Graph theory package for Giac/Xcas

User manual

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Chapter 1
Introduction

This document contains an overview of the graph theory commands built in the Giac/Xcas software, including the syntax, the detailed description and practical examples for each command.

Chapter 2
Constructing graphs

2.1 Creating graphs from scratch

There are two commands in Giac that allow construction of custom graphs: `graph` and `digraph`.

The command `graph` accepts between one and three mandatory arguments, each of them being one of the following structural elements of the resulting graph:

- the number or list of vertices (a vertex may be any atomic object, such as an integer, a symbol or a string); it must be the first argument if used,
- the set of edges (each edge is a list containing two vertices), a permutation, a trail of edges or a sequence of trails; it can be either the first or the second argument if used,
- the adjacency or weight matrix.

Additionally, some of the following options may be appended to the sequence of arguments:

- `directed = true` or `false`,
- `weighted = true` or `false`,
- `color =` an integer or a list of integers representing color(s) of the vertices,
- `coordinates =` a list of vertex 2D or 3D coordinates.

The `graph` command may also be called by passing a string, representing the name of a special graph, as its only argument. In that case the corresponding graph will be constructed and returned. The supported graphs and their names are listed below.

1. Clebsch graph: `clebsch`
2. Coxeter graph: `coxeter`
3. Desargues graph: `desargues`
4. Dodecahedral graph: `dodecahedron`
5. Dürer graph: `durer`
6. Dyck graph: `dyck`
7. Grinberg graph: `grinberg`

8. Grotzsch graph: `grotzsch`
9. Harries graph: `harries`
10. Harries–Wong graph: `harries-wong`
11. Heawood graph: `heawood`
12. Herschel graph: `herschel`
13. Icosahedral graph: `icosahedron`
14. Levi graph: `levi`
15. Ljubljana graph: `ljubljana`
16. McGee graph: `mcgee`
17. Möbius–Kantor graph: `mobius-kantor`
18. Nauru graph: `nauru`
19. Octahedral graph: `octahedron`
20. Pappus graph: `pappus`
21. Petersen graph: `petersen`
22. Robertson graph: `robertson`
23. Truncated icosahedral graph: `soccerball`
24. Shrikhande graph: `shrikhande`
25. Tetrahedral graph: `tehtrahedron`

The `digraph` command is used for creating directed graphs, although it is also possible with the `graph` command by specifying the option `directed=true`. Actually, calling `digraph` is the same as calling `graph` with that option appended to the sequence of arguments. However, creating special graphs is not supported by `digraph` since they are all undirected. Edges in directed graphs are called *arcs*. Edges and arcs are different structures: an edge is represented by a two-element set containing its endpoints, while an arc is represented by the ordered pairs of its endpoints.

The following series of examples demonstrates the various possibilities when using `graph` and `digraph` commands.

2.1.1 Creating vertices

A graph consisting only of vertices and no edges can be created simply by providing the number of vertices or the list of vertex labels.

```
> graph(5)
```

an undirected unweighted graph with 5 vertices and 0 edges

```
> graph([a,b,c])
```

an undirected unweighted graph with 3 vertices and 0 edges

2.1.2 Creating single edges and arcs

Edges/arcs must be specified inside a set so that it can be distinguished from a (adjacency or weight) matrix. If only a set of edges/arcs is specified, the vertices needed to establish these will be created automatically. Note that, when constructing a directed graph, the order of the vertices in an arc matters; in undirected graphs it is not meaningful.

```
> graph(%{[a,b],[b,c],[a,c]%})
```

an undirected unweighted graph with 3 vertices and 3 edges

Edge weights may also be specified.

```
> graph(%{[[a,b],2],[[b,c],2.3],[[c,a],3/2]%})
```

an undirected weighted graph with 3 vertices and 3 edges

If the graph contains isolated vertices (not connected to any other vertex) or a particular order of vertices is desired, the list of vertices has to be specified first.

```
> graph([d,b,c,a],%{[a,b],[b,c],[a,c]%})
```

an undirected unweighted graph with 4 vertices and 3 edges

2.1.3 Creating paths and trails

A directed graph can also be created from a list of n vertices and a permutation of order n. The resulting graph consists of a single directed path with the vertices ordered according to the permutation.

```
> graph([a,b,c,d],[1,2,3,0])
```

a directed unweighted graph with 4 vertices and 3 arcs

Alternatively, one may specify edges as a trail.

```
> digraph([a,b,c,d],trail(b,c,d,a))
```

a directed unweighted graph with 4 vertices and 3 arcs

Using trails is also possible when creating undirected graphs. Also, some vertices in a trail may be repeated, which is not allowed in a path.

```
> graph([a,b,c,d],trail(b,c,d,a,c))
```

an undirected unweighted graph with 4 vertices and 4 edges

There is also the possibility of specifying several trails in a sequence, which is useful for designing more complex graphs.

```
> graph(trail(1,2,3,4,2),trail(3,5,6,7,5,4))
```

an undirected unweighted graph with 7 vertices and 9 edges

2.1.4 Specifying adjacency or weight matrix

A graph can be created from a single square matrix $A = [a_{ij}]_n$ of order n. If it contains only ones and zeros and has zeros on its diagonal, it is assumed to be the adjacency matrix for the desired graph. Otherwise, if an element outside the set $\{0, 1\}$ is encountered, it is assumed that the matrix of edge weights is passed as input, causing the resulting graph to be weighted accordingly. In each case, exactly n vertices will be created and i-th and j-th vertex will be connected iff $a_{ij} \neq 0$. If the matrix is symmetric, the resulting graph will be undirected, otherwise it will be directed.

```
> graph([[0,1,1,0],[1,0,0,1],[1,0,0,0],[0,1,0,0]])
```

an undirected unweighted graph with 4 vertices and 3 edges

```
> graph([[0,1.0,2.3,0],[4,0,0,3.1],[0,0,0,0],[0,0,0,0]])
```

a directed weighted graph with 4 vertices and 4 arcs

List of vertex labels can be specified before the matrix.

```
> graph([a,b,c,d],[[0,1,1,0],[1,0,0,1],[1,0,0,0],[0,1,0,0]])
```

an undirected unweighted graph with 4 vertices and 3 edges

When creating a weighted graph, one can first specify the list of n vertices and the set of edges, followed by a square matrix A of order n. Then for every edge $\{i, j\}$ or arc (i, j) the element a_{ij} of A is assigned as its weight. Other elements of A are ignored.

```
> digraph([a,b,c],%{[a,b],[b,c],[a,c]%}, [[0,1,2],[3,0,4],[5,6,0]])
```

a directed weighted graph with 3 vertices and 3 arcs

When a special graph is desired, one just needs to pass its name to the `graph` command. An undirected unweighted graph will be returned.

```
> graph("petersen")
```

an undirected unweighted graph with 10 vertices and 15 edges

2.2 Promoting to directed and/or weighted graphs

To promote an existing undirected graph to a directed one or an unweighted graph to a weighted one, use the commands `make_directed` and `make_weighted`, respectively.

