

# Graph theory package for Giac/Xcas

## Reference manual

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# Table of contents

<b>Introduction</b>	11
<b>1 Constructing graphs</b>	13
1.1 General graphs	13
1.1.1 Undirected graphs	13
1.1.2 Directed graphs	15
1.1.3 Examples	15
Creating vertices	15
Creating edges and arcs	16
Creating paths and trails	16
Specifying adjacency or weight matrix	17
Creating special graphs	17
1.2 Cycle and path graphs	18
1.2.1 Cycle graphs	18
1.2.2 Path graphs	18
1.2.3 Trails of edges	19
1.3 Complete graphs	19
1.3.1 Complete (multipartite) graphs	19
1.3.2 Complete trees	20
1.4 Sequence graphs	21
1.4.1 Creating graphs from degree sequences	21
1.4.2 Validating graphic sequences	21
1.5 Intersection graphs	22
1.5.1 Interval graphs	22
1.5.2 Kneser graphs	22
1.5.3 Johnson graphs	23
1.6 Special graphs	24
1.6.1 Hypercube graphs	24
1.6.2 Star graphs	24
1.6.3 Wheel graphs	25
1.6.4 Web graphs	25
1.6.5 Prism graphs	25
1.6.6 Antiprism graphs	26
1.6.7 Grid graphs	26
1.6.8 Sierpiński graphs	28
1.6.9 Generalized Petersen graphs	28
1.6.10 Snark graphs	29
1.6.11 Paley graphs	30
1.6.12 Haar graphs	31
1.6.13 LCF graphs	32
1.7 Isomorphic copies of graphs	33
1.7.1 Creating isomorphic copies from permutations	33
1.7.2 Permuting vertices	34
1.7.3 Relabeling vertices	35
1.8 Subgraphs	35
1.8.1 Extracting subgraphs	35
1.8.2 Induced subgraphs	36

1.8.3	Underlying graphs	36
1.8.4	Fundamental cycles	36
1.8.5	Finding cycles in digraphs	39
1.9	Operations on graphs	39
1.9.1	Graph complement	39
1.9.2	Graph switching	40
1.9.3	Transposing graphs	41
1.9.4	Union of graphs	41
1.9.5	Disjoint union of graphs	42
1.9.6	Joining two graphs	42
1.9.7	Power graphs	42
1.9.8	Graph products	43
1.9.9	Transitive closure graph	45
1.9.10	Line graph	45
1.9.11	Plane dual graph	46
1.9.12	Truncating planar graphs	47
1.10	Random graphs	49
1.10.1	Random general graphs	49
1.10.2	Random bipartite graphs	52
1.10.3	Random trees	53
1.10.4	Random planar graphs	55
1.10.5	Random graphs from a given degree sequence	57
1.10.6	Random regular graphs	57
1.10.7	Random tournaments	58
1.10.8	Random network graphs	58
1.10.9	Randomizing edge weights	60
<b>2</b>	<b>Modifying graphs</b>	<b>61</b>
2.1	Promoting to directed and weighted graphs	61
2.1.1	Converting edges to arcs	61
2.1.2	Assigning weight matrix to unweighted graphs	61
2.2	Modifying vertices of a graph	62
2.2.1	Adding and removing vertices	62
2.2.2	Contracting subgraphs	63
2.3	Modifying edges of a graph	64
2.3.1	Adding and removing edges	64
2.3.2	Accessing and modifying edge weights	65
2.3.3	Contracting edges	65
2.3.4	Subdividing edges	66
2.4	Using attributes	67
2.4.1	Graph attributes	67
2.4.2	Vertex attributes	68
2.4.3	Edge attributes	69
<b>3</b>	<b>Import and export</b>	<b>71</b>
3.1	Importing graphs	71
3.1.1	Loading graphs from DOT and LST files	71
3.1.2	The DOT file format specification	72
3.1.3	The lst file format specification	73
3.2	Exporting graphs	73
<b>4</b>	<b>Graph properties</b>	<b>77</b>
4.1	Basic properties	77
4.1.1	Determining the type of a graph	77
4.1.2	Listing vertices and edges	77

4.1.3	Equality of graphs	78
4.1.4	Vertex degrees	79
4.1.5	Regular graphs	80
4.1.6	Strongly regular graphs	81
4.1.7	Vertex adjacency	82
4.1.8	Tournament graphs	83
4.1.9	Bipartite graphs	84
4.1.10	Edge incidence	85
4.2	Algebraic properties	85
4.2.1	Adjacency matrix	85
4.2.2	Laplacian matrix	86
4.2.3	Incidence matrix	88
4.2.4	Weight matrix	89
4.2.5	Characteristic polynomial	89
4.2.6	Graph spectrum	90
4.2.7	Seidel spectrum	90
4.2.8	Integer graphs	91
4.3	Graph isomorphism	91
4.3.1	Isomorphic graphs	91
4.3.2	Canonical labeling	94
4.3.3	Graph automorphisms	94
4.3.4	Test for isomorphism against subgraphs	95
4.3.5	Recognizing special graphs	97
4.4	Graph polynomials	98
4.4.1	Tutte polynomial	98
4.4.2	Chromatic polynomial	100
4.4.3	Flow polynomial	101
4.4.4	Reliability polynomial	101
4.5	Connectivity	103
4.5.1	Connected, biconnected and triconnected graphs	103
4.5.2	Connected and biconnected components	104
4.5.3	Vertex connectivity	106
4.5.4	Graph rank	106
4.5.5	Articulation points	106
4.5.6	Strongly connected components	107
4.5.7	Edge connectivity	108
4.5.8	Edge cuts	108
4.5.9	Two-edge-connected graphs	109
4.6	Trees	110
4.6.1	Tree graphs	110
4.6.2	Forest graphs	111
4.6.3	Height of a tree	111
4.6.4	Prüfer sequences	112
4.6.5	Lowest common ancestor of a pair of nodes	113
4.6.6	Arborescence graphs	114
4.7	Networks	114
4.7.1	Network graphs	114
4.7.2	Maximum flow	115
4.7.3	Minimum cut	117
4.8	Distance in graphs	118
4.8.1	Vertex distance	118
4.8.2	All-pairs vertex distance	118
4.8.3	Diameter	120
4.8.4	Girth	120
4.9	Acyclic graphs	121
4.9.1	Acyclic graphs	121

