$ vertices in an input chordal graph

Input A chordal graph $G = (V, E)$ and an integer $k$.

Output All maximum independent sets with $k$ vertices in $G$.

Complexity $O(1)$ delay and $O(k|V|(|V| + |E|))$ time and space for preprocessing.

Comment The number of independent sets with $k$ vertices in an input chordal graph needs $O(k^2(|V| + |E|))$ time.

Reference [180]

2.18 Interval graph

2.18.1 Enumeration of all interval supergraph that contains a given graph

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

Output All interval supergraphs each of which contain $G$.

Complexity $O(|V|^3)$ time for each and $O(|V|^2)$ space.

Reference [128]
2.18.2 Enumeration of all interval graph of a given graph

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

Output All interval graphs of $G$.

Complexity $O((|V| + |E|)^2)$ time for each.

Reference [128]

2.18.3 Enumeration of Proper Interval Graphs

Input An integer $n$.

Output All proper interval graphs with $n$ vertices.

Complexity $O(1)$ time per proper interval graph and $O(n)$ space, after $O(n^2)$ preprocessing time.

Comment Preprocessing: generating the complete graph with $n$ vertices.

Reference [209]

2.19 Matching

2.19.1 Enumeration of the $k$ best perfect matchings of a graph

Input A graph $G = (V, E)$ and an integer $k$.

Output The $k$ best perfect matchings of $G$ in order.

Complexity $O(k|V|^3)$ total time.

Reference [45]

2.19.2 Enumeration of all stable marriage

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

Output All stable marriage of $G$.

Complexity $O(|V|)$ time per solution and $O(|V|^2)$ space.

Reference [97]
2.19.3 Enumeration of all minimum cost perfect matchings in an weighted bipartite graph

Input  An weighted bipartite graph $B = (V, E)$.

Output  All minimum cost perfect matchings in $B$.

Complexity  $O(|V|(|V| + |E|))$ time per solution and $O(|V| + |E|)$ space

Reference [83]

2.19.4 Enumeration of all perfect matchings in a bipartite graph

Input  A bipartite graph $B = (U, V, E)$, where $|U| = |V|$.

Output  All perfect matchings in $B$.

Complexity  $O(c(|V|+|E|))$ total time and $O(|V|+|E|)$ space, after $O(n^{2.5})$ preprocessing time.

Comment  $c$ is the number of solutions.

Reference [82]

2.19.5 Enumeration of the $k$ best perfect matchings of a graph

Input  A graph $G = (V, E)$ and an integer $k$.

Output  The $k$ best perfect matchings of $G$ in decreasing order.

Complexity  $O(k|V|^3)$ total time with $O(k|V|^2)$ space.

Reference [155]

2.19.6 Enumeration of all perfect, maximum, and maximal matchings in bipartite graphs

Input  A bipartite graph $B = (V, E)$.

Output  All perfect, maximum, and maximal matching in $B$.

Complexity  $O(|V|)$ time per matching.

Reference [243]
2.19.7 Enumeration of all maximal matchings in a graph

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

**Output** All maximal matchings in $G$.

**Complexity** $O(|V| + |E| + \Delta N)$ total time and $O(|V| + |E|)$ space.

**Comment** $N$ is the number of solutions and $\Delta$ is the maximum degree in $G$.

**Reference** [241]

2.19.8 Enumeration of all minimal blocker in a bipartite graph

**Input** A bipartite graph $G = (U, V, E)$.

**Output** All minimal blocker in $G$.

**Complexity** Polynomial delay and space.

**Comment** A *blocker* of $G$ is an edge subset $X$ of $E$ such that $G' = (U, V, E \setminus X)$ has no perfect matching.

**Reference** [30]

2.19.9 Enumeration of all basic perfect 2-matchings in a graph

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

**Output** All basic perfect 2-matchings in $G$.

**Complexity** Incremental polynomial delay.

**Comment** A *basic 2-matching* of $G$ is a subset of edges that cover the vertices with vertex-disjoint edges and vertex-disjoint odd cycles.

**Reference** [30]

2.19.10 Enumeration of all $d$-factor in a bipartite graph

**Input** A bipartite graph $G = (U, V, E)$ and any non negative function $d : A \cup B \to \{0, 1, \cdots , |U| + |V|\}$.

**Output** All $d$-factor in $G$. 
Complexity $O(|E|)$ delay.

Comment A $d$-factor in $G$ is a subgraph $G' = (U, V, X)$ covering all vertices of $G$, whose each vertex $v$ has degree $d(v)$. If for any $v \in U \cup V$, $d(v) = 1$, $G'$ is a perfect matching.

Reference [30]

2.19.11 Enumeration of all maximal induced matchings in a triangle-free graph

Input A triangle-free graph $G$.

Output All maximal induced matchings in $G$.

Complexity $O(1.4423^n)$ total time with polynomial delay.

Comment $n$ is the number of vertices in $G$.

Reference [15]

2.20 Matroid

2.20.1 Enumeration of all bases of a graphic matroid in a graph

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

Output All bases of a graphic matroid in $G$.

Complexity $O(|V| + |E| + N)$ total time and $O(|V| + |E|)$ space.

Comment $N$ is the number of solutions. If $G$ is connected, any base is a spanning tree.

Reference [242]

2.20.2 Enumeration of all bases of a linear matroid in a graph

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

Output All bases of a linear matroid in $G$.

Complexity $O(|V|)$ time per solution and $O(|V|^2|E|)$ preprocessing after time.

Reference [242]
2.20.3 Enumeration of all bases of a matching matroid in a graph

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

**Output** All bases of a matching matroid in $G$.

**Complexity** $O(|V| + |E|)$ time per solution.

**Reference** [242]

2.21 Ordering

2.21.1 Enumeration of all topological sortings of a directed graph

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

**Output** All topological sortings of $G$.

**Complexity** $O(|V| + |E|)$ time per sorting and $O(|V| + |E|)$ space.

**Reference** [133]

2.21.2 Enumeration of all topological sortings of a given set in lexicographically

**Input** An $n$-element set $S$.

**Output** All topological sortings of $S$ in lexicographically.

**Complexity** $O(m)$ time per solution(?).

**Reference** [132]

2.21.3 Enumeration of all topological sortings of a po set

**Input** A partial order set $P$.

**Output** All topological sortings of $P$.

**Complexity** $O(|P|)$ time per solution.

**Comment** $|P|$ is the number of objects in $P$.

**Reference** [248]
2.21.4 Enumeration of all topological sortings in a directed acyclic graph

Input  A directed graph $G$.
Output  All topological sortings in $G$.
Complexity  $O(1)$ amortized time per solution with $O(|G|)$.
Comment  Linear extensions correspond to topological sortings.
Reference  [191]

2.21.5 Enumeration of all topological sortings

Input  A graph $G$.
Output  All topological sortings in $G$.
Complexity  $O(1)$ amortized time per solution.
Comment  A topological sorting is also known as a linear extension.
Reference  [199]

2.21.6 Enumeration of all topological sortings

Input  A directed acyclic graph $D$.
Output  All topological sortings $D$.
Complexity  $O(1)$ amortized time per topological sorting and $O(|V|)$ space in addition to the space used for $D$.
Comment  Linear sortings correspond to topological sortings.
Reference  [190]

2.21.7 Enumeration of all linear extensions of a given poset

Input  A poset $P$.
Output  All linear extensions of $P$.
Complexity  $O(1)$ time per solution.
Comment  Their algorithm is a loop-free algorithm.
Reference  [38]
2.21.8 Enumeration of all topological sortings of an acyclic directed graph

**Input** An acyclic directed graph $G = (V, E)$.

**Output** All topological sortings of $G$.

**Complexity** $O(|V|N)$ total time and $O(|V||E|)$ space.

**Comment** $N$ is the number of solutions.

**Reference** [7]

2.21.9 Enumeration of all perfect elimination orderings

**Input** A chordal graph $G$.

**Output** All perfect elimination orderings of $G$.

**Complexity** Constant amortized time per solution.

**Reference** [41]

2.21.10 Enumeration of all forest extensions of a partially ordered set

**Input** A partially ordered set $P$.

**Output** All forest extensions of $P$.

**Complexity** $O(|E|^2)$ delay and $O(|E||R|)$ space.

**Comment** $E$ is the set of elements. $R$ is the binary relation on $E$.

**Reference** [231]

2.21.11 Enumeration of all topological sortings of a directed acyclic graph

**Input** A directed acyclic graph $D$.

**Output** All topological sortings $D$.

**Complexity** $O(1)$ delay per topological sorting.

**Comment** Linear extensions correspond to topological sortings.

**Reference** [181]
2.21.12 Enumeration of all realizer of a triangulated planar graph

**Input** A triangulated planar graph $G = (V, E)$.

**Output** All realizer of $G$.

**Complexity** $O(|V|)$ time per realizer.

**Reference** [267]

2.21.13 Enumeration of all perfect elimination orderings of a chordal graph

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

**Output** All perfect elimination orderings of $G$.

**Complexity** $O(1)$ time per solution on average with $O(|V|^2)$ space and $O(|V|^3)$ with $O(|V|^2)$ space pre-computation.