The command `make_directed` is called with one or two arguments, an undirected graph $G(V, E)$ and optionally a square matrix of order $|V|$. Every edge $\{i, j\} \in E$ is replaced with the pair of arcs (i, j) and (j, i). If matrix A is specified, a_{ij} and a_{ji} are assigned as weights of these arcs, respectively. Thus a directed (and possibly weighted) graph is created and returned.

```
> make_directed(cycle_graph(4))
```

C4: a directed unweighted graph with 4 vertices and 8 arcs

```
> make_directed(cycle_graph(4), [[0,0,0,1],[2,0,1,3],[0,1,0,4],[5,0,
  4,0]])
```

C4: a directed weighted graph with 4 vertices and 8 arcs

The command `make_weighted` accepts one or two arguments, an unweighted graph $G(V, E)$ and optionally a square matrix A of order $|V|$. If the matrix specification is omitted, a square matrix of ones is assumed. Then a copy of G is returned where each edge/arc $(i, j) \in E$ gets a_{ij} assigned as its weight. If G is an undirected graph, it is assumed that A is symmetric.

```
> make_weighted(graph(%{[1,2],[2,3],[3,1]%}), [[0,2,3],[2,0,1],[3,1,
  0]])
```

an undirected weighted graph with 3 vertices and 3 edges

2.3 Cycle graphs

Cycle graphs can be created by using the command `cycle_graph`.

`cycle_graph` accepts a positive integer n or a list of distinct vertices as its only argument and returns the graph consisting of a single cycle through the specified vertices in the given order. If n is specified it is assumed to be the desired number of vertices, in which case they will be created and labeled with the first n integers (starting from 0 in Xcas mode and from 1 in Maple mode). The resulting graph will be given the name `Cn`, for example `C4` for $n = 4$.

```
> cycle_graph(5)
```

C5: an undirected unweighted graph with 5 vertices and 5 edges

```
> cycle_graph(["a","b","c","d","e"])
```

C5: an undirected unweighted graph with 5 vertices and 5 edges

2.4 Path graphs

Path graphs can be created by using the command `path_graph`.

`path_graph` accepts a positive integer n or a list of distinct vertices as its only argument and returns a graph consisting of a single path through the specified vertices in the given order. If n is specified it is assumed to be the desired number of vertices, in which case they will be created and labeled with the first n integers (starting from 0 in Xcas mode and from 1 in Maple mode).

Note that a path cannot intersect itself. Paths that are allowed to cross themselves are called *trails* (see the command `trail`).

```
> path_graph(5)
```

an undirected unweighted graph with 5 vertices and 4 edges

```
> path_graph(["a","b","c","d","e"])
```

an undirected unweighted graph with 5 vertices and 4 edges

2.5 Trail of edges

If the dummy command `trail` is called with a sequence of vertices as arguments, it returns the symbolic expression representing the trail of edges through the specified vertices. The resulting symbolic object is recognizable by `graph` and `digraph` commands. Note that a trail may cross itself (some vertices may be repeated in the given sequence).

```
> T:=trail(1,2,3,4,2):; graph(T)
```

Done, an undirected unweighted graph with 4 vertices and 4 edges

2.6 Complete graphs

To create complete (multipartite) graphs, use the command `complete_graph`.

If `complete_graph` is called with a single argument, a positive integer n or a list of distinct vertices, it returns the complete graph with the specified vertices. If integer n is specified, it is assumed that it is the desired number of vertices and they will be created and labeled with the first n integers (starting from 0 in Xcas mode and from 1 in Maple mode).

If a sequence of positive integers n_1, n_2, ..., n_k is passed as argument, `complete_graph` returns the complete multipartite graph with partitions of size n_1, $n_2, \ldots, n_k$.

```
> complete_graph(5)
```

an undirected unweighted graph with 5 vertices and 10 edges

```
> complete_graph([a,b,c])
```

an undirected unweighted graph with 3 vertices and 3 edges

```
> complete_graph(2,3)
```

an undirected unweighted graph with 5 vertices and 6 edges

2.6.1 Complete trees

To construct the complete binary tree of depth n, use the command `complete_binary_tree` which accepts n (a positive integer) as its only argument.

```
> complete_binary_tree(2)
```

an undirected unweighted graph with 7 vertices and 6 edges

To construct the complete k-ary tree of the specified depth use the command `complete_kary_tree`.

`complete_kary_tree` accepts k and n (positive integers) as its arguments and returns the complete k-ary tree of depth n. For example, to get a ternary tree with two levels, input:

```
> complete_kary_tree(3,2)
```

an undirected unweighted graph with 13 vertices and 12 edges

2.7 Creating graph from a graphic sequence

To construct a graph from its degree sequence, use the command `sequence_graph` which accepts a list L of positive integers as its only argument. If the list represents a graphic sequence, the corresponding graph is constructed by using Havel–Hakimi algorithm with complexity $O(|L|^2 \log |L|)$. If the argument is not a graphic sequence, an error is returned.

```
> sequence_graph([3,2,4,2,3,4,5,7])
```

an undirected unweighted graph with 8 vertices and 15 edges

The command `is_graphic_sequence` is used to check whether a list of integers represents the degree sequence of some graph.

`is_graphic_sequence` accepts a list L of positive integers as its only argument and returns `true` if there exists a graph $G(V, E)$ with degree sequence $\{\deg v : v \in V\}$ equal to L, else it returns `false`. The algorithm is based on Erdős–Gallai theorem and has the complexity $O(|L|^2)$.

```
> is_graphic_sequence([3,2,4,2,3,4,5,7])
```

true

2.8 Interval graphs

The command `interval_graph` is used for creating interval graphs.

`interval_graph` accepts a sequence or list of real-line intervals as its argument and returns an undirected unweighted graph with these intervals as vertices (the string representations of the intervals are used as labels), each two of them being connected with an edge if and only if the corresponding intervals intersect.

```
> interval_graph(0..8,1..pi,exp(1)..20,7..18,11..14,17..24,23..25)
```

an undirected unweighted graph with 7 vertices and 10 edges

2.9 Star graphs

The command `star_graph` is used for creating star graphs.