4.9.2	Topological sorting	121
4.9.3	st ordering	122
4.9.4	Graph condensation	123
4.10	Matching in graphs	124
4.10.1	Maximum matching	124
4.10.2	Maximum matching in bipartite graphs	125
4.11	Vertex covers	127
4.11.1	Finding a vertex cover of the specified size	127
4.11.2	Minimum vertex cover	128
4.12	Cliques and independent sets	129
4.12.1	Clique graphs	129
4.12.2	Finding maximal cliques	130
4.12.3	Maximum clique	131
4.12.4	Maximum independent set	132
4.12.5	Greedy clique finding	132
4.12.6	Minimum clique cover	134
4.12.7	Clique cover number	134
4.12.8	Split graphs	135
4.12.9	Simplicial vertices	135
4.13	Network analysis	136
4.13.1	Counting triangles	136
4.13.2	Clustering coefficient	138
4.13.3	Network transitivity	139
4.13.4	Centrality measures	140
4.14	Graph coloring	142
4.14.1	Greedy vertex coloring	143
4.14.2	Minimal vertex coloring	143
4.14.3	Chromatic number	144
4.14.4	Mycielski graphs	145
4.14.5	$k$ -coloring	146
4.14.6	Minimal edge coloring	146
4.14.7	Chromatic index	147
<b>5</b>	<b>Traversing graphs</b>	<b>149</b>
5.1	Walks and tours	149
5.1.1	Eulerian graphs	149
5.1.2	Hamiltonian graphs	150
5.2	Optimal routing	152
5.2.1	Shortest unweighted paths	152
5.2.2	Cheapest weighted paths	152
5.2.3	$k$ -shortest paths	154
5.2.4	Traveling salesman problem	154
5.3	Spanning trees	157
5.3.1	Construction of spanning trees	157
5.3.2	Minimal spanning tree	158
5.3.3	Counting the spanning trees in a graph	159
5.3.4	Vertex reachability	159
<b>6</b>	<b>Visualizing graphs</b>	<b>161</b>
6.1	Drawing graphs	161
6.1.1	Overview	161
6.1.2	Spring method	162
6.1.3	Drawing trees	164
6.1.4	Drawing planar graphs	165
6.1.5	Circular graph drawings	166
6.1.6	Drawing disconnected graphs	167



6.1.7	Setting layout position, size, and title . . . . .	168
6.2	Vertex positions . . . . .	169
6.2.1	Setting vertex positions . . . . .	169
6.2.2	Generating vertex positions . . . . .	170
6.2.3	Custom layout example: spectral graph drawing . . . . .	170
6.3	Highlighting parts of graphs . . . . .	173
6.3.1	Highlighting vertices . . . . .	173
6.3.2	Highlighting edges and trails . . . . .	173
6.3.3	Highlighting subgraphs . . . . .	175
<b>Bibliography . . . . .</b>		<b>177</b>
<b>Command Index . . . . .</b>		<b>181</b>



# Introduction

This document<sup>1</sup> contains an overview of the library of graph theory commands built in GIAC computation kernel and supported within the XCAS GUI. For each command, the calling syntax is presented along with a more detailed description of its functionality and followed by examples.

Angular brackets “ $\langle$ ” and “ $\rangle$ ” in the calling syntax indicate that the enclosed portion may be omitted. The vertical bar “ $|$ ” stands for *or*. Data types are enclosed by “ $\langle$ ” and “ $\rangle$ ”, such as  $\langle\text{real}\rangle$  or  $\langle\text{string}\rangle$ .

Although the development focus was on simplicity, the implemented algorithms are reasonably fast. Some difficult tasks, such as traveling salesman problem, optimal graph colorings, minimum vertex covers, and graph isomorphism, rely on optional third party libraries, precisely the GNU Linear Programming Kit (GLPK) and NAUTY.

---

1. This manual was written in GNU  $\text{\TeX}_{\text{MACS}}$ , a scientific document editing platform. All examples were entered as interactive GIAC sessions.



# Chapter 1

## Constructing graphs

### 1.1 General graphs

The commands `graph` and `digraph` are used for constructing general [graphs](#).

#### 1.1.1 Undirected graphs

```
graph(n|V, <opts>)
graph(V,E, <opts>)
graph(E, <opts>)
graph(V,T, <opts>)
graph(T, <opts>)
graph(V,T1,T2,T3,...,Tk, <opts>)
graph(T1,T2,T3,...,Tk, <opts>)
graph(A, <opts>)
graph(V,E,A, <opts>)
graph(V,P, <opts>)
graph(str)
```

Undirected graphs are created by using the command `graph`. It takes between one and three main arguments and returns an undirected graph  $G(V, E)$ . Throughout this manual, an edge  $e \in E$  with endpoints  $u, v \in V$  is denoted by  $e = uv$  or  $e = \{u, v\}$ . The order of the endpoints does not matter when  $G$  is undirected; hence  $uv = vu$ .

The following arguments may be passed to the `graph` command.

- number  $n$  or list of vertices  $V$  (a vertex may be any atomic object, such as an integer, a symbol or a string); it must be the first argument if used
- set of edges  $E$  (each edge is represented by the list of its endpoints), a permutation, a trail of edges or a sequence of trails; it can be either the first or the second argument if used
- trail  $T = \text{trail}(u, v, \dots)$  or a sequence of trails  $T_1, T_2, \dots, T_k$
- permutation  $P$  of vertices
- adjacency or weight matrix  $A$
- a string `str` representing a special graph

The following optional arguments may be appended as `opts`.

- `directed=true|false` — set the graph to be (un)directed.
- `weighted=true|false` — set the graph to be (un)weighted.
- `color=<int>|<list>` — set the color(s) of the vertices. If a single integer is given, it is used as the color for all vertices. If a list is given, it should represent colors for all vertices in the order as returned by `vertices`.
- `coordinates=<list>` — set 2D or 3D coordinates of the vertices.

Special graphs supported in GIAC are listed below.

special graph	GIAC name
Balaban 10-cage	balaban10
Balaban 11-cage	balaban11
Barnette-Bosák-Lederberg graph	barnette-bosak-lederberg
Bidiakis cube	bidiakis
Biggs-Smith graph	biggs-smith
2 <sup>nd</sup> Blanuša snark	blanusa
Brinkmann graph	brinkmann
Brouwer-Haemers graph	brouwer-haemers
Bull graph	bull
Butterfly graph	butterfly
Clebsch graph	clebsch
Chvátal graph	chvatal
Coxeter graph	coxeter
Desargues graph	desargues
Diamond graph	diamond
Dodecahedral graph	dodecahedron
Double star snark	double-star
Doyle graph	doyle
Dürer graph	duerer
Dyck graph	dyck
Errera graph	errera
F26A graph	f26a
Folkman graph	folkman
Foster graph	foster
Franklin graph	franklin
Frucht graph	frucht
Gewirtz graph	gewirtz
Goldner-Harary graph	goldner-harary
Golomb graph	golomb
Gosset graph	gosset
Gray graph	gray
Grinberg graph	grinberg
Grötzsch graph	groetzsch
Harborth graph	harborth
Harries graph	harries
Harries-Wong graph	harries-wong
Heawood graph	heawood
Herschel graph	herschel
Higman-Sims graph	higman-sims
Hoffman graph	hoffman
Hoffman-Singleton graph	hoffman-singleton
Icosahedral graph	icosahedron
Kittell graph	kittell
Krackhardt kite graph	krackhardt
Levi graph (Tutte 8-cage)	levi
Ljubljana graph	ljubljana
Markström graph	markstroem

McGee graph	mcgee
Meredith graph	meredith
Meringer graph	meringer
Moser spindle	moser
Möbius–Kantor graph	moebius-kantor
Nauru graph	nauru
Octahedral graph	octahedron
Pappus graph	pappus
Petersen graph	petersen
Perkel graph	perkel
Poussin graph	poussin
Robertson graph	robertson
Robertson-Wegner graph	robertson-wegner
Shrikhande graph	shrikhande
Schläfli graph	schlaefli
Sousselier graph	sousselier
Sylvester graph	sylvester
Szerekes snark	szerekes
Tetrahedral graph	tehtrahedron
Tietze graph	tietze
Truncated icosahedral graph	soccerball
Tutte graph	tutte
Tutte 12-cage	tutte12
Wagner graph	wagner
Walther graph	walther
Watkins snark	watkins
Wells graph	wells
Wiener-Araya graph	wiener-araya
Wong graph	wong

---

### 1.1.2 Directed graphs

The `digraph` command is used for creating [directed graphs](#), although it is also possible with the `graph` command by specifying the option `directed=true`. The calling syntax for `digraph` is the same as for `graph` with the above option appended to the sequence of arguments. However, creating special graphs is not supported by `digraph` since these are all undirected.