**Reference** [157]

2.21.14 Enumeration of all perfect sequences in a chordal graph

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

**Output** All perfect sequences of $G$.

**Complexity** $O(1)$ time per graph with $O(|V|^2)$ space with $O(|V|^3)$ time and $O(|V|^2)$ space pre-computation.

**Reference** [158]

2.22 Orientation

2.22.1 Enumeration of all acyclic orientation of a graph

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

**Output** All acyclic orientation of $G$.

**Complexity** $O(N(|V|+|E|))$ total time ($O(|V|(|V|+E|))$ delay) and $O(|V|+|E|)$ space.

**Comment** A acyclic orientation of $G$ is an assignment of directions of each edge such that $G$ is acyclic.

**Reference** [12]
2.22.2  Enumeration of all \((s, t)\)-orientations of a biconnected planar graph

**Input**  A biconnected planar graph \(G = (V, E)\) and an edge \((s, t)\) in \(G\).

**Output**  All \((s, t)\)-orientations of \(G\).

**Complexity**  \(O(|V|)\) time per solution.

**Reference**  [222]

2.23  Other

2.23.1  Enumeration of all Hamiltonian centers in a graph

**Input**  A graph \(G\).

**Output**  All Hamiltonian centers in \(G\).

**Reference**  [272]

2.23.2  Enumeration of all CA-sets of a directed graph

**Input**  Directed graph \(G = (V, E)\).

**Output**  All CA-sets of \(G\).

**Complexity**  \(O(|V|^{2.49} + \gamma)\).

**Comment**  \(\gamma\) is the output size. \(S \subset V\) is a CA-set if, for each \(v \in S\), all ancestor of \(v\) belongs to \(S\).

**Reference**  [119]

2.23.3  Enumeration of all maximal induced subgraphs for (connected) hereditary graph properties

**Input**  A graph \(G\).

**Output**  All maximal induced subgraphs in \(\mathcal{P}(G)\).

**Complexity**  See the paper.

**Comment**  \(\mathcal{P}\) is a set of subgraphs of \(G\) with (connected) hereditary graph properties.

**Reference**  [48]
2.24 Path

2.24.1 Enumeration of all simple paths in a graph

Input  A graph $G$.

Output  All simple paths in $G$.

Complexity

Reference [186]

2.24.2 Enumeration of all Hamiltonian paths in a graph

Input  A graph $G$.

Output  All Hamiltonian paths in $G$.

Reference [272]

2.24.3 Enumeration of all directed paths in a directed graph

Input  A directed graph $G$.

Output  All directed paths in $G$.

Reference [113]

2.24.4 Enumeration of all paths in a graph

Input  A graph $G$.

Output  All paths in $G$.

Reference [139]

2.24.5 Enumeration of all paths in a graph

Input  A graph $G$.

Output  All paths in $G$.

Reference [53]
2.24.6 Enumeration of $k$ shortest paths in a graph

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

Output  $K$ shortest paths in $G$.

Complexity  $O(|V|^3)$ total time.

Reference  [274]

2.24.7 Enumeration of $k$ shortest paths in a graph

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

Output  $k$ shortest paths in $G$.

Complexity  $O(k|V|c(|V|))$ total time.

Comment  (?) $c(n)$ is the time complexity to find an optimal solution to a problem with $n$ (0, 1) variables.

Reference  [142]

2.24.8 Enumeration of all paths in a graph

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

Output  All paths in $G$.

Complexity  $O(|E|)$ time per path with $O(|E|)$ space.

Reference  [193]

2.24.9 Enumeration of all paths in a directed graph

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

Output  All paths in $G$.

Complexity  $O(|E|)$ time per path with $O(|E|)$ space.

Reference  [193]
2.24.10  Enumeration of \( k \) shortest paths in a graph

**Input**  A graph \( G = (V, E) \).

**Output**  \( K \) shortest paths in \( G \).

**Complexity**  \( O(k|V|^3) \) total time.

**Reference**  [224]

2.24.11  Generation of the \( k \)-th longest path in a tree

**Input**  A tree \( T = (V, E) \) and an integer \( k \).

**Output**  The \( k \)-th longest path in \( T \).

**Complexity**  \( O(n \log^2 n) \) time.

**Reference**  [164]

2.24.12  Enumeration of all shortest paths in a graph

**Input**  A graph \( G \).

**Output**  All shortest paths in \( G \).

**Reference**  [77]

2.24.13  Enumeration of \( k \) shortest paths of a directed graph

**Input**  A graph \( G = (V, E) \).

**Output**  \( k \) shortest paths that may contains cycles in \( G \).

**Reference**  [151]

2.24.14  Enumeration of all quickest paths in a network

**Input**  A network \( N = (V, E, c, \ell) \).

**Output**  All quickest paths in \( N \).

**Complexity**  \( O(rS|V| |E| + rS|V|^2 \log |V|) \) total time.

**Comment**  \( c \) is a positive edge weight function and \( \ell \) is a nonnegative edge weight function. \( r \) is the number of distinct capacity value of \( N \). \( S \) is the number of solutions.
2.24.15 Counting all acyclic walks in a graph

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

Output The number of acyclic walks in $G$.

Reference [9]

2.24.16 Enumeration of the $k$ shortest paths in a graph

Input  A graph $G = (V, E)$ and an integer $k$.

Output The $k$ smallest shortest paths in $G$.

Complexity $O(k|E|)$ total time.

Reference [8]

2.24.17 Enumeration of all constrained quickest paths in a network

Input  Network $N = (V, E)$ and constraints $L$ and $C$.

Output All quickest paths in $N$.

Complexity $O(k|V|^2|E|)$ total time.

Comment $k$ is the number of solutions. A quickest path is a variant of a shortest path.

Reference [91]

2.24.18 Enumeration of the $k$ shortest paths in a directed graph

Input  A directed graph $G = (V, E)$ and an integer $k$.

Output The $k$ smallest shortest paths in $G$.

Complexity $O(k|E|)$ total time

Reference [63]
2.24.19 Enumeration of all minimal path conjunctions in a graph

**Input** A directed graph $G = (V, E)$, $s_1, s_2, t_1 \in V$, $T_2 \subseteq V$, and $\mathcal{P} = \{(s_1, t_1)\} \cup \{(s_2, t) : t \in T_2\}$.

**Output** All minimal path conjunctions in $G$.

**Complexity** Polynomial delay.

**Comment** A path conjunction is a edge subset $E' \subseteq E$ such that for all $(s, t) \in \mathcal{P}$, $s$ is connected to $t$ in the graph $G' = (V, E')$.

**Reference** [29]

2.24.20 Enumeration of all st-paths in a graph

**Input** A graph $G = (V, E)$ and $s, v \in V$.

**Output** All st-paths in $G$.

**Complexity** $O(|E| + \sum_{\pi \in \mathcal{P}_{st}(G)} |\pi|)$ total time.

**Comment** $\mathcal{P}_{st}(G)$ is the set of all st-paths in $G$.

**Reference** [23]

2.24.21 Enumeration of all $P_3$’s in a graph

**Input** A graph $G$.

**Output** All of all $P_3$’s in $G$.

**Complexity** $O(|E|^{1.5} + p_3(G))$ total time.

**Comment** $P_3$ is a induced path of $G$ with three vertices and $p_3(G)$ is the number of $P_3$ in $G$.

**Reference** [104]

2.24.22 Enumeration of all $P_k$’s in a graph

**Input** A graph $G$ and an integer $k \geq 4$.

**Output** All of all $P_k$’s in $G$.

**Complexity** $O(|V|^{k-1} + p_k(G) + k \cdot c_k(G))$ total time.
Comment $P_k$ and $C_k$ are a induced path and cycle of $G$ with $k$ vertices, respectively. $p_k(G)$ and $c_k(G)$ are the number of $P_k$ and $C_k$ in $G$, respectively.

Reference [104]

2.24.23 Enumeration of all $C_k$’s in a graph

Input A graph $G$ and an integer $k \geq 4$.

Output All of all $C_k$’s in $G$.

Complexity $O(|V|^{k-1} + p_k(G) + c_k(G))$ total time.

Comment $P_k$ and $C_k$ are a induced path and cycle of $G$ with $k$ vertices, respectively. $p_k(G)$ and $c_k(G)$ are the number of $P_k$ and $C_k$ in $G$, respectively.

Reference [104]

2.24.24 Enumeration of all chordless $st$-paths in a graph

Input A graph $G = (V, E)$ and two vertices $s, t \in V$.

Output All chordless $st$-paths in $G$.

Complexity $\tilde{O}(|E| + |V| \cdot P)$ total time.

Comment $P$ is the number of chordless $st$-paths in $G$.

Reference [76]

2.24.25 Enumeration of all chordless st-paths in a graph

Input A graph $G = (V, E)$ and $s, t \in V$.

Output All chordless st-paths (from $s$ to $t$) in $G$.

Complexity $O(|V| + |E|)$ time per chordless st-path.

Reference [247]
2.25 Permutation graph

2.25.1 Enumeration of all connected bipartite permutation graphs with \( n \) vertices

**Input** A graph size \( n \).

**Output** All connected bipartite permutation graphs.

**Complexity** \( O(1) \) time per graph with \( O(n) \) space.

**Reference** [208]

2.26 Pitch

2.26.1 Enumeration of all stories in a graph

**Input** A directed graph \( G = (V, E, S, T) \) that has the set of source vertices \( S \) and the set of target vertices of \( T \).

**Output** All stories in \( G \).

**Comment** A pitch \( P \) of \( G \) is a set of arcs \( E' \subseteq E \), such that the subgraph \( G' = (V', E') \) of \( G \), where \( V' \subseteq V \) is the set of vertices of \( G \) having at least one out-going or in-coming arc in \( E' \), is acyclic and for each vertex \( w \in V' \setminus S \), \( w \) is not a source in \( G' \), and for each vertex \( w \in V' \setminus T \), \( w \) is not a target in \( G' \). \( P \) is a story if \( P \) is maximal.

**Reference** [1]

2.26.2 Enumeration of all pitches

**Input** A directed graph \( G = (V, E, S, T) \) that has the set of source vertices \( S \) and the set of target vertices of \( T \).