`star_graph` accepts a positive integer n as its only argument and returns the star graph with $n + 1$ vertices, which is equal to the complete bipartite graph `complete_graph(1,n)` i.e. a n-ary tree with one level.

```
> star_graph(5)
```

an undirected unweighted graph with 6 vertices and 5 edges

2.10 Wheel graphs

The command `wheel_graph` is used for creating wheel graphs.

`wheel_graph` accepts a positive integer n as its only argument and returns the wheel graph with $n+1$ vertices.

```
> wheel_graph(5)
```

an undirected unweighted graph with 6 vertices and 10 edges

2.11 Web graphs

The command `web_graph` is used for creating web graphs.

`web_graph` accepts two positive integers a and b as its arguments and returns the web graph with parameters a and b, namely the Cartesian product of `cycle_graph(a)` and `path_graph(b)`.

```
> web_graph(7,3)
```

an undirected unweighted graph with 21 vertices and 35 edges

2.12 Prism graphs

The command `prism_graph` is used for creating prism graphs.

`prism_graph` accepts a positive integer n as its only argument and returns the prism graph with parameter n, namely `web_graph(n,2)`.

```
> prism_graph(5)
```

an undirected unweighted graph with 10 vertices and 15 edges

2.13 Antiprism graphs

The command `antiprism_graph` is used for creating antiprism graphs.

`antiprism_graph` accepts a positive integer n as its only argument and returns the antiprism graph with parameter n, which is constructed from two concentric cycles of n vertices by joining each vertex of the inner to two adjacent nodes of the outer cycle.

```
> antiprism_graph(5)
```

an undirected unweighted graph with 10 vertices and 20 edges

2.14 Grid graphs

The command `grid_graph` is used for creating rectangular grid graphs.

`grid_graph` accepts two positive integers m and n as its arguments and returns the m by n grid on $m \cdot n$ vertices, namely the Cartesian product of `path_graph(m)` and `path_graph(n)`.

```
> grid_graph(5,3)
```

an undirected unweighted graph with 15 vertices and 22 edges

To create torus grid graphs, use the command `torus_grid_graph` which accepts two positive integers m and n as its arguments and returns the m by n torus grid on m n vertices, namely the Cartesian product of `cycle_graph(m)` and `cycle_graph(n)`.

```
> torus_grid_graph(5,3)
```

an undirected unweighted graph with 15 vertices and 30 edges

2.15 Kneser graphs

The command `kneser_graph` accepts two positive integers $n \leq 20$ and k as its arguments and returns the Kneser graph $K(n,k)$. The latter is obtained by setting all k-subsets of a set of n elements as vertices and connecting each two of them if and only if the corresponding sets are disjoint.

Kneser graphs can get exceedingly complex even for relatively small values of n and k. Note that the number of vertices in $K(n,k)$ is equal to $\binom{n}{k}$.

```
> kneser_graph(5,2)
```

an undirected unweighted graph with 10 vertices and 15 edges

The command `odd_graph` is used for creating so-called *odd* graphs, which are Kneser graphs with parameters $n=2\,d+1$ and $k=d$ for $d\geqslant 1$.

`odd_graph` accepts a positive integer $d\leq 8$ as its only argument and returns d-th odd graph $K(2\,d+1,d)$. Note that the odd graphs with $d>8$ will not be constructed as they are too big to handle.

```
> odd_graph(3)
```

an undirected unweighted graph with 10 vertices and 15 edges

2.16 Sierpiński graphs

The command `sierpinski_graph` is used for creating Sierpiński-type graphs S_k^n and ST_k^n [1].

`sierpinski_graph` accepts two positive integers n and k as its arguments (and optionally the symbol `triangle` as the third argument) and returns the Sierpiński (triangle) graph with parameters n and k.

The Sierpiński triangle graph ST_k^n is obtained by contracting all non-clique edges in S_k^n. In particular, ST_3^n is the well-known Sierpiński sieve graph of order n.

```
> sierpinski_graph(4,3)
```

an undirected unweighted graph with 81 vertices and 120 edges

```
> sierpinski_graph(4,3,triangle)
```

an undirected unweighted graph with 42 vertices and 81 edges

2.17 Generalized Petersen graphs

The command `petersen_graph` is used for creating generalized Petersen graphs $P(n,k)$.

`petersen_graph` accepts two arguments, n and k (positive integers). The second argument may be omitted, in which case $k=2$ is assumed. The graph $P(n,\,k)$, which is returned, is a connected cubic graph consisting of—in Schläfli notation—an inner star polygon $\{n,k\}$ and an outer regular polygon $\{n\}$ such that the n pairs of corresponding vertices in inner and outer polygons are connected with edges. For $k=1$ the prism graph of order n is obtained.

For example, to obtain the dodecahedral graph $P(10,2)$, input:

```
> petersen_graph(10)
```

an undirected unweighted graph with 20 vertices and 30 edges

To obtain Möbius–Kantor graph $P(8,3)$, input:

```
> petersen_graph(8,3)
```

an undirected unweighted graph with 16 vertices and 24 edges

Note that Desargues, Dürer and Nauru graphs are also generalized Petersen graphs $P(10,3)$, $P(6,2)$ and $P(12,5)$, respectively.

2.18 Creating isomorphic graphs

The commands `isomorphic_copy`, `permute_vertices` and `relabel_vertices`, presented in this section, are used to obtain isomorphic copies of an existing graph.

The command `isomorphic_copy` accepts two arguments, a graph $G(V,E)$ and a permutation σ of order $|V|$, and returns the copy of graph G with vertices rearranged according to σ.

```
> isomorphic_copy(path_graph(5),randperm(5))
```

an undirected unweighted graph with 5 vertices and 4 edges

The command `permute_vertices` accepts two arguments, a graph $G(V,E)$ and a list L of length $|V|$ containing all vertices from V in a certain order, and returns a copy of G with vertices rearranged as specified by L.

```
> permute_vertices(path_graph([a,b,c,d]),[b,d,a,c])
```

an undirected unweighted graph with 4 vertices and 3 edges

The command `relabel_vertices` accepts two arguments, a graph $G(V,E)$ and a list L of vertex labels, and returns the copy of G with vertices relabeled with labels from L.

```
> relabel_vertices(path_graph(4),[a,b,c,d])
```

an undirected unweighted graph with 4 vertices and 3 edges

2.19 Extracting subgraphs of a graph

To extract the subgraph of $G(V,E)$ formed by edges from $L \subset E$, use the command `subgraph` which accepts two arguments: G and L.

```
> subgraph(complete_graph(5),[[1,2],[2,3],[3,4],[4,1]])
```

an undirected unweighted graph with 4 vertices and 4 edges

To obtain the subgraph of G induced by set of vertices $L \subset V$, use the command `induced_subgraph`.