Edges in directed graphs are called **arcs**. Note that in a directed graph edges  $uv$  and  $vu$  are treated as distinct arcs, also denoted as  $(u, v)$  and  $(v, u)$ .

### 1.1.3 Examples

**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

The commands that return graphs often need to generate vertex labels. In these cases ordinal integers are used, which are 0-based in `xcas` mode and 1-based in `maple` mode. Examples throughout this manual are made by using the default, `xcas` mode.

**Creating 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]})
```

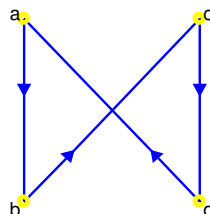
an undirected unweighted graph with 4 vertices and 3 edges

**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 cycle with the vertices ordered according to the permutation.

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

a directed unweighted graph with 4 vertices and 4 arcs

```
> draw_graph(G)
```



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.

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

an undirected unweighted graph with 4 vertices and 4 edges

```
> edges(G)
```

```
[[a,c],[a,d],[b,c],[c,d]]
```

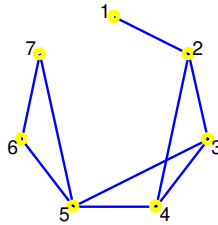
It is possible to specify several trails in a sequence, which is useful when designing more complex graphs.



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

an undirected unweighted graph with 7 vertices and 9 edges

```
> draw_graph(G)
```



**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 if and only if  $a_{ij} \neq 0$ . If the matrix is symmetric, the resulting graph will be undirected, otherwise it will be directed.

```
> G:=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

```
> edges(G)
```

```
[[0, 1], [0, 2], [1, 3]]
```

```
> G:=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

```
> edges(G,weights)
```

```
[[[0, 1], 1.0], [[0, 2], 2.3], [[1, 0], 4], [[1, 3], 3.1]]
```

A list of vertex labels can be specified alongside a 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 from  $i$ -th to  $j$ -th vertex, the element  $a_{ij}$  of  $A$  is assigned as its weight. The remaining elements of  $A$  are ignored.

```
> G:=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

```
> edges(G,weights)
```

```
[[[a, b], 1], [[a, c], 2], [[b, c], 4]]
```

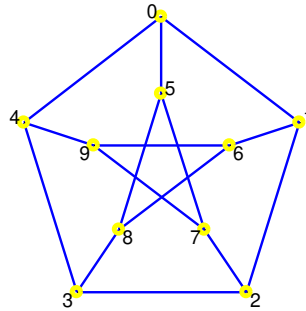
**Creating special graphs** When a special graph is desired, one just needs to pass its name to the `graph` command. An undirected unweighted graph will be returned.

```
> P:=graph("petersen")
```

an undirected unweighted graph with 10 vertices and 15 edges

Some special graphs are constructed together with the corresponding layouts. These are displayed when the graphs are drawn using the default settings.

```
> draw_graph(P)
```



## 1.2 Cycle and path graphs

### 1.2.1 Cycle graphs

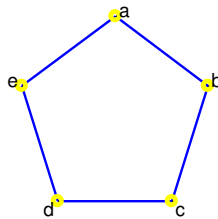
```
cycle_graph(n|V)
```

The command `cycle_graph` is used for constructing [cycle graphs](#) [34, p. 4]. It takes a positive integer  $n$  or a list of vertices  $V$  (without repetitions) as its only argument and returns the graph consisting of a single cycle  $C_{|V|}$  on the specified vertices in the given order. If  $n$  is specified, then  $C_n$  is returned.

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

an undirected unweighted graph with 5 vertices and 5 edges

```
> draw_graph(G)
```



### 1.2.2 Path graphs

```
path_graph(n|V)
```

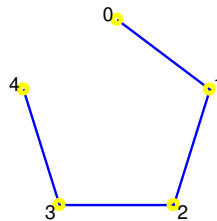
The command `path_graph` is used for constructing [path graphs](#) [34, pp. 4]. It takes a positive integer  $n$  or a list of distinct vertices  $V$  as its only argument and returns a graph consisting of a single path on the specified vertices in the given order. If  $n$  is specified, then a path graph on  $n$  vertices is returned.

Note that a path, by definition, is a walk with no repeated vertices. Walks with no repeated edges but possibly repeated vertices are called **trails** (see the command `trail`).

```
> P:=path_graph(5)
```

an undirected unweighted graph with 5 vertices and 4 edges

```
> draw_graph(P,circle)
```



### 1.2.3 Trails of edges

```
trail(v1,v2,...,vn)
trail2edges(T)
```

If the dummy command `trail` is called with a sequence of vertices  $v_1, v_2, \dots, v_n$  as arguments, it returns the symbolic expression representing the `trail` which visits the specified vertices in the given order. The resulting symbolic object is recognizable by some commands, for example `graph` and `digraph`.

Note that a trail, by definition, is a walk with no repeated edges. Hence some vertices in the sequence  $v_1, v_2, \dots, v_k$  may be repeated, but the sets  $\{v_i, v_{i+1}\}$  in undirected graphs resp. the pairs  $(v_i, v_{i+1})$  in digraphs must be mutually distinct for  $i = 1, 2, \dots, n - 1$ , since they represent edges resp. arcs.

Any trail  $T$  is easily converted to the corresponding list of edges by calling the `trail2edges` command, which takes the trail as its only argument.

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

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

```
> trail2edges(T)
```

```
[[1, 2], [2, 3], [3, 4], [4, 2]]
```

## 1.3 Complete graphs

### 1.3.1 Complete (multipartite) graphs

```
complete_graph(n|V)
complete_graph(n1,n2,...,nk)
```

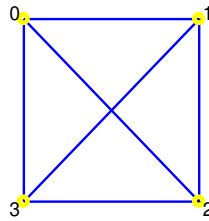
The command `complete_graph` is used for constructing `complete` (`multipartite`) graphs. It can be called with a single argument, a positive integer  $n$  or a list of distinct vertices  $V$ , in which case it returns the complete graph  $K_{|V|}$  [34, pp. 2] on the specified vertices. If integer  $n$  is specified, then  $K_n$  is returned.