**Output** All pitches in \( G \).

**Complexity** \( O(|V| + |E|) \) delay with \( O(|V| + |E|) \) space.

**Comment** A pitch \( P \) of \( G \) is a set of arcs \( E' \subseteq E \), such that the subgraph \( G' = (V', E') \) of \( G \), where \( V' \subseteq V \) is the set of vertices of \( G \) having at least one out-going or in-coming arc in \( E' \), is acyclic and for each vertex \( w \in V' \setminus S \), \( w \) is not a source in \( G' \), and for each vertex \( w \in V' \setminus T \), \( w \) is not a target in \( G' \). Enumeration of all stories (maximal pitches) is still open.
2.27 Planar graph

2.27.1 Enumeration of all maximal planar graphs with \( n \) vertices

Input  An integer \( n \).

Output All maximal planar graph with \( n \) vertices.

Complexity \( O(n^3) \) time per graph with \( O(n) \) space.

Comment A planar graph with \( n \) vertices is maximal if it has exactly \( 3n - 6 \) edges.

Reference [145]

2.27.2 Enumeration of all based floorplans with at most \( n \) faces

Input  An integer \( n \).

Output All based floorplans with at most \( n \) faces.

Complexity \( O(1) \) time per solution with \( O(n) \) space.

Comment A planar graph is called a floorplan if every face is a rectangle. A based floorplan is a floorplan with one designated base line segment on the outer face.

Reference [171]

2.27.3 Enumeration of all based floorplans with exactly \( n \) faces

Input  An integer \( n \).

Output All based floorplans with exactly \( n \) faces.

Complexity \( O(1) \) time per solution with \( O(n) \) space.

Comment A planar graph is called a floorplan if every face is a rectangle. A based floorplan is a floorplan with one designated base line segment on the outer face.

Reference [171]
2.27.4 Enumeration of all floorplans with exactly \( n \) faces

**Input** An integer \( n \).

**Output** All floorplans with exactly \( n \) faces.

**Complexity** \( O(1) \) time per solution with \( O(n) \) space.

**Comment** A planar graph is called a *floorplan* if every face is a rectangle.

**Reference** [171]

2.27.5 Enumeration of all internally triconnected planar graphs

**Input** Integers \( n \) and \( g \).

**Output** All internally triconnected planar graphs with exactly \( n \) vertices such that \( \kappa(G) = 2 \) and the size of each inner face is at most \( g \).

**Complexity** \( O(n^3) \) time per solution on average with \( O(n) \) space.

**Reference** [280]
Comment Use gray code.

Reference [2]

2.28.3 Enumeration of all plane spanning trees on a given point set in the plane

Input A point set $P$ in the plane.

Output All plane spanning trees on $P$.

Complexity $O(|P| \log |P|)$ time per solution.

Comment Use gray code.

Reference [2]

2.28.4 Enumeration of all plane graphs

Input $m$: the maximum number of edges.

Output All connected rooted plane graphs with at most $m$ edges.

Complexity amortized $O(1)$ time per graph with $O(m)$ space.

Comment This algorithm does not outputs the entire graph but the difference from previous one.

Reference [268]

2.28.5 Enumeration of all plane graphs

Input $m$: the maximum number of edges.

Output All connected non-rooted plane graphs with at most $m$ edges.

Complexity $O(m^3)$ time per graph with $O(m)$ space.

Comment This algorithm does not outputs the entire graph but the difference from previous one.

Reference [268]
2.28.6 Enumeration of all plane graphs on a given point set in the plane

Input A fixed point set $P$.

Output All plane graphs on $P$.

Complexity $O(N)$ total time.

Comment $N$ is the number of solutions.

Reference [121]

2.28.7 Enumeration of all non-crossing spanning connected graphs on a given point set in the plane

Input A fixed point set $P$.

Output All non-crossing spanning connected graphs on $P$.

Complexity $O(N)$ total time.

Comment $N$ is the number of solutions.

Reference [121]

2.28.8 Enumeration of all non-crossing spanning trees on a given point set in the plane

Input A fixed point set $P$.

Output All non-crossing spanning trees on $P$.

Complexity $O(N + |P|tri(P))$ total time.

Comment $N$ is the number of solutions and $tri(P)$ is the number of triangulations of $P$.

Reference [121]
2.28.9 Enumeration of all non-crossing minimally rigid frameworks on a given point set in the plane

**Input** A fixed point set $P$.

**Output** All non-crossing minimally rigid frameworks on $P$.

**Complexity** $O(|P|^2 N)$ total time.

**Comment** $N$ is the number of solutions.

**Reference** [121]

2.28.10 Enumeration of all non-crossing perfect matchings on a given point set in the plane

**Input** A fixed point set $P$.

**Output** All non-crossing perfect matchings on $P$.

**Complexity** $O(|P|^{3/2}tri(P) + |P|^{5/2} N)$ total time.

**Comment** $N$ is the number of solutions and $tri(P)$ is the number of triangulations of $P$.

**Reference** [121]

2.28.11 Enumeration of all triconnected rooted plane graphs

**Input** Integers $n$ and $g$.

**Output** All triconnected rooted plane graphs with $n$ vertices, whose each inner face has the length at most $g$.

**Complexity** $O(1)$ delay with $O(n)$ space after $O(n)$ time preprocessing.

**Reference** [281]

2.28.12 Enumeration of all triconnected rooted plane graphs

**Input** An integer $n$.

**Output** All triconnected rooted plane graphs with $n$ vertices.

**Complexity** $O(n^3)$ delay with $O(n)$ space after $O(n)$ time preprocessing.

**Reference** [281]
2.28.13 Enumeration of all biconnected rooted plane graphs

**Input** Integers $n$ and $g$.

**Output** All biconnected rooted plane graphs with exactly $n$ vertices such that each inner face is of length at most $g$.

**Complexity** $O(1)$ delay with $O(n)$ space, after an $O(n)$ time preprocessing.

**Reference** [279]

2.28.14 Enumeration of all biconnected plane graphs

**Input** Integers $n$ and $g$.

**Output** All biconnected plane graphs with at most $n$ vertices such that each inner face is of length at most $g$.

**Complexity** $O(n^3)$ time per solution on average with $O(n)$ space.

**Reference** [279]

2.28.15 Enumeration of all biconnected rooted plane graphs

**Input** Integers $n$ and $g$.

**Output** All biconnected rooted plane graphs with at most $n$ vertices such that each inner face is of length at most $g$.

**Complexity** $O(1)$ delay with $O(n)$ space.

**Reference** [279]

2.28.16 Enumeration of all rooted plane graphs in $\mathcal{G}_{\text{int}}(n,g) - \mathcal{G}_{3}(n,g)$

**Input** Integers $n$ and $g$.

**Output** All rooted plane graphs in $\mathcal{G}_{\text{int}}(n,g) - \mathcal{G}_{3}(n,g)$

**Complexity** $O(1)$ delay with $O(n)$ space and time preprocessing.

**Reference** [280]
2.29 Polytope
2.29.1 Enumeration of all 3-polytopes of a graph

Input A graph $G = (V, E)$.
Output All 3-polytopes of $G$.
Reference [55]

2.30 Quadrangle
2.30.1 Enumeration of all quadrangles in a graph

Input A connected graph $G = (V, E)$.
Output All quadrangles in $G$.
Complexity $O(\alpha(G)|E|)$ total time and $O(|E|)$ space.
Comment $\alpha(G)$ is the minimum number of edge-disjoint spanning forests into which $G$ can be decomposed.
Reference [47]

2.31 Quadrangulation
2.31.1 Enumeration of all based biconnected plane quadrangulations with at most $f$ faces

Input An integer $f$.
Output All based biconnected plane quadrangulations with at most $f$ faces.
Complexity $O(1)$ time per quadrangulation and $O(f)$ space.
Comment A plane quadrangulation is a plane graph such that each inner face has exactly four edges on its contour. A based plane quadrangulation is a plane quadrangulation with one designated edge on the outer face.
Reference [144]
2.32 Regular graph

2.32.1 Enumeration of all cubic graphs with less than or equal to $n$ vertices

Input An integer $n$.

Output All cubic graphs with less than or equal to $n$ vertices.

Reference [34]

2.33 Series-parallel

2.33.1 Enumeration of all series-parallel graphs with at most $m$ edges

Input An integer $m$.

Output All series-parallel graphs with at most $m$ edges.

Complexity $O(m)$ time per graph.

Reference [123]

2.34 Spanning subgraph

2.34.1 Enumeration of all minimal $k$-vertex connected spanning subgraphs in a $k$-connected graph.

Input A $k$-connected graph $G$.

Output All minimal $k$-vertex connected spanning subgraphs in $G$.

Complexity $O(K^3|E|^3|n| + K^2|E|^5|V|^4 + K|V|^k|E|^2)$ total time.

Comment $K$ is the number of solutions. A graph $G$ is $k$-connected if a subgraph of $G$ obtained by removing at most $k-1$ vertices is still connected.

Reference [31]
2.35 Spanning tree

2.35.1 Enumeration of all spanning trees in a graph

**Input** A graph $G$.

**Output** All spanning trees in $G$.

**Complexity**

**Reference** [99]

2.35.2 Enumeration of all spanning trees in a graph

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

**Output** All spanning trees of $G$.

**Comment** In this paper, 'trees' indicate 'spanning trees'.

**Reference** [165]

2.35.3 Enumeration of all spanning trees of a graph

**Input** A graph $G$.

**Output** All spanning trees of $G$.

**Reference** [160]

2.35.4 Enumeration of all spanning trees in a graph

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

**Output** All spanning trees in $G$.

**Complexity** $O(|V||E|^2)$ time per spanning tree with $O(|V||E|)$ space.

**Reference** [193]
2.35.5 Enumeration of the $k$ smallest weight spanning trees in a graph

**Input** A graph $G = (V, E)$ and an integer $k$.

**Output** The $k$ smallest weight spanning trees in $G$.

**Complexity** $O(k|E|\alpha(|E|, |V|) + |E|\log |E|)$ total time and $O(k + |E|)$ space, $\alpha(\cdot)$ is Tarjan’s inverse of Ackermann’s function.