`induced_subgraph` accepts two arguments G and L and returns the subgraph of G formed by all edges in E which have endpoints in L.

```
> induced_subgraph(petersen_graph(5),[1,2,3,6,7,9])
```

an undirected unweighted graph with 6 vertices and 6 edges

2.20 Underlying graph

For every graph $G(V, E)$ there is an undirected and unweighted graph $U(V, E')$, called the *underlying graph* of G, where E' is obtained from E by dropping edge directions.

To construct U use the command `underlying_graph` which accepts G as its only argument. The result is obtained by copying G and "forgetting" the directions of arcs and weights of edges/arcs.

```
> G:=digraph(%{[[1,2],6],[[2,3],4],[[3,1],5]%})
```

a directed weighted graph with 3 vertices and 3 arcs

```
> U:=underlying_graph(G)
```

an undirected unweighted graph with 3 vertices and 3 edges

```
> edges(U)
```

$$\begin{pmatrix} 1 & 2 \\ 1 & 3 \\ 2 & 3 \end{pmatrix}$$

2.21 Reversing edge directions

The command `reverse_graph` is used for reversing arc directions in digraphs.

`reverse_graph` accepts a graph $G(V, E)$ as its only argument and returns the reverse graph $G^T(V, E')$ of G where $E' = \{(j, i) : (i, j) \in E\}$, i.e. returns the copy of G with the directions of all edges reversed.

Note that `reverse_graph` is defined for both directed and undirected graphs, but gives meaningful results only for directed graphs.

G^T is also called the *transpose graph* of G because adjacency matrices of G and G^T are transposes of each other (hence the notation).

```
> G:=digraph(6, %{[1,2],[2,3],[2,4],[4,5]%})
```

a directed unweighted graph with 6 vertices and 4 arcs

```
> GT:=reverse_graph(G)
```

a directed unweighted graph with 6 vertices and 4 arcs

```
> edges(GT)
```

$$\begin{pmatrix} 2 & 1 \\ 3 & 2 \\ 4 & 2 \\ 5 & 4 \end{pmatrix}$$

2.22 Graph complement

The command `graph_complement` is used for constructing complements of graphs.

`graph_complement` accepts a graph $G(V, E)$ as its only argument and returns the complement $G^c(V, E^c)$ of G, where E^c is the largest set containing only edges/arcs not present in G.

```
> graph_complement(cycle_graph(5))
```

an undirected unweighted graph with 5 vertices and 5 edges

2.23 Union of graphs

The command `graph_union` is used for constructing union of two or more graphs.

`graph_union` accepts a sequence of graphs $G_k(V_k, E_k)$ for $k = 1, 2, \ldots, n$ as its argument and returns the graph $G(V, E)$ with $V = V_1 \cup V_2 \cup \cdots \cup V_k$ and $E = E_1 \cup E_2 \cup \cdots \cup E_k$.

```
> G1:=graph([1,2,3],%{[1,2],[2,3]%})
```

an undirected unweighted graph with 3 vertices and 2 edges

```
> G2:=graph([1,2,3],%{[3,1],[2,3]%})
```

an undirected unweighted graph with 3 vertices and 2 edges

```
> G:=graph_union(G1,G2)
```

an undirected unweighted graph with 3 vertices and 3 edges

```
> edges(G)
```

$$\begin{pmatrix} 1 & 2 \\ 1 & 3 \\ 2 & 3 \end{pmatrix}$$

To construct disjoint union of graphs use the command `disjoint_union`.

`disjoint_union` accepts a sequence of graphs $G_k(V_k, E_k)$ for $k = 1, 2, \ldots, n$ as its argument and returns the graph obtained by labeling all vertices with strings `k:v` where $v \in V_k$ and all edges with strings `k:e` where $e \in E_k$ and calling the `graph_union` command subsequently. As all vertices and edges are labeled differently, it follows $|V| = \sum_{k=1}^{n} |V_k|$ and $|E| = \sum_{k=1}^{n} |E_k|$.

```
> disjoint_union(cycle_graph(3),path_graph(3))
```

an undirected unweighted graph with 6 vertices and 5 edges

2.24 Joining two graphs

The command `graph_join` is used for joining graphs.

`graph_join` accepts two graphs G and H as its arguments and returns the graph which is obtained by connecting all the vertices of G to all vertices of H. The vertex labels in the resulting graph are strings of the form `1:u` and `2:v` where u is a vertex in G and v is a vertex in H.

```
> graph_join(path_graph(2),graph(3))
```

an undirected unweighted graph with 5 vertices and 7 edges

2.25 Graph power

The command `graph_power` is used for constructing the powers of a graph.

`graph_power` accepts two arguments, a graph $G(V, E)$ and a positive integer k, and returns the k-th power G^k of G with vertices V such that $v, w \in V$ are connected with an edge if and only if there exists a path of length at most k in G.

The graph G^k is constructed from its adjacency matrix A_k which is obtained by adding powers of the adjacency matrix A of G:

$$A_k = \sum_{i=1}^{k} A^k.$$

The above sum is obtained by assigning $A_k \leftarrow A$ and repeating $k - 1$ times the instruction $A_k \leftarrow (A_k + I)\, A$, so exactly k matrix multiplications are required.

```
> graph_power(path_graph(5),2)
```

an undirected unweighted graph with 5 vertices and 7 edges

```
> graph_power(path_graph(5),3)
```

an undirected unweighted graph with 5 vertices and 9 edges

2.26 Graph product

There are two distinct operations for computing the product of two graphs: Cartesian product and tensor product. These operations are available in Giac as the commands `cartesian_product` and `tensor_product`, respectively.