If `complete_graph` is given a sequence of positive integers  $n_1, n_2, \dots, n_k$  as its argument, it returns a complete multipartite graph  $K_{n_1 n_2 \dots n_k}$  with partitions of size  $n_1, n_2, \dots, n_k$ .

```
> K4:=complete_graph(4)
```

an undirected unweighted graph with 4 vertices and 6 edges

```
> draw_graph(K4)
```



```
> K3:=complete_graph([a,b,c])
```

an undirected unweighted graph with 3 vertices and 3 edges

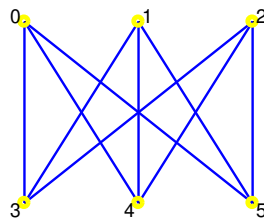
```
> edges(K3)
```

```
[[a,b],[a,c],[b,c]]
```

```
> K33:=complete_graph(3,3)
```

an undirected unweighted graph with 6 vertices and 9 edges

```
> draw_graph(K33)
```



### 1.3.2 Complete trees

```
complete_binary_tree(n)
```

```
complete_kary_tree(k,n)
```

The commands `complete_binary_tree` and `complete_kary_tree` are used for construction of complete [binary trees](#) and complete [k-ary trees](#), respectively.

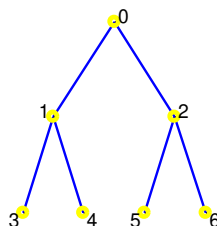
`complete_binary_tree` takes a positive integer  $n$  as its only argument and returns a complete binary tree with depth  $n$  on  $2^{n+1} - 1$  vertices. The lowest-indexed vertex is the root of the tree.

`complete_kary_tree` takes positive integers  $k$  and  $n$  as its arguments and returns the complete  $k$ -ary tree on  $\frac{k^{n+1} - 1}{k - 1}$  vertices with depth  $n$ . The vertex with smallest number is the root of the tree. The command `complete_kary_tree(2,n)` is equivalent to `complete_binary_tree(n)`.

```
> T1:=complete_binary_tree(2)
```

an undirected unweighted graph with 7 vertices and 6 edges

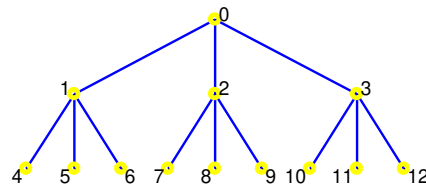
```
> draw_graph(T1)
```



```
> T2:=complete_kary_tree(3,2)
```

an undirected unweighted graph with 13 vertices and 12 edges

```
> draw_graph(T2)
```



## 1.4 Sequence graphs

### 1.4.1 Creating graphs from degree sequences

`sequence_graph(L)`

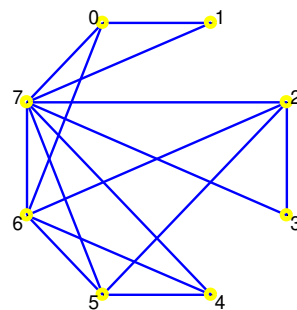
The command `sequence_graph` is used for constructing graphs from [degree sequences](#). It takes a list  $L$  of positive integers as its only argument and, if  $L$  represents a graphic sequence, the corresponding undirected graph  $G$  with  $|L|$  vertices is returned. If the argument is not a graphic sequence, an error is returned.

Sequence graphs are constructed in  $O(|L|^2 \log |L|)$  time by applying the algorithm of HAVEL and HAKIMI [38].

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

an undirected unweighted graph with 8 vertices and 15 edges

```
> draw_graph(G,circle)
```



```
> degree_sequence(G)
```

```
[3, 2, 4, 2, 3, 4, 5, 7]
```

### 1.4.2 Validating graphic sequences

`is_graphic_sequence(L)`

The command `is_graphic_sequence` is used for determining whether a list of integers represents the degree sequence of some graph. It takes 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  $L$  and `false` otherwise. The algorithm, which has the complexity  $O(|L|^2)$ , is based on the [theorem](#) of ERDŐS and GALLAI.

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

```
true
```

## 1.5 Intersection graphs

### 1.5.1 Interval graphs

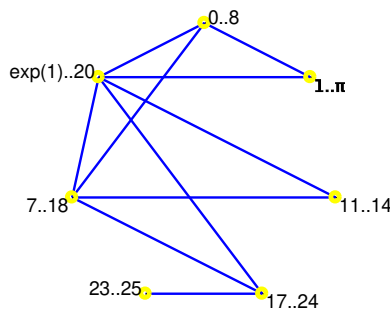
`interval_graph(L)`

The command `interval_graph` is used for construction of [interval graphs](#). It takes a sequence or list  $L$  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.

```
> G:=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

```
> draw_graph(G)
```



### 1.5.2 Kneser graphs

`kneser_graph(n,k)`

`odd_graph(d)`

Commands `kneser_graph` and `odd_graph` are used for generating [Kneser graphs](#) and [odd graphs](#), respectively.

`kneser_graph` takes two positive integers  $2 \leq n \leq 20$  and  $k < n$  as its arguments and returns the Kneser graph  $K(n, k)$  with  $\binom{n}{k}$   $k$ -subsets of the set  $\{1, 2, \dots, n\}$  as vertices. Two vertices are connected if and only if their associated subsets are disjoint. Each vertex is labeled by the list of elements in the corresponding subset.

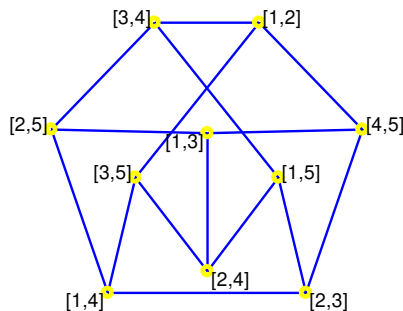
`odd_graph` takes an integer  $2 \leq d \leq 10$  and returns  $d$ -th odd graph  $O_d = K(2d - 1, d - 1)$ .

Kneser graphs quickly get exceedingly large, hence  $n$  is restricted as above.

```
> K:=kneser_graph(5,2)
```

an undirected unweighted graph with 10 vertices and 15 edges

```
> draw_graph(K, spring)
```



```
> G:=kneser_graph(12,5)
```

an undirected unweighted graph with 792 vertices and 8316 edges

```
> odd_graph(8)
```

an undirected unweighted graph with 6435 vertices and 25740 edges

1.204 sec

### 1.5.3 Johnson graphs

`johnson_graph(n,k)`

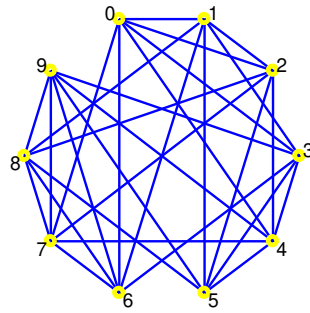
The command `johnson_graph` is used for generating [Johnson graphs](#). It takes two positive integers  $2 \leq n \leq 20$  and  $k < n$  as its arguments and returns the Johnson graph  $J(n, k)$  with  $\binom{n}{k}$   $k$ -subsets of a set of  $n$  elements as vertices. Two vertices are connected if and only if their associated subsets have exactly  $k - 1$  elements in common.

Johnson graphs quickly get exceedingly large, hence  $n$  is restricted as above.