**Reference** [86]

2.35.6 Enumeration of all spanning trees in a graph

**Input** A graph $G = (V, E)$ and an integer $k$.

**Output** The all spanning trees in $G$ in order.

**Complexity** $O(N|V|)$ total time and $O(N + |E|)$ space, $N$ is the number of spanning trees in $G$.

**Reference** [86]

2.35.7 Enumeration of all spanning trees in an undirected graph

**Input** An undirected graph $G = (V, E)$.

**Output** All spanning trees in $G$.

**Complexity** $O(|V| + |E| + |V||N|)$ total time and $O(|V| + |E|)$ space.

**Comment** $N$ is the number of spanning trees in $G$.

**Reference** [87]

2.35.8 Enumeration of all spanning trees in a directed graph

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

**Output** All spanning trees in $G$.

**Complexity** $O(|V| + |E| + |E||N|)$ total time and $O(|V| + |E|)$ space.

**Comment** $N$ is the number of spanning trees in $G$.

**Reference** [87]
2.35.9 Enumeration of the $k$ smallest weight spanning trees in a graph

**Input** A graph $G = (V, E)$ and an integer $k$.

**Output** The $k$ smallest weight spanning trees in $G$.

**Complexity** $O(k|E| + \min(|V|^2, |E| \log \log |V|))$ total time and $O(k + |E|)$ space.

**Reference** [120]

2.35.10 Enumeration of all spanning trees in an undirected graph

**Input** An undirected graph $G$.

**Output** All spanning trees in $G$.

**Comment** They analyzed Char’s enumeration algorithm.

**Reference** [108]

2.35.11 Enumeration of the $k$ smallest weight spanning trees in a graph in increasing order

**Input** A graph $G = (V, E)$ and an integer $k$.

**Output** The $k$ smallest weight spanning trees in $G$.

**Complexity** $O(|E| \log \log (2 + |E|/|V|)) n + k^2 \sqrt{|E|})$ total time and $O(|E| + k\sqrt{|E|})$ space.

**Reference** [79]

2.35.12 Enumeration of the $k$ smallest weight spanning trees in a planar graph in increasing order

**Input** A planar graph $G = (V, E)$ and an integer $k$.

**Output** The $k$ smallest weight spanning trees in $G$.

**Complexity** $O(|V| + k^2(\log |V|)^2)$ total time and $O(|V| + k(\log |V|)^2)$ space.

**Reference** [79]
2.35.13 Enumeration of all undirected minimum spanning trees in an undirected graph

**Input** An undirected graph $G = (V, E)$.

**Output** All undirected minimum spanning trees in $G$.

**Complexity** $O(|E| \log \beta(|E|, |V|))$ total time.

**Comment** $\beta(|E|, |V|) = \min\{i | \log^i |V| \leq |E|/|N|\}$.

**Reference** [88]

2.35.14 Enumeration of all directed minimum spanning trees in an directed graph

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

**Output** All directed minimum spanning trees in $G$.

**Complexity** $O(|V| \log \beta(|E|, |V|))$ total time.

**Comment** $\beta(|E|, |V|) = \min\{i | \log^i |V| \leq |E|/|N|\}$.

**Reference** [88]

2.35.15 Enumeration of all spanning tree in a graph

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

**Output** All spanning tree of $G$.

**Complexity** $O(|V| + |E| + N)$ total time and $O(|V||E|)$ space.

**Comment** $N$ is the number of spanning trees in $G$.

**Reference** [118]

2.35.16 Enumeration of all spanning tree in an weighted graph

**Input** An weighted graph $G = (V, E)$.

**Output** All spanning tree of $G$ in increasing order of weight.

**Complexity** $O(N \log |V| + |V||E|)$ total time and $O(N + |V|^2|E|)$ space.

**Comment** $N$ is the number of spanning trees in $G$.

**Reference** [118]
2.35.17 Enumeration of all spanning tree in a directed graph

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

**Output**  All spanning tree of $G$.

**Complexity**  $O(N|V| + |V|^3)$ total time and $O(|V|^2)$ space.

**Comment**  $N$ is the number of spanning trees in $G$.

**Reference**  [118]

2.35.18 Enumeration of the $k$ best spanning trees in a graph

**Input**  A graph $G = (V, E)$ and an integer $k$.

**Output**  The $k$ best spanning trees of $G$.

**Complexity**  $O(m \log \beta(|E|, |V|) + k^2)$ total time.

**Comment**  $eta(|E|, |V|) = \min \{\log^i |V| \leq |E|/|V|\}$.

**Reference**  [64]

2.35.19 Enumeration of the $k$ best spanning trees in a planar graph

**Input**  A planar graph $G = (V, E)$ and an integer $k$.

**Output**  The $k$ best spanning trees of $G$.

**Complexity**  $O(n + k^2)$ total time.

**Reference**  [64]

2.35.20 Generation of the $k$-th minimum spanning tree in a graph

**Input**  A graph $G = (V, E)$ and an integer $k$.

**Output**  The $k$-th minimum spanning tree of $G$.

**Complexity**  $O((|V||E|)^{k-1})$ time.

**Reference**  [161]
2.35.21 Enumeration of all spanning trees

Input A graph \( G = (V, E) \).

Output All spanning trees in \( G \).

Complexity \( O(N + |V| + |E|) \) total time and \( O(|V||E|) \) space.

Comment \( N \) is the number of spanning trees in \( G \).

Reference [225]

2.35.22 Enumeration of all spanning trees in a directed graph

Input A directed graph \( G = (V, E) \).

Output All spanning trees in \( G \).

Complexity INCORRECT: \( O(N \log |V| + |V|^2 \alpha(V, V) + |V||E|) \)

Comment \( \alpha \): the inverse Ackermann’s function. [KR2000] gives this result is wrong.

Reference [101]

2.35.23 Enumeration of all spanning trees in a directed graph

Input A directed graph \( G = (V, E) \).

Output All spanning trees in \( G \).

Complexity \( O(|E| + ND(|V|, |E|)) \) total time and \( O(|E| + DS(|V|, |E|)) \) space.

Comment \( D(|V|, |E|) \) and \( DS(|V|, |E|) \) are the time and space complexities of the data structure for updating the minimum spanning tree in an undirected graph with \( |V| \) vertices and \( |E| \) edges. Here \( N \) denotes the number of directed spanning trees in \( G \).

Reference [244]
2.35.24 Enumeration of all spanning trees in a graph

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

**Output** All spanning trees included in $G$.

**Complexity** $O(N + |V| + |E|)$ total time and $O(|V| + |E|)$ space.

**Comment** $N =$ number of spanning trees in $G$.

**Reference** [226]

2.35.25 Enumeration of the $k$ smallest weight spanning trees in a graph

**Input** A graph $G = (V, E)$ and an integer $k$.

**Output** The $k$ smallest weight spanning trees in $G$.

**Complexity** $O(m \log \log n + k \min(n, k)^{1/2})$ total time, or a randomized version taking $O(m + k \min(n, k)^{1/2})$ total time.

**Reference** [68]

2.35.26 Enumeration of all spanning trees in a graph

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

**Output** All spanning trees in $G$.

**Complexity** $O(|V| + |E| + \tau)$ time and $O(|V| + |E|)$ space (depth first manner) or $O(\tau|V| + |E|)$ space (breadth first manner).

**Comment** By using breadth first manner, the proposed algorithm can be used in a parallel computer.

**Reference** [154]

2.35.27 Enumeration of all spanning trees in a graph in non-decreasing order

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

**Output** All spanning trees in $G$ in non-decreasing order.

**Complexity** $O(|V| + |E| + \tau)$ time and $O(\tau|V| + |E|)$ space.
Comment Using breadth first manner.

Reference [154]

2.35.28 Enumeration of all directed spanning trees in a directed
graph
Input A directed graph $G = (V, E)$.
Output All directed spanning trees in $G$.
Complexity $O(|E| \log |V| + |V| + N \log^2 |V|)$ total time and $O(|E| + |V|)$ space.
Comment $N$ is the number of directed spanning trees.
Reference [246]

2.35.29 Enumeration of all spanning trees of an weighted graph
in order of increasing cost
Input An weighted graph $G = (V, E)$.
Output All spanning trees of $G$ in order of increasing cost.
Complexity $O(N|E| \log |E| + N^2)$ total time and $O(N|E|)$ space.
Comment $N$ is the number of spanning trees of $G$.
Reference [227]

2.35.30 Enumeration of all the minimum spanning trees in a
graph
Input An weighted graph $G = (V, E)$.
Output All the minimum spanning trees in $G$.
Complexity $O(N|E| \log |V|)$ total time and $O(|E|)$ space.
Comment $N$ is the number of the minimum spanning trees in $G$.
Reference [265]
2.36 Steiner tree

2.36.1 Enumeration of all Steiner $W$-trees in a connected graph

**Input** A connected graph $G = (V, E)$, a vertex set $W \subseteq V$ such that $|W| = k$, for a fixed integer $k$.

**Output** Enumeration of all Steiner $W$-trees in $G$.

**Complexity** $O(|V|^2(|V|+|E|)+|V|^{k-2}+N|V|)$ total time with $O(|V|^{k-2}+|V|^2(|V|+|E|))$ space.

**Comment** A connected subgraph $T$ of $G$ is a Steiner $W$-tree if $W \subseteq V(T)$ and $|E(T)|$ is minimum.

**Reference** [58]

2.37 Subforest

2.37.1 Enumeration of all $k$-trees in a graph

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

**Output** All $k$-trees in $G$.

**Comment** A $k$-tree is a forest with $k$ connected components.

**Reference** [98]

2.38 Subgraph

2.38.1 Enumeration of all connected induced subgraph of a graph

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

**Output** All connected induced subgraph of $G$.

**Complexity** $O(|V||E|N)$ total time and $O(|V|+|E|)$ space.

**Comment** $N$ is the number of solutions.

**Reference** [7]
2.38.2 Enumeration of all connected common maximal subgraphs in two graphs

Input Two graphs $G$ and $G'$. 
Output All connected common maximal subgraphs in $G$ and $G'$. 
Reference [134]