The command `cartesian_product` accepts a sequence of graphs $G_k(V_k, E_k)$ for $k = 1, 2, ..., n$ as its argument and returns the Cartesian product $G_1 \times G_2 \times \cdots \times G_n$ of the input graphs. The Cartesian product $G(V, E) = G_1 \times G_2$ is the graph with list of vertices $V = V_1 \times V_2$, labeled with strings `v1:v2` where $v_1 \in V_1$ and $v_2 \in V_2$, such that (`u1:v1`,`u2:v2`) is member of E if and only if u_1 is adjacent to u_2 and $v_1 = v_2$ **or** $u_1 = u_2$ and v_1 is adjacent to v_2.

```
> G1:=graph(trail(1,2,3,4,1,5))
```

an undirected unweighted graph with 5 vertices and 5 edges

```
> G2:=star_graph(3)
```

an undirected unweighted graph with 4 vertices and 3 edges

```
> cartesian_product(G1,G2)
```

an undirected unweighted graph with 20 vertices and 35 edges

The command `tensor_product` accepts a sequence of graphs $G_k(V_k, E_k)$ for $k = 1, 2, ..., n$ as its argument and returns the tensor product $G_1 \times G_2 \times \cdots \times G_n$ of the input graphs. The tensor product $G(V, E) = G_1 \times G_2$ is the graph with list of vertices $V = V_1 \times V_2$, labeled with strings `v1:v2` where $v_1 \in V_1$ and $v_2 \in V_2$, such that (`u1:v1`,`u2:v2`) is in E if and only if u_1 is adjacent to u_2 **and** v_1 is adjacent to v_2.

```
> tensor_product(G1,G2)
```

an undirected unweighted graph with 20 vertices and 30 edges

2.27 Seidel switch

The command `seidel_switch` is used for Seidel switching in graphs.

`seidel_switch` accepts two arguments, an undirected and unweighted graph $G(V, E)$ and a list of vertices $L \subset V$. The result is a copy of G in which, for each vertex $v \in L$, its neighbors become its non-neighbors and vice versa.

```
> seidel_switch(cycle_graph(5),[1,2])
```

an undirected unweighted graph with 5 vertices and 7 edges

Chapter 3
Modifying graphs

3.1 Adding and removing vertices

For adding and removing vertices to/from graphs use the commands `add_vertex` and `delete_vertex`, respectively.

The command `add_vertex` accepts two arguments, a graph $G(V, E)$ and a single label v or a list of labels L, and returns the graph $G'(V \cup \{v\}, E)$ or $G''(V \cup L, E)$ if a list L is given.

```
> add_vertex(complete_graph(5),6)
```

an undirected unweighted graph with 6 vertices and 10 edges

```
> add_vertex(complete_graph(5),[a,b,c])
```

an undirected unweighted graph with 8 vertices and 10 edges

Note that vertices already present in G won't be added. For example:

```
> add_vertex(complete_graph([1,2,3,4,5]),[4,5,6])
```

an undirected unweighted graph with 6 vertices and 10 edges

The command `delete_vertex` accepts two arguments, a graph $G(V, E)$ and a single label v or a list of labels L, and returns the graph

$$G'(V \setminus \{v\}, \{e \in E : e \text{ is not incident to } v\})$$

or, if a list L is given,

$$G''(V \setminus L, \{e \in E : e \text{ is not incident to any } v \in L\}).$$

If any of the specified vertices does not belong to G, an error is returned.

```
> delete_vertex(complete_graph(5),2)
```

an undirected unweighted graph with 4 vertices and 6 edges

```
> delete_vertex(complete_graph(5),[2,3])
```

an undirected unweighted graph with 3 vertices and 3 edges

3.2 Adding and removing edges or arcs

For adding and removing edges or arcs to/from graphs use the commands `add_edge` or `add_arc` and `delete_edge` and `delete_arc`, respectively.

The command `add_edge` accepts two arguments, an undirected graph $G(V, E)$ and an edge or a list of edges or a trail of edges (entered as a list of vertices), and returns the copy of G with the specified edges inserted. Edge insertion implies creation of its endpoints if they are not already present.

```
> add_edge(cycle_graph(4),[1,3])
```

C4: an undirected unweighted graph with 4 vertices and 5 edges

```
> add_edge(cycle_graph(4),[1,3,5,7])
```

C4: an undirected unweighted graph with 6 vertices and 7 edges

The command `add_arc` works similarly to `add_edge` but applies only to directed graphs. Note that the order of endpoints in an arc matters.

```
> add_arc(digraph(trail(a,b,c,d,a)),[[a,c],[b,d]])
```

a directed unweighted graph with 4 vertices and 6 arcs

When adding edge/arc to a weighted graph, its weight should be specified alongside its endpoints, or it will be assumed that it equals to 1.

```
> add_edge(graph(%{[[1,2],5],[[3,4],6]%}),[[2,3],7])
```

an undirected weighted graph with 4 vertices and 3 edges

3.3 Setting edge weights

The commands `get_edge_weight` and `set_edge_weight` are used to access and modify the weight of an edge/arc in a weighted graph, respectively.

`set_edge_weight` accepts three arguments: a weighted graph $G(V, E)$, edge/arc $e \in E$ and the new weight w, which may be any number. It returns the modified copy of G.

The command `get_edge_weight` accepts two arguments, a weighted graph $G(V, E)$ and an edge or arc $e \in E$. It returns the weight of e.

```
> G:=set_edge_weight(graph(%{[[1,2],4],[[2,3],5]%}),[1,2],6)
```

an undirected weighted graph with 3 vertices and 2 edges

```
> get_edge_weight(G,[1,2])
```

3.4 Contracting edges

The command `contract_edge` is used for contracting (collapsing) edges in a graph.

`contract_edge` accepts two arguments, a graph $G(V, E)$ and an edge/arc $e = (v, w) \in E$, and merges w and v into a single vertex, deleting the edge e. The resulting vertex inherits the label of v. The command returns the modified graph $G'(V \setminus \{w\}, E')$.

```
> contract_edge(complete_graph(5),[1,2])
```

an undirected unweighted graph with 4 vertices and 6 edges

To contract a set $\{e_1, e_2, ..., e_k\} \subset E$ of edges in G, none two of which are incident (i.e. when the given set is a matching in G), one can use the `foldl` command. For example, if G is the complete graph K_5 and $k = 2$, $e_1 = \{1, 2\}$ and $e_2 = \{3, 4\}$, input:

```
> K5:=complete_graph(5)
```

an undirected unweighted graph with 5 vertices and 10 edges

```
> foldl(contract_edge,K5,[1,2],[3,4])
```

an undirected unweighted graph with 3 vertices and 3 edges

3.5 Subdividing edges

The command `subdivide_edges` is used for subdividing edges of a graph.