```
> J52:=johnson_graph(5,2)
```

an undirected unweighted graph with 10 vertices and 30 edges

```
> draw_graph(J52)
```



```
> chromatic_number(J52)
```

5

$J(n, 2)$  is isomorphic to the Kneser graph  $K(n, 2)$ .

```
> is_isomorphic(J52, graph_complement(kneser_graph(5,2)))
```

true

$J(n, k)$  is isomorphic to  $J(n, n - k)$ .

```
> is_isomorphic(J52, johnson_graph(5,3))
```

true

The clique number of  $J(n, k)$  is equal to  $1 - \frac{\lambda_{\max}}{\lambda_{\min}}$ , where  $\lambda_{\min}$  and  $\lambda_{\max}$  are its least and greatest eigenvalue. The list of eigenvalues can be obtained by the command [graph\\_spectrum](#).

```
> sp:=graph_spectrum(J52)
```

$$\begin{pmatrix} -2 & 5 \\ 1 & 4 \\ 6 & 1 \end{pmatrix}$$

```
> ev:=tran(sp)[0]
```

$$[-2, 1, 6]$$

```
> clique_number(J52) == 1-max(ev)/min(ev)
```

```
true
```

## 1.6 Special graphs

### 1.6.1 Hypercube graphs

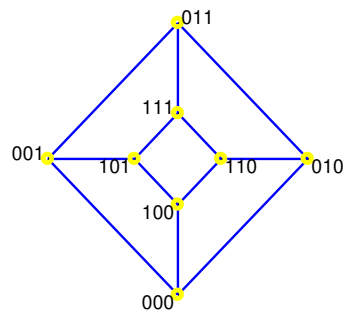
`hypercube_graph(n)`

The command `hypercube_graph` is used for constructing [hypercube graphs](#). It takes a positive integer  $n$  as its only argument and returns the hypercube graph of dimension  $n$  on  $2^n$  vertices. The vertex labels are strings of binary digits of length  $n$ . Two vertices are joined by an edge if and only if their labels differ in exactly one character.

```
> H:=hypercube_graph(3)
```

an undirected unweighted graph with 8 vertices and 12 edges

```
> draw_graph(H,planar)
```



### 1.6.2 Star graphs

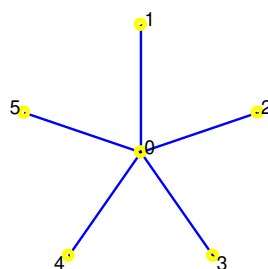
`star_graph(n)`

The command `star_graph` is used for constructing [star graphs](#). It takes 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.

```
> G:=star_graph(5)
```

an undirected unweighted graph with 6 vertices and 5 edges

```
> draw_graph(G)
```





### 1.6.3 Wheel graphs

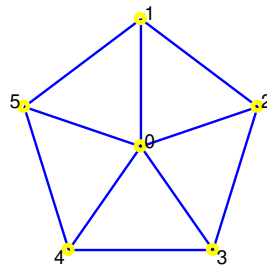
`wheel_graph(n)`

The command `wheel_graph` is used for constructing [wheel graphs](#). It takes a positive integer  $n$  as its only argument and returns the wheel graph with  $n + 1$  vertices.

```
> G:=wheel_graph(5)
```

an undirected unweighted graph with 6 vertices and 10 edges

```
> draw_graph(G)
```



### 1.6.4 Web graphs

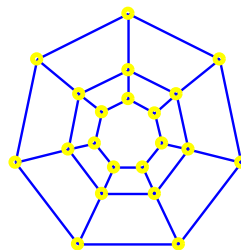
`web_graph(a,b)`

The command `web_graph` is used for constructing web graphs. It takes two positive integers  $a$  and  $b$  as its arguments and returns the Cartesian product of `cycle_graph(a)` and `path_graph(b)`.

```
> G:=web_graph(7,3)
```

an undirected unweighted graph with 21 vertices and 35 edges

```
> draw_graph(G,labels=false)
```



### 1.6.5 Prism graphs

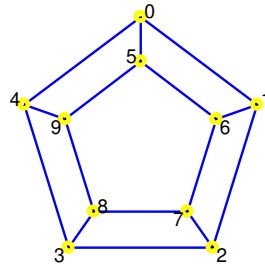
`prism_graph(n)`

The command `prism_graph` is used for constructing [prism graphs](#). It takes a positive integer  $n$  as its only argument and returns the prism graph with parameter  $n$ , namely `petersen_graph(n,1)`.

```
> G:=prism_graph(5)
```

an undirected unweighted graph with 10 vertices and 15 edges

```
> draw_graph(G)
```



### 1.6.6 Antiprism graphs

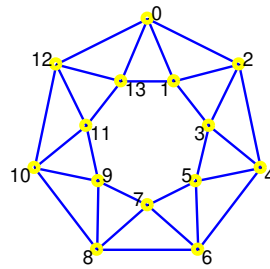
`antiprism_graph(n)`

The command `antiprism_graph` is used for constructing [antiprism graphs](#). It takes 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.

```
> G:=antiprism_graph(7)
```

an undirected unweighted graph with 14 vertices and 28 edges

```
> draw_graph(G)
```



### 1.6.7 Grid graphs

`grid_graph(m,n,<triangle>)`

`torus_grid_graph(m,n)`

The command `grid_graph` resp. `torus_grid_graph` is used for constructing rectangular/triangular resp. torus [grid graphs](#).

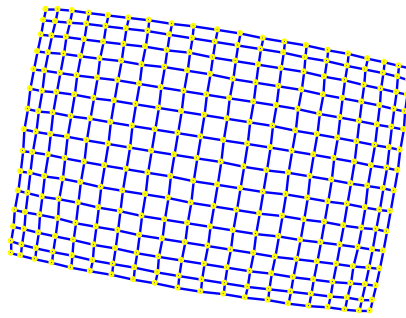
`grid_graph` takes two positive integers  $m$  and  $n$  as its arguments and returns the  $m$  by  $n$  grid on  $mn$  vertices, namely the Cartesian product of `path_graph(m)` and `path_graph(n)`. If the option `triangle` is passed as the third argument, the returned graph is a triangular grid on  $mn$  vertices defined as the underlying graph of the [strong product](#) of two directed path graphs with  $m$  and  $n$  vertices, respectively [2, Definition 2, p. 189]. Strong product is defined as the [union](#) of Cartesian and tensor [products](#).

`torus_grid_graph` takes two positive integers  $m$  and  $n$  as its arguments and returns the  $m$  by  $n$  torus grid on  $mn$  vertices, namely the Cartesian product of `cycle_graph(m)` and `cycle_graph(n)`.