2.38.3 Enumeration of all minimal spanning graph

Input A graph $G = (V, E)$, $S \subseteq V$, and requirements $r(u, v)$ for all $(u, v) \in V \times V$. 
Output All minimal spanning graph $H$ of $G$ satisfying $\lambda_S^H \geq r(u, v) \forall (u, v) \in V \times V$. 
Complexity Incremental polynomial time. 
Comment The $S$-connectivity $\lambda_S^H(u, v)$ of $(u, v)$ in $G$ is the maximum number of $uv$-paths such that no two of them have an edge or a node in $S \setminus \{u, v\}$ in common. This complexity holds for edge-connectivity. 
Reference [178]

2.38.4 Enumeration of all $k$-outconnected minimal spanning graph

Input A graph $G = (V, E)$, a vertex $s \in V$, and an integer $k$. 
Output All minimal $k$-outconneted from $s$ spanning subgraph of $G$. 
Complexity Incremental polynomial time. 
Comment A graph is $k$-outconnected from $s$ if it contains $k$ internally-disjoint $st$-paths for every $t \in V$. This complexity holds for both vertex and edge-connectivity. 
Reference [178]

2.38.5 Enumeration of all $k$-outconnected minimal spanning graph

Input A directed graph $G = (V, E)$, a vertex $s \in V$, and an integer $k$. 
Output All minimal $k$-outconneted from $s$ spanning subgraph of $G$. 
Complexity Incremental polynomial time.
Comment A graph is $k$-outconnected from $s$ if it contains $k$ internally-disjoint $st$-paths for every $t \in V$. This complexity holds for both vertex and edge-connectivity.

Reference [178]

2.38.6 Enumeration of all $k$-connected minimal spanning graph

Input A directed graph $G = (V, E)$ and an integer $k$.

Output All minimal $k$-connected spanning subgraph of $G$.

Complexity Incremental polynomial time.

Comment This complexity holds for both vertex and edge-connectivity.

Reference [178]

2.39 Subtree

2.39.1 Enumeration of all subtrees in an input tree

Input A tree $T = (V, E)$.

Output All subtrees included in $T$.

Complexity $O(|V|)$ delay and $O(|V|)$ space.

Reference [201]

2.39.2 Enumeration of all $k$-noded subtrees in a tree

Input A tree $T$ and an integer $k$.

Output All $k$-noded subtrees in $T$.

Reference [103]

2.39.3 Enumeration of all $k$-subtrees in a graph

Input A graph $G = (V, E)$ and a positive integer $k$.

Output All $k$-subtrees included in $G$.

Complexity $O(sk)$ total time, $O(k)$ amortized time per solution, and $O(|E|)$ space.
Comment $s =$ number of $k$-subtrees in $G$, a $k$-subtree means a connected, acyclic, and edge induced subgraph with $k$ vertices.

Reference [75]

2.39.4 Enumeration of all $k$-subtrees in an input tree

Input A tree $T = (V, E)$ and an integer $k$.

Output All $k$-subtrees included in $T$.

Complexity $O(1)$ delay and $O(|V|)$ space after $O(|V|)$ time preprocessing.

Comment A $k$-subtree is a connected, acyclic, and edge induced subgraph with $k$ vertices.

Reference [253]

2.39.5 Enumeration of all $k$-cardinality subtrees of a tree with $w$ vertices

Input An integer $k$ and a tree $T$ with $w$ element, where $k \leq w$.

Output All subtrees with $k$ vertices of $T$.

Complexity $O(Nw^5)$ total time.

Comment $N$ is the number of ideals.

Reference [262]

2.39.6 Enumeration of all induced subtrees in a $k$-degenerate graph

Input A $k$-degenerate graph $G = (V, E)$.

Output All induced subtrees in $G$.

Complexity $O(k)$ amortized time per solution with $O(|V| + |E|)$ space and preprocessing time.

Reference [252]
2.40 Tour

2.40.1 Enumeration of $k$ best solutions to the Chinese postman problem solutions

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

**Output** $K$ best solutions to the Chinese postman problem.

**Complexity** $O(S(n, m) + K(n + m + \log k + nT(n + m, m)))$ where $S(s, t)$ denotes the time complexity of an algorithm for ordinary Chinese postman problems and $T(s, t)$ denotes the time complexity of a post-optimal algorithm for non-bipartite matching problems defined on a graph with $s$ vertices and $t$ edges.

**Reference** [210]

2.41 Tree

2.41.1 Enumeration of all binary trees with fixed number leaves in lexicographically

**Input** An integer $n$.

**Output** All binary trees with $n$ leaves in lexicographically.

**Complexity** $O(1)$ time per binary tree.

**Reference** [197]

2.41.2 Enumeration of all $t$-ary trees with fixed number leaves in lexicographically

**Input** An integer $n$.

**Output** All $t$-ary trees with $n$ leaves in lexicographically.

**Complexity** $O(t)$ time per binary tree.

**Reference** [200]
2.41.3 Enumeration of all $k$-ary trees with $n$ vertices
Input Integers $k$ and $n$.
Output All $k$-ary trees with $n$ vertices
Complexity $O(1)$ time per solution
Reference [238]

2.41.4 Enumeration of all binary trees with $n$ vertices
Input An integer $n$.
Output All binary trees with $n$ vertices.
Reference [196]

2.41.5 Enumeration of all $k$-ary trees with $n$ vertices
Input Integers $k$ and $n$.
Output All $k$-ary trees with $n$ vertices
Reference [277]

2.41.6 Enumeration of all rooted trees with $n$ vertices
Input An integer $n$.
Output All rooted trees with $n$ vertices.
Complexity $O(1)$ amortized time per solution.
Reference [21]

2.41.7 Enumeration of all binary trees with $n$ vertices
Input An integer $n$.
Output All binary trees with $n$ vertices.
Reference [187]
2.41.8  Enumeration of all \( k \)-ary trees in lexicographically

Input  An integer \( n \).

Output All \( k \)-ary trees with \( n \) internal vertices in lexicographically

Complexity \( O(1 - (k - 1)^{k^{-1}/k^k})^{-1} \) time per solution. This limit is 4/3
for the binary case.

Reference [276]

2.41.9  Enumeration of all regular \( k \)-ary trees with \( n \) ndoes

Input  Integers \( k \) and \( n \).

Output All regular \( k \)-ary trees with \( n \) ndoes.

Reference [275]

2.41.10 Enumeration of all binary trees with \( n \) vertices in the
lexicographic ordering

Input  An integer \( n \).

Output All binary trees with \( n \) vertices in the lexicographic ordering

Complexity \( O(1) \) time per solution on average.

Reference [278]

2.41.11  Enumeration of all binary trees with \( n \) vertices

Input  An integer \( n \).

Output All binary trees with \( n \) vertices.

Complexity \( O(n) \) time per solution.

Reference [188]

2.41.12  Enumeration of all ordered trees with \( n \) internal vertices

Input  An integer \( n \).

Output All ordered trees with \( n \) internal vertices.

Reference [71]
2.41.13 Enumeration of all free trees with $n$ vertices

**Input** An integer $n$.

**Output** All free trees with $n$ vertices.

**Complexity** $O(1)$ time per solution.

**Reference** [263]

2.41.14 Enumeration of all $t$-ary trees with $n$ vertices

**Input** Integers $t$ and $n$.

**Output** All $t$-ary trees with $n$ vertices.

**Reference** [72]

2.41.15 Enumeration of all binary trees with $n$ vertices

**Input** An integer $n$.

**Output** All binary trees with $n$ vertices.

**Complexity** $O(1)$ time per solution.

**Reference** [147]

2.41.16 Enumeration of all trees with $n$ vertices and $m$ leaves

**Input** Integers $n$ and $m$.

**Output** All trees with $n$ vertices and $m$ leaves

**Reference** [182]

2.41.17 Enumeration of all $t$-ary trees in A-order

**Input** Integers $t$ and $n$.

**Output** All $t$-ary trees with $n$ vertices in A-order.

**Complexity** $O(1)$ amortized time per solution.

**Reference** [14]
2.41.18 Enumeration of all binary trees with \( n \) leaves

**Input** An integer \( n \).

**Output** All binary trees with \( n \) leaves.

**Complexity** \( O(1) \) amortized time per solution.

**Comment** A strong Gray code can be listed in constant average time per solution.

**Reference** [203]

2.41.19 Enumeration of all binary trees with \( n \) vertices

**Input** An integer \( n \).

**Output** All binary trees with \( n \) vertices.

**Complexity** \( O(1) \) time per solution.

**Comment** A loopless generation algorithm is an algorithm where the amount of computation to go from one object to the next is \( O(1) \).