`subdivide_edges` accepts two or three arguments, a graph $G(V, E)$, a single edge/arc or a list of edges/arcs in E and optionally a positive integer r (which defaults to 1). Each of the specified edges/arcs will be subdivided with exactly r new vertices, labeled with the smallest available integers. The resulting graph, which is homeomorphic to G, is returned.

```
> G:=graph(%{[1,2],[2,3],[3,1]%})
```

an undirected unweighted graph with 3 vertices and 3 edges

```
> subdivide_edges(G,[2,3])
```

an undirected unweighted graph with 4 vertices and 4 edges

```
> subdivide_edges(G,[[1,2],[1,3]])
```

an undirected unweighted graph with 5 vertices and 5 edges

```
> subdivide_edges(G,[2,3],3)
```

an undirected unweighted graph with 6 vertices and 6 edges

3.6 Attributes

3.6.1 Graph attributes

The graph structure maintains a set of attributes as key-value pairs. The command `set_graph_attribute` is used to modify the existing values or add new attributes.

`set_graph_attribute` accepts two arguments, a graph G and a sequence or list of graph attributes in form `tag=value` where `tag` is any string. Alternatively, attributes may be specified as a sequence of two lists `[tag1,tag2,...]` and `[value1,value2,...]`. The command sets the specified values to the indicated attribute slots, which are meant to represent some global properties of the graph G, and returns the modified copy of G. Two tags are predefined and used by the CAS commands: `"directed"` and `"weighted"`, so it is not advisable to overwrite their values using this command. Instead, use `make_directed`, `make_weighted` and `underlying_graph` commands.

The previously set graph attribute values can be fetched with the command `get_graph_attribute` which accepts two arguments: a graph G and a sequence or list of tags. The corresponding values will be returned in a sequence or list, respectively. If some attribute is not set, `undef` is returned as its value.

To list all graph attributes of G for which the values are set, use the `list_graph_attributes` command which takes G as its only argument.

To discard a graph attribute, use the `discard_graph_attribute` command. It accepts two arguments: a graph G and a sequence or list of tags to be cleared, and returns the modified copy of G.

```
> G:=digraph(trail(1,2,3,1))
```

a directed unweighted graph with 3 vertices and 3 arcs

```
> G:=set_graph_attribute(G,"name"="C3","shape"=triangle)
```

C3: a directed unweighted graph with 3 vertices and 3 arcs

```
> get_graph_attribute(G,"shape")
```

$'\text{triangle}'$

```
> list_graph_attributes(G)
```

$[\text{directed} = \text{true}, \text{weighted} = \text{false}, \text{name} = C3, \text{shape} = '\text{triangle}']$

```
> G:=discard_graph_attribute(G,"shape")
```

C3: a directed unweighted graph with 3 vertices and 3 arcs

```
> list_graph_attributes(G)
```

$[\text{directed} = \text{true}, \text{weighted} = \text{false}, \text{name} = C3]$

3.6.2 Vertex attributes

For every vertex of a graph, the list of attributes in form of key-value pairs is maintained. The command `set_vertex_attribute` is used to modify the existing values or to add new attributes.

`set_vertex_attribute` accepts three arguments, a graph $G(V, E)$, a vertex $v \in V$ and a sequence or list of attributes in form `tag=value` where `tag` is any string. Alternatively, attributes may be specified as a sequence of two lists `[tag1,tag2,...]` and `[value1,value2,...]`. The command sets the specified values to the indicated attributes of the vertex v and returns the modified copy of G.

The previously set attribute values for v can be fetched with the command `get_vertex_attribute` which accepts three arguments: G, v and a sequence or list of tags. The corresponding values will be returned in a sequence or list, respectively. If some attribute is not set, `undef` is returned as its value.

To list all attributes of v for which the values are set, use the `list_vertex_attributes` command which takes two arguments, G and v.

To discard attribute(s) assigned to v call the `discard_vertex_attribute` command, which accepts three arguments: G, v and a sequence or list of tags to be cleared, and returns the modified copy of G.

```
>
```

3.6.3 Edge attributes

For every edge of a graph, the list of attributes in form of key-value pairs is maintained. The command `set_edge_attribute` is used to change existing values or add new attributes.

`set_edge_attribute` accepts three arguments, a graph $G(V, E)$, an edge/arc $e \in E$ and a sequence or list of attributes in form `tag=value` where `tag` is any string. Alternatively, attributes may be specified as a sequence of two lists `[tag1,tag2,...]` and `[value1,value2,...]`. The command sets the specified values to the indicated attributes of the edge/arc e and returns the modified copy of G.

The previously set attribute values for e can be fetched with the command `get_edge_attribute` which accepts three arguments: G, e and a sequence or list of tags. The corresponding values will be returned in a sequence or list, respectively. If some attribute is not set, `undef` is returned as its value.

To list all attributes of e for which the values are set, use the `list_edge_attributes` command which takes two arguments, G and e.

To discard attribute(s) assigned to e call the `discard_edge_attribute` command, which accepts three arguments: G, e and a sequence or list of tags to be cleared, and returns the modified copy of G.

```
>
```

Chapter 4
Import and export

4.1 Loading graphs from dot files

The command `import_graph` accepts a string `filename` as its only argument and returns the graph constructed from instructions written in the file `filename` or `undef` on failure. The passed string should contain the path to a file in the `dot` format. The file extension `.dot` may be omitted in the `filename` since `dot` is the only supported format. If a relative path to the file is specified, i.e. if it does not contain a leading forward slash, the current working directory (which can be obtained by calling the `pwd` command) will be used as the reference. The working directory can be changed by using the command `cd`.

For the details about the `dot` format see Section 4.3.

For example, assume that the file `philosophers.dot` is saved in the directory `Documents/dot/`, containing the graph describing the famous "dining philosophers" problem. To import it, input:

```
> G:=import_graph("Documents/dot/philosophers.dot")
```

an undirected unweighted graph with 21 vertices and 27 edges

4.2 Saving graphs to dot and LaTeX files

The command `export_graph` is used for saving graphs to disk in `dot` or LaTeX format.

`export_graph` accepts two mandatory arguments, a graph G and a string `filename`, and writes G to the file specified by `filename`, which must be a path to the file, either relative or absolute; in the former case the current working directory will be used as the reference. If only two arguments are given the graph is saved in `dot` format. The file name may be entered with or without `.dot` extension. The command returns 1 on success and 0 on failure.

```
> export_graph(G,"Documents/dot/copy_of_philosophers")
```

1

An optional third argument in form `latex[=<params>]` may be given, in which case the drawing of G (obtained by calling the `draw_graph` command) will be saved to the LaTeX file indicated by `filename` (the extension `.tex` may be omitted). Optionally, one can specify a parameter or list of parameters `params` which will be passed to the `draw_graph` command.