```
> G:=grid_graph(15,20)
```

an undirected unweighted graph with 300 vertices and 565 edges

```
> draw_graph(G, spring)
```



In the following example, the Möbius strip is constructed by connecting the vertices in the opposite sides of a narrow grid graph.

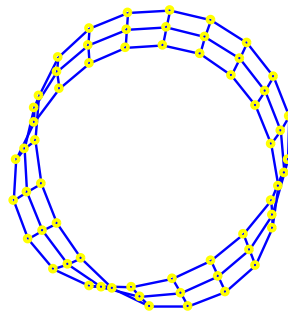
```
> G:=grid_graph(20,3)
```

an undirected unweighted graph with 60 vertices and 97 edges

```
> G:=add_edge(G,["0:0","19:2"],["0:1","19:1"],["0:2","19:0"])
```

an undirected unweighted graph with 60 vertices and 100 edges

```
> draw_graph(G,spring,labels=false)
```

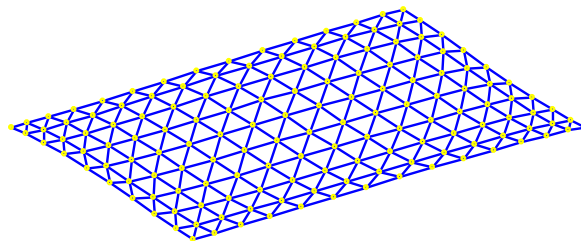


A triangular grid is created by passing the option `triangle`.

```
> G:=grid_graph(10,15,triangle)
```

an undirected unweighted graph with 150 vertices and 401 edges

```
> draw_graph(G,spring)
```

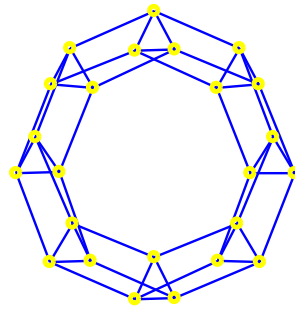


The following example demonstrates creating a torus grid graph with eight triangular levels.

```
> G:=torus_grid_graph(8,3)
```

an undirected unweighted graph with 24 vertices and 48 edges

```
> draw_graph(G,spring,labels=false)
```



### 1.6.8 Sierpiński graphs

`sierpinski_graph(n,k,<triangle>)`

The command `sierpinski_graph` is used for constructing Sierpiński-type graphs  $S_k^n$  and  $ST_k^n$  [42]. It takes two positive integers  $n$  and  $k$  as its arguments and optionally the option `triangle` as the third argument. It 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  $S_k^n$ . To detect such edges the command `find_cliques` is used, which can be time consuming for  $n > 6$ .

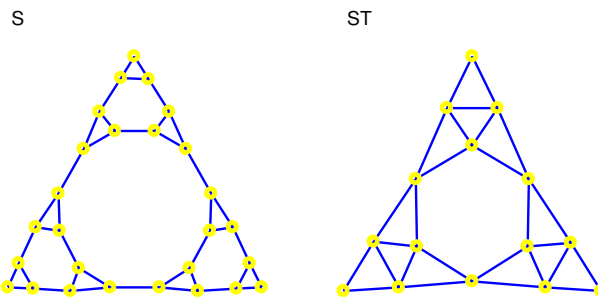
```
> S:=sierpinski_graph(3,3)
```

an undirected unweighted graph with 27 vertices and 39 edges

```
> ST:=sierpinski_graph(3,3,triangle)
```

an undirected unweighted graph with 15 vertices and 27 edges

```
> draw_graph(S,spring,labels=false,[0,0],size=[0,1],title="S");
draw_graph(ST,spring,labels=false,[1.5,0],size=[0,1],title="ST");
```



### 1.6.9 Generalized Petersen graphs

`petersen_graph(n,<k>)`

The command `petersen_graph` is used for constructing [generalized Petersen graphs](#). It takes two positive integers  $n$  and  $k$  as its arguments. The second argument may be omitted, in which case  $k = 2$  is assumed. The return value is the graph  $P(n, k)$ , which 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.

The famous Petersen graph is equal to the generalized Petersen graph  $P(5, 2)$ . It can also be constructed by calling `graph("petersen")`.

To obtain the dodecahedral graph  $P(10, 2)$ , input:

```
> G:=petersen_graph(10)
```

an undirected unweighted graph with 20 vertices and 30 edges

```
> is_isomorphic(G,graph("dodecahedron"))
```

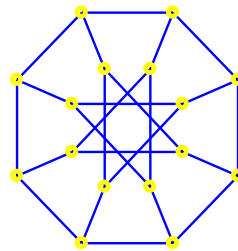
true

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

```
> G:=petersen_graph(8,3)
```

an undirected unweighted graph with 16 vertices and 24 edges

```
> draw_graph(G,labels=false)
```



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

### 1.6.10 Snark graphs

```
flower_snark(n)
```

```
goldberg_snark(n)
```

Commands `flower_snark` and `goldberg_snark` are used for generating *flower snarks* and *Goldberg snarks* [32]. Both commands take an odd integer  $n \geq 3$  as their only argument and return the flower snark  $J_n$  resp. the Goldberg snark on  $8n$  vertices.

```
> J3:=flower_snark(3)
```

an undirected unweighted graph with 12 vertices and 18 edges

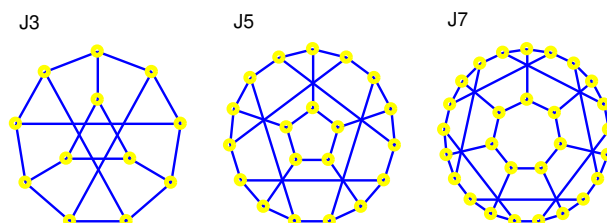
```
> J5:=flower_snark(5)
```

an undirected unweighted graph with 20 vertices and 30 edges

```
> J7:=flower_snark(7)
```

an undirected unweighted graph with 28 vertices and 42 edges

```
> draw_graph(J3,[0,0],size=[1,0],title="J3",labels=false);
draw_graph(J5,[1.3,0],size=[1,0],title="J5",labels=false);
draw_graph(J7,[2.6,0],size=[1,0],title="J7",labels=false)
```



The first flower snark  $J_3$  (which, strictly speaking, is not a snark because its girth is smaller than 5) is isomorphic to Tietze graph.

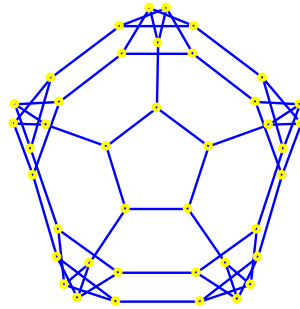
```
> is_isomorphic(J3,graph("tietze"))
```

true

```
> G:=goldberg_snark(5)
```

an undirected unweighted graph with 40 vertices and 60 edges