**Reference** [13]

2.41.20 Enumeration of all \( k \)-ary trees in natural order

**Input** Two integers \( k \) and \( n \).

**Output** All \( k \)-ary trees with \( n \) vertices.

**Reference** [70]

2.41.21 Enumeration of all binary trees with \( n \) vertices

**Input** An integer \( n \).

**Output** All binary trees with \( n \) vertices.

**Complexity** \( O(1) \) delay.

**Reference** [148]
2.41.22 Enumeration of all binary trees with $n$ vertices

**Input**  An integer $n$.

**Output**  All binary trees with $n$ vertices.

**Reference** [11]

2.41.23 Enumeration of all $k$-ary tree

**Input**  An integer $k$.

**Output**  All $k$-ary trees.

**Complexity** $O(1)$ delay.

**Reference** [137]

2.41.24 Enumeration of all binary trees

**Output**  All binary trees.

**Complexity** $O(1)$ time per tree.

**Reference** [264]

2.41.25 Enumeration of all $k$-ary trees with $n$ vertices

**Input**  Two integers $k$ and $n$.

**Output**  All $k$-ary trees with $n$ vertices.

**Complexity** $O(1)$ delay.

**Comment**  Shifts and loopless algorithm.

**Reference** [138]

2.41.26 Enumeration of all rooted plane trees with at most $n$ vertices

**Input**  An integer $n$.

**Output**  All rooted plane trees with at most $n$ vertices.

**Complexity** $O(1)$ time per tree with $O(n)$ space.
Comment: A *rooted plane tree* is a rooted tree with a left-to-right ordering specified for the children of each vertex.

Reference [169]

2.41.27 Enumeration of all rooted plane trees with exactly \( n \) vertices

Input: An integer \( n \).

Output: All rooted plane trees with exactly \( n \) vertices.

Complexity: \( O(1) \) time per tree with \( O(n) \) space.

Comment: A *rooted plane tree* is a rooted tree with a left-to-right ordering specified for the children of each vertex.

Reference [169]

2.41.28 Enumeration of all rooted plane trees with at most \( n \) vertices and the maximum degree \( D \)

Input: Integers \( n \) and \( D \).

Output: All rooted plane trees with at most \( n \) vertices and the maximum degree \( D \).

Complexity: \( O(1) \) time per tree with \( O(n) \) space.

Comment: A *rooted plane tree* is a rooted tree with a left-to-right ordering specified for the children of each vertex.

Reference [169]

2.41.29 Enumeration of all rooted plane trees with exactly \( n \) vertices and exactly \( c \) leaves

Input: An integer \( n \).

Output: All rooted plane trees with exactly \( n \) vertices and exactly \( c \) leaves.

Complexity: \( O(n - c) \) time per tree with \( O(n) \) space.
Comment A rooted plane tree is a rooted tree with a left-to-right ordering specified for the children of each vertex.

Reference [169]

2.41.30 Enumeration of all plane trees with exactly $n$ vertices

Input An integer $n$.

Output All plane trees with exactly $n$ vertices.

Complexity $O(n^3)$ time per tree with $O(n)$ space.

Comment A plane tree is a tree with a left-to-right ordering specified for the children of each vertex.

Reference [169]

2.41.31 Enumeration of all rooted trees with at most $n$ vertices

Input An integer $n$.

Output All rooted tree with at most $n$ vertices.

Complexity $O(1)$ time per tree and $O(n)$ space.

Reference [174]

2.41.32 Enumeration of all $n$-trees

Input An integer $n$.

Output All $n$-trees.

Complexity $O(n^4N)$ total time.

Comment Reverse search. $N$ is the number of solutions.

Reference [5]
2.41.33  Enumeration of all trees with \( n \) vertices and \( d \) diameter

**Input**  Integers \( n \) and \( d \).

**Output**  All trees with \( n \) vertices and \( d \) diameter.

**Complexity**  \( O(1) \) time per tree with \( O(n) \) space.

**Comment**  By using the algorithm for each \( d = 2, \ldots, n - 1 \), all trees can be enumerated.

**Reference**  [173]

2.41.34  Enumeration of all \( c \)-tree with at most \( v \) vertices and diameter \( d \)

**Input**  Integers \( n \) and \( d \)

**Output**  All \( c \)-tree with at most \( v \) vertices and diameter \( d \).

**Complexity**  \( O(1) \) time per tree.

**Comment**  A tree is a \( c \)-tree if each vertex has a color \( c \in \{c_1, \ldots, c_m\} \).

**Reference**  [175]

2.41.35  Enumeration of all nonisomorphic rooted plane trees with \( n \) vertices

**Input**  An integer \( n \).

**Output**  All nonisomorphic rooted plane trees with \( n \) vertices.

**Complexity**  Constant amortized time per solution.

**Reference**  [216]

2.41.36  Enumeration of all nonisomorphic free plane trees with \( n \) vertices

**Input**  An integer \( n \).

**Output**  All nonisomorphic free plane trees with \( n \) vertices.

**Complexity**  Constant amortized time per solution.

**Reference**  [216]
2.41.37 Enumeration of all multitrees satisfying given constraints

**Input** A set $\Sigma$ of labels, a function $\text{val} : \Sigma \rightarrow \mathbb{Z}^+$, and a feature vector $g$ of level $K$.

**Output** All $(\Sigma, \text{val})$-labeled multitrees $T$ such that $f_K(T) = g$ and $\text{deg}(v; T) = \text{val}(\ell(v))$ for all vertices $v \in T$.

**Comment** This algorithm is for chemical graphs.

**Reference** [106]

2.41.38 Enumeration of all ordered trees with $n$ vertices and $k$ leaves

**Input** Integers $n$ and $k$.

**Output** All ordered trees with $n$ vertices and $k$ leaves.

**Complexity** $O(1)$ delay and $O(n)$ space.

**Reference** [269]

2.41.39 Enumeration of all trees with specified degree sequence

**Input** A degree sequence $D$.

**Output** All trees with $D$.

**Complexity** $O(1)$ time per tree.

**Reference** [172]

2.42 Triangle

2.42.1 Enumeration of all minimal triangle graphs with a fixed number vertices

**Input** An integer $n$.

**Output** All minimal triangle graphs with $n$ vertices.

**Complexity**

**Reference** [32]
2.42.2 Enumeration of all triangles in a graph

**Input** A graph \(G = (V, E)\).

**Output** All triangles in \(G\).

**Complexity** \(O(\alpha(G)|E|)\) total time and linear space.

**Comment** \(\alpha(G)\) is the minimum number of edge-disjoint spanning forests into which \(G\) can be decomposed. If \(G\) is planar, then the time complexity becomes \(O(|V|)\).

**Reference** [47]

2.43 Triangulation

2.43.1 Enumeration of all triangulations of 2-sphere

**Input** A 2-sphere \(G\).

**Output** All triangulations of \(G\).

**Complexity**

**Reference** [33]

2.43.2 Enumeration of all \(r\)-rooted 2-connected triangulations of a planar graph

**Input** A planar graph \(G = (V, E)\) and an integer \(r\).

**Output** All \(r\)-rooted 2-connected triangulations of \(G\).

**Complexity** \(O(|V|^2N)\) total time and \(O(|V|)\) space.

**Comment** \(N\) is the number of solutions.

**Reference** [6]

2.43.3 Enumeration of all \(r\)-rooted 3-connected triangulations of a planar graph

**Input** A planar graph \(G = (V, E)\) and an integer \(r\).

**Output** All \(r\)-rooted 3-connected triangulations of \(G\).

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Complexity $O(|V|^2N)$ total time and $O(|V|)$ space.

Comment $N$ is the number of solutions.

Reference [6]

2.43.4 Enumeration of all based plane triangulations with $n$ vertices

Input An integer $n$.

Output All based plane triangulations.

Complexity $O(1)$ time per based plane triangulation with $O(n)$ space.

Comment A based plane triangulation is a plane triangulation with one designated edge on the outer face. The algorithm does not output entire solution but output the difference from the previous solution.

Reference [145]

2.43.5 Enumeration of all biconnected based plane triangulations with $n$ vertices and $r$ vertices on the outer face

Input Integers $n$ and $r$.

Output All biconnected based plane triangulations with $n$ vertices and $r$ vertices on the outer face.

Complexity $O(1)$ time per based plane triangulation with $O(n)$ space.

Comment A based plane triangulation is a plane triangulation with one designated edge on the outer face. The algorithm does not output entire solution but output the difference from the previous solution.

Reference [145]

2.43.6 Enumeration of all biconnected plane triangulations with $n$ vertices and $r$ vertices on the outer face

Input Integers $n$ and $r$.

Output All biconnected based plane triangulations with $n$ vertices and $r$ vertices on the outer face.
Complexity $O(r^2n)$ time per based plane triangulation with $O(n)$ space.

Reference [145]

2.43.7 Enumeration of all rooted triconnected plane triangulations with at most $n$ vertices

Input An integer $n$.

Output All triconnected rooted plane triangulations with at most $n$ vertices.

Complexity $O(1)$ time per tree and $O(n)$ space.

Comment A rooted plane triangulation is a plane triangulation with one designated vertex on the outer face.

Reference [170]

2.43.8 Enumeration of all rooted triconnected plane triangulations with exactly $n$ vertices and $r$ leaves

Input An integer $n$.

Output All triconnected rooted plane triangulations with exactly $n$ vertices and $r$ leaves.

Complexity $O(r)$ time per tree and $O(n)$ space.

Comment A rooted plane triangulation is a plane triangulation with one designated vertex on the outer face.

Reference [170]

2.43.9 Enumeration of all triconnected plane triangulations with exactly $n$ vertices and $r$ leaves

Input An integer $n$.

Output All triconnected plane triangulations with exactly $n$ vertices and $r$ leaves.

Complexity $O(r^n)$ time per triangulation and $O(n)$ space.