For example, let's create a nice drawing of the Sierpiński sieve graph of order $n=5$, i.e. the graph ST_3^5.

```
> G:=sierpinski_graph(5,3,triangle)
```

an undirected unweighted graph with 123 vertices and 243 edges

```
> export_graph(G,"Documents/st53.tex",latex=[spring,labels=false])
```

1

The LaTeX file obtained by exporting a graph is easily converted into an EPS file, which can subsequently be inserted in a paper, report or some other document. A Linux user simply needs to launch the terminal, navigate to the directory in which the exported file, in this case `st53.tex`, is stored and enter the following command:

```
latex st53.tex && dvips st53.dvi && ps2eps st53.ps
```

This will produce the (properly cropped) `st53.eps` file in the same directory. Afterwards, it is recommended to enter

```
rm st53.tex st53.aux st53.log st53.dvi st53.ps
```

to delete the intermediate files. The above two commands can be combined in a simple shell script which takes the name of the exported file (without the extension) as its input argument:

```
#!/bin/bash
# convert LaTeX to EPS
FILE=$1
latex ${FILE}.tex
dvips ${FILE}.dvi
ps2eps ${FILE}.ps
rm ${FILE}.tex ${FILE}.aux ${FILE}.log ${FILE}.dvi ${FILE}.ps
```

Assuming that the script is stored under the name `latex2eps` in the same directory as `st53.tex`, to do the conversion it is enough to input:

```
bash latex2eps st53
```

4.3 The dot file format overview

Giac has some basic support for the dot language[4.1]. Each file is used to hold exactly one graph and should look like this:

```
strict? (graph | digraph) name? {
  ...
```

4.1. For the complete syntax definition see https://www.graphviz.org/doc/info/lang.html

```
}
```

The keyword `strict` may be omitted, as well as the `name` of the graph, as indicated by the question marks. The former is used to differentiate between simple graphs (strict) and multigraphs (non-strict). Since this package supports only simple graphs, `strict` is redundant.

For specifying undirected graphs the keyword `graph` is used, while the `digraph` keyword is used for undirected graphs.

The `graph`/`digraph` environment contains a series of instructions describing how the graph should be built. Each instruction ends with the semicolon `;` and has one of the following forms.

- Creating isolated vertices: `vertex_name [attributes]?`
- Creating edges and trails: `V1 <edgeop> V2 <edgeop> ... <edgeop> Vk [attributes]?`
- Setting graph attributes: `graph [attributes]`

Here, `attributes` is a comma-separated list of tag-value pairs in form `tag=value`, `<edgeop>` is `--` for undirected and `->` for directed graphs. Each of `V1`, `V2` etc. is either a vertex name or a set of vertex names in form `{vertex_name1 vertex_name2 ...}`. In the case a set is specified, each vertex from that set is connected to the neighbor operands. Every specified vertex will be created if it does not exist yet.

Any line beginning with `#` is ignored. C-like line and block comments are recognized and skipped as well.

Using the `dot` syntax it is easy to specify a graph with adjacency lists. For example, the following is the contents of a file which defines the octahedral graph with 6 vertices and 12 edges.

```
# octahedral graph
graph "octahedron" {
  1 -- {3 6 5 4};
  2 -- {3 4 5 6};
  3 -- {5 6};
  4 -- {5 6};
}
```

```
>
```

Chapter 5
Graph properties

5.1 Cliques

The graph is a *clique* if it is complete, i.e. if each two of its vertices are adjacent to each other. To check if a graph is a clique one can use the `is_clique` command.

`is_clique` accepts a graph $G(V, E)$ as its only argument and returns `true` if G is a complete graph; else the returned value is `false`.

```
> K5:=complete_graph(5)
```

an undirected unweighted graph with 5 vertices and 10 edges

```
> is_clique(K5)
```

true

```
> G:=delete_edge(K5,[1,2])
```

an undirected unweighted graph with 5 vertices and 9 edges

```
> is_clique(G)
```

false

Each subgraph of a graph $G(V, E)$ which is itself a complete graph is called a clique in G. A clique is *maximal* if it cannot be extended by adding more vertices from V to it. To count all maximal cliques in a graph one can use the `clique_stats` command.

`clique_stats` accepts G as the only mandatory argument. If it is the only argument given, the command returns a list of pairs, each pair consisting of two integers: clique cardinality k (first) and the number $n_k > 0$ of k-cliques in G (second). Therefore, the sum of second members of all returned pairs is equal to the total count of all maximal cliques in G. As an optional second argument one may give a positive integer k or an interval m .. n with integer bounds. In the first case only the number of k-cliques for the given k is returned; in the second case, only cliques with cardinality between m and n (inclusive) are counted.

The algorithm used to generate all maximal cliques in a graph is a variant of Bron-Kerbosch algorithm developed by in [3]. Its worst-case running time is $O(3^{|V|/3})$ although the performance is usually almost instantaneous for graphs up to 100 vertices.

```
> G:=random_graph(50,0.5)
```

an undirected unweighted graph with 50 vertices and 588 edges

233 msec

```
> clique_stats(G)
```

$$\begin{pmatrix} 3 & 14 \\ 4 & 185 \\ 5 & 370 \\ 6 & 201 \\ 7 & 47 \\ 8 & 5 \end{pmatrix}$$

237 msec

```
> G:=random_graph(100,0.5)
```

an undirected unweighted graph with 100 vertices and 2461 edges

229 msec

```
> clique_stats(G,5)
```

3124

214 msec

```
> G:=random_graph(500,0.25)
```

an undirected unweighted graph with 500 vertices and 31250 edges

```
> clique_stats(G,5..7)
```

$$\begin{pmatrix} 5 & 148657 \\ 6 & 17834 \\ 7 & 356 \end{pmatrix}$$

1.254 sec

5.1.1 Maximum clique

The largest maximal clique in a graph G is called *maximum clique*. The command `maximum_clique` can be used to find one in the given graph.

`maximum_clique` accepts the graph G as its only argument and returns maximum clique in G as a list of vertices. The clique may subsequently be extracted from G using the command `induced_subgraph`.

The algorithm used to find maximum clique is an improved variant of Carraghan and Pardalos algorithm as described in [2].

```
> G:=sierpinski_graph(5,5)
```

an undirected unweighted graph with 3125 vertices and 7810 edges

```
> maximum_clique(G)
```

$$[1562, 1560, 1561, 1563, 1564]$$

231 msec

```
> G:=random_graph(300,0.3)
```

an undirected unweighted graph with 300 vertices and 13505 edges

```
> maximum_clique(G)
```

$$[231, 225, 187, 239, 164, 292, 296]$$

232 msec

5.1.2 Minimal clique vertex cover

The *minimal clique vertex cover* for graph G is the smallest set $S = \{C_1, C_2, ..., C_k\}$ of cliques in G such that for every $v \in V$ there exists $i \leqslant k$ such that $v \in C_i$. In Giac, such cover can be obtained by calling the `clique_cover` command.