```
> draw_graph(G, spring, labels=false)
```



```
> chromatic_index(G) == 4
```

true

3.18 sec

```
> girth(G)
```

5

### 1.6.11 Paley graphs

`paley_graph(p,⟨k⟩)`

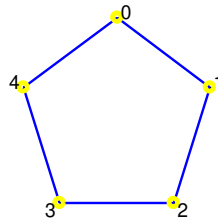
The command `paley_graph` is used for generating [Paley graphs](#). It takes a prime number  $p \geq 3$  as its mandatory argument and optionally a positive integer  $k$  which defaults to 1. It returns the Paley (di)graph  $P$  on  $p^k$  vertices which is constructed as follows.

- If  $k = 1$  and  $p \equiv 1 \pmod{4}$ , then  $P$  is an undirected graph with vertices  $0, 1, \dots, p-1$  in which the edge  $\{i, j\}$ , where  $i < j$ , is present in  $P$  if  $j - i$  is a quadratic residue in  $\mathbb{Z}_p$ .
- If  $k = 1$  and  $p \equiv 3 \pmod{4}$ , then  $P$  is a directed graph with vertices  $0, 1, \dots, p-1$  in which the arc  $(i, j)$  is present in  $P$  if  $j - i$  is a quadratic residue in  $\mathbb{Z}_p$ .
- If  $k > 1$  and  $q = p^k \equiv 1 \pmod{4}$ , then  $P$  is an undirected graph with vertices  $0, 1, \dots, q-1$  in which the edge  $\{i, j\}$ , where  $i < j$ , is present in  $P$  if  $y - x$  is a square in the finite field  $\text{GF}(q)$ , where  $x$  is the  $i$ -th element and  $y$  is the  $j$ -th element in  $\text{GF}(q)$ . If  $g$  is a generator of the corresponding multiplicative group, then the elements of  $\text{GF}(q)$  are  $0, 1, g, g^2, \dots, g^{p^k-2}$ .
- If  $k > 1$  and  $q = p^k \equiv 3 \pmod{4}$ , then  $P$  is a directed graph with vertices  $0, 1, \dots, q-1$  in which the arc  $(i, j)$  is present in  $P$  if  $y - x$  is a square in the finite field  $\text{GF}(q)$ , where  $x$  is the  $i$ -th element and  $y$  is the  $j$ -th element in  $\text{GF}(q)$ . If  $g$  is a generator of the corresponding multiplicative group, then the elements of  $\text{GF}(q)$  are  $0, 1, g, g^2, \dots, g^{p^k-2}$ .

```
> P1:=paley_graph(5)
```

an undirected unweighted graph with 5 vertices and 5 edges

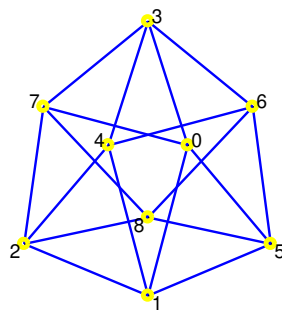
```
> draw_graph(P1)
```



```
> P2:=paley_graph(3,2)
```

an undirected unweighted graph with 9 vertices and 18 edges

```
> draw_graph(P2, spring)
```



Paley graphs are self-complementary.

```
> is_isomorphic(P2, graph_complement(P2))
```

true

```
> P3:=paley_graph(3,3)
```

a directed unweighted graph with 27 vertices and 351 arcs

Paley (di)graphs are strongly regular.

```
> is_strongly_regular(P3)
```

true

Every Paley digraph is a tournament.

```
> is_tournament(P3)
```

true

### 1.6.12 Haar graphs

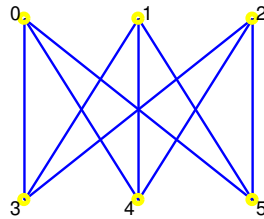
`haar_graph(n)`

The command `haar_graph` is used for generating Haar graphs [43]. It takes a positive integer  $n$  as its only argument and returns the Haar graph with index  $n$ , which is a regular bipartite graph on  $2k$  vertices  $v_0, v_1, \dots, v_{2k-1}$ , where  $k = 1 + \lfloor \log_2 n \rfloor$ , with independent sets  $U = \{v_i : i = 0, 1, \dots, k-1\}$  and  $V = \{v_j : j = k, k+1, \dots, 2k-1\}$ . Two vertices  $v_i \in U$  and  $v_j \in V$  are connected if the  $m$ -th digit in the binary expansion of  $n$  is nonzero, where  $m = \text{irem}(j-i, k)$ .

```
> H1:=haar_graph(7)
```

an undirected unweighted graph with 6 vertices and 9 edges

```
> draw_graph(H1)
```



```
> H2:=haar_graph(69)
```

an undirected unweighted graph with 14 vertices and 21 edges

```
> is_isomorphic(H2,graph("heawood"))
```

true

```
> H3:=haar_graph(32786)
```

an undirected unweighted graph with 32 vertices and 48 edges

```
> is_isomorphic(H3,petersen_graph(16,7))
```

true

### 1.6.13 LCF graphs

`lcf_graph(L,⟨n⟩)`

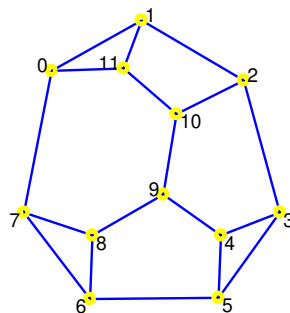
The command `lcf_graph` is used for constructing cubic Hamiltonian graphs from [LCF notation](#). It takes one or two arguments, a list  $L$  of nonzero integers, called *jumps*, and optionally a positive integer  $n$ , called the *exponent*, which defaults to 1. The command returns the graph on  $n|L|$  vertices obtained by iterating the sequence of jumps  $n$  times.

The following command creates the [Frucht graph](#).

```
> F:=lcf_graph([-5,-2,-4,2,5,-2,2,5,-2,-5,4,2])
```

an undirected unweighted graph with 12 vertices and 18 edges

```
> draw_graph(F,planar)
```



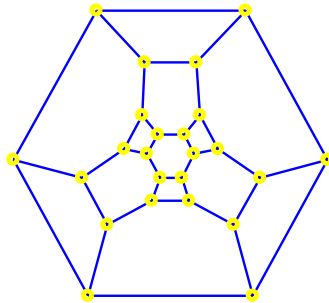
Constructing the truncated octahedral graph from its LCF notation:



```
> G:=lcf_graph([3,-7,7,-3],6)
```

an undirected unweighted graph with 24 vertices and 36 edges

```
> draw_graph(G,planar,labels=false)
```



```
> is_isomorphic(G,truncate_graph(graph("octahedron")))
true
```

## 1.7 Isomorphic copies of graphs

### 1.7.1 Creating isomorphic copies from permutations

```
isomorphic_copy(G,<sigma>)
```

The command `isomorphic_copy` is used for creating isomorphic copies of a graph without changing the order of its vertices. It takes one or two arguments, a graph  $G(V, E)$  and optionally a permutation  $\sigma$  of order  $|V|$ . It returns a new graph where the adjacency lists are reordered according to  $\sigma$  or a random permutation if the second argument is omitted. The vertex labels, as well as the order of vertices, are the same as in  $G$ . This command, however, discards all vertex and edge attributes present in  $G$ .