Reference [170]
2.43.10 Enumeration of all triangulations

**Input** A set $S$ of $n$ points in the general position in the plane.

**Output** all the triangulations whose vertex set is $S$ and edge set includes the convex hull of $S$.

**Complexity** $O(\log \log n)$ time per triangulation and linear space.

**Comment** Whether there is the algorithm that outputs all triangulations in constant time delay?

**Reference** [20]

2.43.11 Enumeration of all biconnected plane triangulations with $n$ vertices and $r$ vertices on the outer faces

**Input** Integers $n$ and $r$.

**Output** All biconnected plane triangulations with $n$ vertices and $r$ vertices on the outer faces.

**Complexity** $O(rn)$ time per triangulation and $O(n)$ space.

**Reference** [176]

2.43.12 Enumeration of all triangulations of a triconnected plane graph of $n$ vertices

**Input** A triconnected planar graph $G$ with $n$ vertices.

**Output** All triangulations of $G$.

**Complexity** $O(1)$ time per triangulation and $O(n)$ space.

**Reference** [185]

2.44 Vertex cover

2.44.1 Enumeration of all minimal vertex covers in a graph

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

**Output** All minimal vertex covers of size up to $k$ in $G$.

**Complexity** $O^*(1.6181^k)$ total time.
Comment  This algorithm also lists some non-minimal vertex covers. This algorithm uses compact representation technique.

Reference  [74]

2.44.2 Enumeration of all minimal vertex covers of size at most $k$ in a graph

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

Output  All minimal vertex covers of size at most $k$ in $G$.

Complexity $O(|E| + k^{2^k})$ total time.

Reference  [52]

3 Hypergraph

3.1 Acyclic subhypergraph

3.1.1 Enumeration of all maximal $\alpha$-acyclic subhypergraphs in a hypergraph

Input  A hypergraph $H = (V, \mathcal{E})$.

Output  All maximal $\alpha$-acyclic subhypergraphs in $H$.

Complexity $O(|\mathcal{E}|^2(|V| + |\mathcal{E}|))$ delay and $O(|\mathcal{E}|)$ space.

Comment  The name of their algorithm is GenMAS. This algorithm uses the algorithm FindMAS that outputs a maximal $\alpha$-acyclic subhypergraph.

Reference  [51]

3.1.2 Enumeration of all Berge acyclic subhypergraphs in a hypergraph

Input  A hypergraph $\mathcal{H}$.

Output  All Berge acyclic subhypergraphs in $\mathcal{H}$.

Complexity $O(rd\tau(m))$ time per subhypergraph.

Comment  $r$ and $d$ are the rank and the degree of $\mathcal{H}$ and $\tau(m) = O((\log \log m)^2 / \log \log \log(m))$.

Reference  [254]
3.2 Independent set

3.2.1 Enumeration of all maximal independent set of a hypergraph of bounded dimension

Input A hypergraph $H$ of bounded dimension.

Output All maximal independent set of a hypergraph of bounded dimension.

Comment The proposed algorithm runs in parallel.

Reference [26]

3.2.2 Enumeration of all maximal independent sets in a c-conformal hypergraph

Input A c-conformal hypergraph $\mathcal{H} \in \mathcal{A}(k, r)$, where $c \leq$ constant and $k + r \leq c$.

Output All maximal independent sets in $\mathcal{H}$.

Complexity Incremental polynomial time.

Comment $\mathcal{A}(k, r)$ is the class of hyperedges with $(k, r)$-bounded intersections, i.e. in which the intersection of any $k$ distinct hyperedges has size at most $r$.

Reference [28]

3.2.3 Enumeration of all maximal independent sets in a hypergraph of bounded intersections

Input A hypergraph $\mathcal{H} \in \mathcal{A}(k, r)$, where $k + r \leq$ constant.

Output All maximal independent sets in $\mathcal{H}$.

Complexity Incremental polynomial time with polynomial space.

Comment $\mathcal{A}(k, r)$ is the class of hyperedges with $(k, r)$-bounded intersections, i.e. in which the intersection of any $k$ distinct hyperedges has size at most $r$.

Reference [28]
3.3 Transversal

3.3.1 Enumeration of all minimal transversal of a hypergraph

Input A hypergraph $\mathcal{H}$.

Output All minimal transversal of $\mathcal{H}$.

Complexity $(n + N)^{O(\log n)}$ total time with $O(n \log n)$ words.

Comment $n = \sum_{X \in \mathcal{H}} |X|$ and $N$ is the number of solutions.

Reference [234]

3.3.2 Enumeration of all minimal transversal in a hypergraph

Input A hypergraph $\mathcal{H} \in A(k, r)$.

Output All minimal transversal in $\mathcal{H}$.

Complexity $O(n^{k+r+1}|\mathcal{H}|^{d|r+1})$ total time and $O(N^{r+1})$ total space.

Comment $A(k, r)$ is the class of hyperedges with $(k, r)$-bounded intersections, i.e. in which the intersection of any $k$ distinct hyperedges has size at most $r$. Minimal transversals of hypergraphs in some restricted classes can be enumerating in polynomial delay and space.

Reference [28]

4 Matroid

4.1 Basis

4.1.1 Enumeration of all common bases in two matroids

Input Two matroids $M_1 = (E, \beta_1)$ and $M_2 = (E, \beta_2)$.

Output All $B \in \beta_1 \cap \beta_2$.

Complexity $O(|E|(2|E|^2 + t)\lambda)$ total time and $O(|E|^2)$ space.

Comment $\lambda$ is the number of common bases and $t$ is time complexity of one pivot operation.

Reference [84]
4.1.2 Enumeration of all basis of a matroid

**Input** A matroid $M$ on the ground set $P$ with rank $m$.

**Output** All basis of $M$.

**Complexity** $O((m|P| + t(Piv))N)$ total time and space complexity independent of $N$.

**Comment** $N$ is the number of solutions. $t(Piv)$ is the time necessary to do one pivot operation.

**Reference** [7]

4.2 Spanning

4.2.1 Enumeration of all minimal spanning and connected subsets in a matroid

**Input** A matroid $M$.

**Output** All minimal spanning and connected subsets in $M$.

**Complexity** Incremental quasi-polynomial time.

**Comment** $f(x)$ is a quasi-polynomial if $f(x) \in O(2^{\text{polylog}(n)})$.

**Reference** [124]

4.3 Subset

4.3.1 Enumeration of all maximal subset

**Input** A binary matroid $M$ on ground set $S$ and $B = \{b_1, b_2\} \subseteq S$.

**Output** All maximal subsets $X$ of $A := S \setminus B$ that span neither $b_1$ nor $b_2$.

**Complexity** Incremental polynomial time.

**Reference** [126]
5 Order

5.1 Ideal

5.1.1 Enumeration of all $k$-cardinarity ideals of a $w$-element poset

\textbf{Input} An integer $k$ and a poset $P$ with $w$ element, where $k \leq w$.

\textbf{Output} All $k$-cardinarity ideals of $P$.

\textbf{Complexity} $O(Nw^3)$ total time.

\textbf{Comment} $N$ is the number of ideals.

\textbf{Reference} [262]

6 Other

6.1 Assignment

6.1.1 Enumeration of all assignment

\textbf{Input} An integer $n$ and $n \times n$ cost matrix $C = (c_{ij})$.

\textbf{Output} All assignments that minimizes $\sum_{i=1}^{j=n} \sum_{j=1}^{i=n} c_{ij}x_{ij}$ subject to $\sum_{i=1}^{j=n} x_{ij} = 1 (j = 1, \ldots, n)$, $\sum_{j=1}^{i=n} x_{ij} = 1 (i = 1, \ldots, n)$, and $x_{ij} \geq 0$.

\textbf{Reference} [168]

6.2 Full disjunction

6.2.1 Enumeration of all full disjunction in an acyclic set

\textbf{Input} An acyclic set of relation $R$ with $N$ tuples.

\textbf{Output} All full disjunctions of $R$.

\textbf{Complexity} $O(N)$ delay.

\textbf{Reference} [49]
6.3 Matrix

6.3.1 Enumeration of all minimal sets of at most $k$ rows the deletion of which leaves a PP matrix

**Input** A binary $n \times m$ matrix $B$ and a positive integer $k$, where $n > 4k$.

**Output** All minimal sets of at most $k$ rows the deletion of which leaves a PP matrix.

**Complexity** $O(3^k nm)$ time.

**Comment** A PP matrix is a perfect phylogeny matrix.

**Reference** [52]

6.4 Round-robin tournament score

6.4.1 Enumeration of all round-robin tournament scores of $n$ players

**Input** An integer $n$.

**Output** All round-robin tournament scores of $n$ players.

**Reference** [177]

7 Permutation

7.1 Arrangements

7.1.1 Enumeration of all arrangements with $n$ marks

**Input** An integer $n$.

**Output** All arrangements with $n$ marks.

**Complexity** $O(n!)$ total time.

**Reference** [258]
7.1.2 Enumeration of all arrangements with $n$ marks

**Input** An integer $n$.

**Output** All arrangements with $n$ marks.

**Complexity** $O(n!)$ total time.

**Reference** [111]

7.2 Ladder lottery

7.2.1 Enumeration of all optimal ladder lotteries

**Input** A permutation.

**Output** All optimal ladder lotteries with satisfying the permutation.

**Complexity** $O(1)$ time per solution on average, $O(n^2)$ space, and $O(n^2)$ time preprocessing.

**Comment** $n$ is the length of the input permutation. We call a ladder lottery is an optimal when the number of horizontal lines in the ladder lottery is minimum. Ladder lotteries are also known as arrangements of pseudolines.

**Reference** [270]

7.2.2 Enumeration of all ladder lotteries with $k$ bars

**Input** A permutation $\pi$ and integer $k$.

**Output** All ladder lotteries of $\pi$ with $k$ bars.

**Complexity** $O(1)$ time per ladder lottery.

**Comment** Ladder lotteries are also known as Amida kuji in Japan.

**Reference** [266]
7.3 Set

7.3.1 Enumeration of all permutations of a set of elements

Input A set $S$.