`clique_cover` accepts graph G as its mandatory argument and returns the smallest possible cover. Optionally, a positive integer may be passed as the second argument. In that case the requirement that k is less or equal to the given integer is set. If no such cover is found, `clique_cover` returns empty list.

The strategy is to find the minimal vertex coloring (see Section 5.2) in the complement G^c of G (note that these two graphs share the same set of vertices). Each set of equally colored vertices in G^c corresponds to a clique in G. Therefore, the color classes of G^c map to the elements $C_1, ..., C_k$ of the minimal clique cover in G.

There is a special case in which G is triangle-free, which is treated separately. Such a graph G contains only 1- and 2-cliques; in fact, every clique cover in G consists of a matching M together with the singleton sets (isolated vertices) which remain unmatched. Since the number of cliques in the cover is equal to $|V| - |M|$, to find the minimal cover one needs to find maximum matching in G, which can be done in polynomial time.

```
> G:=random_graph(30,0.5)
```

an undirected unweighted graph with 30 vertices and 218 edges

```
> clique_cover(G)
Constructing conflict graph...
Conflict graph has 109 + 5 = 114 vertices
```

$[[26, 20, 4, 3, 0], [25, 18, 13, 7, 1], [28, 22, 17, 10, 2], [27, 14, 12, 6, 5], [23, 21, 9, 8], [24, 19, 16, 11], [29, 15]]$

To find minimal clique cover in the truncated icosahedral graph it suffices to find maximum matching.

```
> clique_cover(graph("soccerball"))
```

$[[1, 2], [5, 4], [6, 7], [3, 16], [11, 12], [21, 22], [26, 27], [10, 9], [8, 49], [30, 29], [53, 52], [15, 14], [13, 54], [58, 57], [17, 18], [20, 19], [59, 60], [38, 37], [25, 24], [23, 39], [43, 42], [28, 44], [48, 47], [31, 32], [35, 34], [36, 40], [33, 46], [41, 45], [51, 55], [56], [50]]$

5.2 Vertex coloring

5.2.1 Greedy coloring

5.2.2 Minimal coloring

Chapter 6
Traversing graphs

6.1 Shortest path in unweighted graphs

The command `shortest_path` is used to find the shortest path between two vertices in an undirected unweighted graph.

`shortest_path` accepts three arguments: a graph $G(V, E)$, the source vertex $s \in V$ and the target vertex $t \in V$ or a list T of target vertices. The shortest path from source to target is returned. If more targets are specified, the list of shortest paths from the source to each of these vertices is returned.

The strategy is to run breadth-first traversal on the graph G starting from the source vertex s. The complexity of the algorithm is therefore $O(|V| + |E|)$.

```
> shortest_path(graph("dodecahedron"),1,9)
```

$$[1, 5, 4, 9]$$

```
> shortest_path(graph("dodecahedron"),1,[7,9])
```

$$[[1, 2, 7], [1, 5, 4, 9]]$$

6.2 Cheapest path in weighted graphs

The command `dijkstra` is used to find the cheapest path between two vertices of an undirected weighted graph.

`dijkstra` accepts two or three arguments: a weighted graph $G(V, E)$ with non-negative weights, a vertex $s \in V$ and optionally a vertex $t \in V$ or list T of vertices in V. It returns the cheapest path from s to t or, if more target vertices are given, the list of such paths to each target vertex $t \in T$, computed by DIJKSTRA's algorithm in $O(|V|^2)$ time. If no target vertex is specified, all vertices in $V \setminus \{s\}$ are assumed to be targets.

A cheapest path from s to t is represented with a list `[[v1,v2,...,vk],c]` where the first element consists of path vertices with $v_1 = s$ and $v_k = t$, while the second element c is the weight (cost) of that path, equal to the sum of weights of its edges.

```
>
```

6.3 Spanning trees

The command `spanning_tree` accepts one or two arguments, an undirected graph G and optionally a vertex $r \in V$. It returns the spanning tree T of G rooted in r or, if none is given, in the first vertex in the list V, obtained by depth-first traversal in $O(|V| + |E|)$ time.

The command `minimal_spanning_tree` accepts an undirected graph $G(V, E)$ as its only argument and returns its minimal spanning tree obtained by KRUSKAL's algorithm in $O(|E| \log |V|)$ time.

Chapter 7
Visualizing graphs

7.1 Drawing graphs using various algorithms

The command `draw_graph` accepts one or two arguments, the mandatory first one being a graph $G(V, E)$. This command assigns 2D or 3D coordinates to each vertex $v \in V$ and produces a visual representation of G based on these coordinates. The second (optional) argument is a sequence of options. Each option is one of the following:

- `labels=true` or `false`: controls the visibility of vertex labels and edge weights (by default `true`, i.e. the labels and weights are displayed)
- `spring`: draw the graph G using a multilevel force-directed algorithm
- `tree[=r` or `[r1,r2,...]]`: draw the tree or forest G, optionally specifying root nodes for each tree
- `bipartite`: draw the bipartite graph G keeping the vertex partitions separated
- `circle[=L]`: draw the graph G by setting the *hull vertices* from list $L \subset V$ (assuming $L = V$ by default) on the unit circle and all other vertices in origin, subsequently applying a force-directed vertex placement algorithm to generate the layout while keeping the hull vertices fixed
- `planar` or `plane`: draw the planar graph G using TUTTE's barycentric method
- `plot3d`: draw the connected graph G as if the `spring` option was enabled, but with vertex positions in 3D instead of 2D
- any unassigned identifier P: when given, the vertex coordinates will be stored to it in form of a list

The style options `spring`, `tree`, `circle`, `planar` and `plot3d` cannot be mixed, i.e. at most one can be specified. The option `labels` may be combined with any of the style options. Note that edge weights will not be displayed when using `plot3d` option when drawing a weighted graph.

When no style option is specified, the algorithm first checks if the graph G is bipartite or a tree, in which case it is drawn accordingly. Else the graph is drawn as if the option `circle` was specified.

Tree, circle and bipartite drawings can be obtained in linear time with a very small overhead, allowing graphs to be drawn quickly no matter the size. The force-directed algorithms are more expensive and operating in the time which is quadratic in the number of vertices. Their performance is, nevertheless, practically instantaneous for graphs with several hundreds of vertices (or less).

7.2 Storing custom vertex positions

7.3 Highlighting parts of a graph

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