Output All permutations of $S$

Comment He proposed the general algorithm for some combinatorial problems.

Reference [62]

7.3.2 Enumeration of all permutations of a set of elements

Input A set $S$.

Output All permutations of $S$

Reference [54]

8 SAT

8.1 Boolean CSP

8.1.1 Enumeration of all models of $\phi$ by non-decreasing weight

Input A $\Gamma$-formula $\phi$.

Output All models of $\phi$ by non-decreasing weight.

Complexity If $\Gamma$ is Horn or width-2 affine, there exists a polynomial delay algorithm.

Comment Otherwise, such an algorithm does not exist unless $P \neq NP$.

Reference [50]

9 Set

9.1 Bitstring

9.1.1 Enumeration of all bitstrings of length $n$ that contains exactly $k$ 1’s

Input An even integer $n$ and odd integer $k$. 

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Output All bitstrings of length $n$ that contains exactly $k$ 1’s.

Complexity $O(1)$ amortized time per solution.

Reference [198]

9.2 Ideals

9.2.1 Enumeration of all ideals in a poset

Input A poset $\mathcal{P}$.

Output All ideals in $\sqrt{\mathcal{P}}$.

Complexity $O(1)$ delay.

Reference [135]

9.3 Partition

9.3.1 Enumeration of all paritions in natural order

Input An integer $n$.

Output All partitions of $n$ in natural order

Reference [163]

9.3.2 Enumeration of all paritions with restriction

Input Integers $k$ and $n$.

Output All partitions of $n$ whose the smallest part is greater than or equal to $k$.

Reference [260]

9.3.3 Enumeration of all $k$-partitions of $n$

Input Integers $k$ and $n$.

Output All $k$-partitions of $n$.

Reference [177]
9.3.4 Enumeration of all partitions of an integer

**Input** An integer $n$.

**Output** All partitions of $n$.

**Complexity**

**Reference** [73]

9.3.5 Enumeration of all partitions of a set

**Input** A set $S$.

**Output** All partitions of $S$.

**Complexity** $O(1)$ amortized time per solution.

**Reference** [221]

9.3.6 Enumeration of all partitions of $n$ into integers of size at most $k$

**Input** Integers $n$ and $k$.

**Output** All partitions of $n$ into integers of size at most $k$.

**Reference** [212]

9.3.7 Enumeration of all partitions of a set into a fixed number of blocks

**Input** An integer $k$.

**Output** All partitions of a set into $k$ blocks

**Complexity** $O(1)$ amortized time per solution.

**Reference** [202]
9.3.8 Enumeration of all partitions of an integer \( n \)

**Input** Three integers \( n, k, \) and \( \sigma \).

**Output** All partitions \( P_\sigma(n,k) \) of \( n \) into parts of size at most \( k \) in which parts are congruent to 1 modulo \( \sigma \).

**Complexity** \( O(N) \) total time. E.g., \( P_3(11,8) = P_3(11,7) = \{\{7,4\}, \{7,1,1,1,1\}, \{4,4,1,1,1\}, \{4,1,1,1,1,1\}\} \).

**Comment** \( N \) is the number of partitions.

**Reference** [192]

9.3.9 Enumeration of all partitions of an integer \( n \)

**Input** Two integers \( n \) and \( k \).

**Output** All partitions \( D(n,k) \) of \( n \) into distinct parts of size at most \( k \).

**Complexity** \( O(N) \) total time. E.g., \( D(10,5) = \{\{5,4,1\}, \{5,3,2\}, \{4,3,2,1\}\} \) and \( D(11,4) = \emptyset \).

**Comment** \( N \) is the number of partitions.

**Reference** [192]

9.3.10 Enumeration of all partition of \( \{1, \ldots , n\} \) into \( k \) non-empty subsets

**Input** An integer \( k \).

**Output** All partition of \( \{1, \ldots , n\} \) into \( k \) non-empty subsets.

**Complexity** \( O(1) \) time per solution.

**Comment** The number of such partitions is known as the Stirling number of the second kind.

**Reference** [122]
9.3.11  Enumeration of all integer partitions in (anti-)lexicographical order

**Input**  An integer \( n \).

**Output**  All integer partitions of \( n \).

**Complexity**  \( O(1) \) time per solution on average.

**Reference**  [229]

10  String

10.1  Binary string

10.1.1  Enumeration of all binary string with fixed number ones

**Input**  Two integers \( n \) and \( k \), where \( n \geq k \).

**Output**  All binary string with length \( n \) and \( k \) ones.

**Complexity**  \( O(1) \) time per binary string.

**Reference**  [24]

10.2  Bracelet

10.2.1  Enumeration of all \( k \)-ary bracelets

**Input**  \( n \): a length of a bracelet, \( k \): a number of alphabet size.

**Output**  All \( k \)-ary bracelets.

**Complexity**  \( O(1) \) amortized per output and \( O(n) \) space.

**Comment**  A bracelet is the lexicographically smallest element of an equivalence class of \( k \)-ary strings under string rotation and reversal.

**Reference**  [215]

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10.3 Lyndon word

10.3.1 Enumeration of all $k$-ary Lyndon brackets of length $n$

Input  Two integers $k$ and $n$.

Output  All $k$-ary Lyndon brackets of length $n$.

Complexity  $O(n)$ time per solution.

Reference  [217]

10.4 Necklace

10.4.1 Enumeration of all $k$-color necklaces with $n$ beads

Input  Integers $k$ and $n$.

Output  All $k$-color necklaces with $n$ beads

Reference  [81]

10.4.2 Enumeration of all necklaces of length $n$ with two colors

Input  An integer $n$.

Output  All necklaces of length $n$ with two colors.

Reference  [80]

10.4.3 Enumeration of all $k$-ary necklaces

Input  $n$: a length of a necklace, $k$: a number of alphabet size.

Output  All $k$-ary necklaces with length $n$.

Complexity  $O(1)$ amortized per output and $O(n)$ space.

Comment  A $k$-ary necklace is an equivalence class of $k$-ary strings under rotation.

Reference  [204]
10.4.4 Enumeration of all $n$-bit necklaces with fixed density $d$

**Input** Two integer $n$ and $d$.

**Output** All $n$-bit necklaces with fixed density $d$.

**Complexity** $O(nN)$ total time and $O(n)$ space.

**Comment** $N$ is the number of solutions. A density of a $n$-bit necklace $T$ is $d$ if $T$ has $d$ ones.

**Reference** [251]

10.4.5 Enumeration of all $k$-ary necklaces with fixed density

**Input** $n$: a length of a necklace, $k$: a number of alphabet size, $d$: a number of nonzero characters.

**Output** All $k$-ary necklaces with fixed density $d$.

**Complexity** $O(1)$ amortized per output and $O(n)$ space.

**Comment** The set of 3-ary necklace with 2-density and 4-length is $N_3(4, 2) = \{0011, 0012, 0021, 0022, 0101, 0102, 0202\}$.

**Reference** [205]

10.4.6 Enumeration of all strings of some family

**Complexity** Constant amortized time per solution.

**Comment** This algorithm can list not only all necklaces but also all strings in other some family with CAT.

**Reference** [39]

10.4.7 Enumeration of all $k$-ary necklaces with fixed content of length $n$

**Input** Two integer $k$ and $n$, and a content.

**Output** All $k$-ary necklaces with fixed content of length $n$.

**Complexity** Constant amortized time per solution.

**Reference** [214]
10.5 Parenthesis

10.5.1 Enumeration of all well-formed parenthesis with length $2n$

**Input** An integer $n$.

**Output** All well-formed parenthesis with length $2n$ in lexicographical ordering.

**Reference** [69]

10.5.2 Enumeration of all well-formed parenthesis strings of size $n$

**Input** An integer $n$.

**Output** All well-formed parenthesis strings of size $n$.

**Complexity** $O(1)$ delay with $O(n)$ space, or $O(n)$ delay with $O(1)$ space.

**Reference** [249]

10.6 Substring

10.6.1 Enumeration of all $k$-ary strings of length $n$ that have no substring equal to $f$

**Input** A $k$-ary string $f$ with length $m$, and a positive integer $n$.

**Output** All $k$-ary strings of length $n$ that have no substring equal to $f$.

**Complexity** $O(1)$ time per string.

**Reference** [206]

10.6.2 Enumeration of all circular $k$-ary strings of length $n$ that have no substring equal to $f$

**Input** A $k$-ary string $f$ with length $m$, and a positive integer $n$.

**Output** All circular $k$-ary strings of length $n$ that have no substring equal to $f$.

**Complexity** $O(1)$ time per string.

**Reference** [206]
10.6.3 Enumeration of all $k$-ary necklaces of length $n$ that have no substring equal to $f$

**Input** A $k$-ary string $f$ with length $m$, and a positive integer $n$.

**Output** All $k$-ary necklaces of length $n$ that have no substring equal to $f$.

**Complexity** $O(1)$ time per string.

**Comment** $f$ is an aperiodic necklace.

**Reference** [206]

11 Survey

11.1 Enumeration

11.1.1 Enumeration of $k$-best enumeration

**Comment** This is the full version of the Springer Encyclopedia of Algorithms, 2014.

**Reference** [65]

11.2 Graph

11.2.1 Algorithms for enumeration of all cycles in a given graph

**Input** A graph $G$.

**Output** All cycles belonging to $G$.

**Comment** 26 cycle enumeration algorithms are introduced.

**Reference** [153]

11.2.2 Enumeration of clique enumeration

**Comment** In Sec.3.

**Reference** [184]

11.2.3 Enumeration of gray code algorithms

**Reference** [211]
11.3 Logic

11.3.1

Comment  The author of this paper investigate the class of databases with constant delay the answers to a query.

Reference  [220]

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