```
> G:=path_graph([1,2,3,4,5])
```

an undirected unweighted graph with 5 vertices and 4 edges

```
> vertices(G), neighbors(G)
```

```
[1, 2, 3, 4, 5], [[2], [1, 3], [2, 4], [3, 5], [4]]
```

```
> H:=isomorphic_copy(G)
```

an undirected unweighted graph with 5 vertices and 4 edges

```
> vertices(H), neighbors(H)
```

```
[1, 2, 3, 4, 5], [[2, 3], [1, 5], [1, 4], [3], [2]]
```

```
> H:=isomorphic_copy(G, [2,4,0,1,3])
```

an undirected unweighted graph with 5 vertices and 4 edges

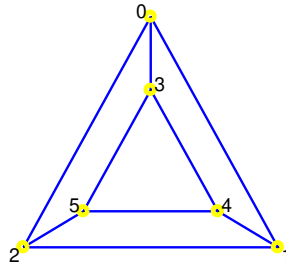
```
> vertices(H), neighbors(H)
```

$$[1, 2, 3, 4, 5], [[4, 5], [5], [4], [1, 3], [1, 2]]$$

```
> P:=prism_graph(3)
```

an undirected unweighted graph with 6 vertices and 9 edges

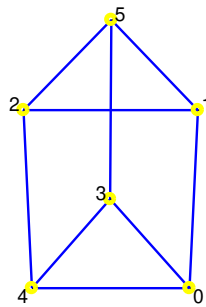
```
> draw_graph(P)
```



```
> H:=isomorphic_copy(P, [3,0,1,5,4,2])
```

an undirected unweighted graph with 6 vertices and 9 edges

```
> draw_graph(H, spring)
```



### 1.7.2 Permuting vertices

```
permute_vertices(G,L)
```

```
permute_vertices(G,⟨shuffle|randperm⟩)
```

The command `permute_vertices` is used for creating isomorphic copies of graphs by changing the order of vertices. It takes one or two arguments, a graph  $G(V, E)$  and optionally a list  $L$  of length  $|V|$  containing all vertices from  $V$ , and returns a copy of  $G$  with vertices rearranged in order they appear in  $L$ . If  $L$  is not given, as well as if `shuffle` or `randperm` are passed as the second argument, then vertices are shuffled randomly. All vertex and edge attributes are preserved in the copy, including any vertex position information. Hence the resulting graph will look the same as  $G$  when drawn.

```
> G:=path_graph([1,2,3,4,5])
```

an undirected unweighted graph with 5 vertices and 4 edges

```
> vertices(G), neighbors(G)
```

$$[1, 2, 3, 4, 5], [[2], [1, 3], [2, 4], [3, 5], [4]]$$

```
> H:=permute_vertices(G, [3,5,1,2,4])
```

an undirected unweighted graph with 5 vertices and 4 edges

```
> vertices(H), neighbors(H)
```

```
[3, 5, 1, 2, 4], [[2, 4], [4], [2], [1, 3], [3, 5]]
```

### 1.7.3 Relabeling vertices

```
relabel_vertices(G,L)
```

The command `relabel_vertices` is used for setting new labels to vertices of a graph without changing their order. It takes two arguments, a graph  $G(V, E)$  and a list  $L$  of vertex labels of length  $|V|$ . It returns a copy of  $G$  with  $L$  as the list of vertex labels.

```
> G:=path_graph([1,2,3,4])
```

an undirected unweighted graph with 4 vertices and 3 edges

```
> edges(G)
```

```
[[1, 2], [2, 3], [3, 4]]
```

```
> H:=relabel_vertices(G, [a,b,c,d])
```

an undirected unweighted graph with 4 vertices and 3 edges

```
> edges(H)
```

```
[[a, b], [b, c], [c, d]]
```

## 1.8 Subgraphs

### 1.8.1 Extracting subgraphs

```
subgraph(G,L)
```

The command `subgraph` is used for extracting subgraphs from graphs. It takes two arguments, a graph  $G(V, E)$  and a list of edges  $L$ . It returns the subgraph  $G'(V', L)$  of  $G$ , where  $V' \subset V$  is a subset of vertices of  $G$  incident to at least one edge from  $L$ .

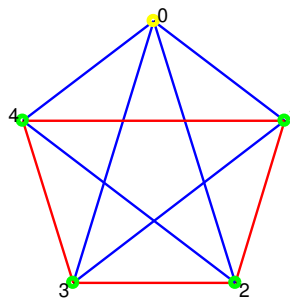
```
> K5:=complete_graph(5)
```

an undirected unweighted graph with 5 vertices and 10 edges

```
> S:=subgraph(K5, [[1,2], [2,3], [3,4], [4,1]])
```

an undirected unweighted graph with 4 vertices and 4 edges

```
> draw_graph(highlight_subgraph(K5,S))
```



### 1.8.2 Induced subgraphs

`induced_subgraph(G,L)`

The command `induced_subgraph` is used for extracting induced subgraphs from graphs. It takes two arguments, a graph  $G(V, E)$  and a list of vertices  $L$ . It returns the subgraph  $G'(L, E')$  of  $G$ , where  $E' \subset E$  contains all edges which have both endpoints in  $L$  [34, p. 3].

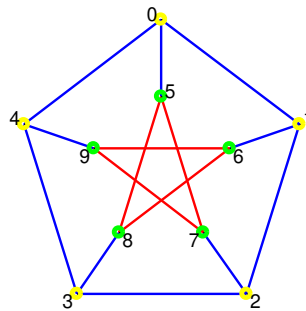
```
> G:=graph("petersen")
```

an undirected unweighted graph with 10 vertices and 15 edges

```
> S:=induced_subgraph(G, [5,6,7,8,9])
```

an undirected unweighted graph with 5 vertices and 5 edges

```
> draw_graph(highlight_subgraph(G,S))
```



### 1.8.3 Underlying graphs

`underlying_graph(G)`

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`. It takes a graph  $G(V, E)$  as its only argument and returns an undirected unweighted copy of  $G$  in which all vertex and edge attributes, together with edge directions, are discarded.

```
> G:=digraph(%{[[1,2],6],[[2,3],4],[[3,1],5],[[3,2],7]%})
```

a directed weighted graph with 3 vertices and 4 arcs

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

an undirected unweighted graph with 3 vertices and 3 edges

```
> edges(U)
```

`[[1,2],[1,3],[2,3]]`

### 1.8.4 Fundamental cycles

`fundamental_cycle(G)`

`cycle_basis(G)`

The command `fundamental_cycle` is used for extracting cycles from **unicyclic graphs** (also called 1-trees). To find a **fundamental cycle basis** of an undirected graph, use the command `cycle_basis`.

`fundamental_cycle` takes one argument, an undirected connected graph  $G(V, E)$  containing exactly one cycle (i.e. a unicyclic graph), and returns that cycle as a graph. If  $G$  is not unicyclic, an error is returned.

`cycle_basis` takes an undirected graph  $G(V, E)$  as its only argument and returns a basis  $B$  of the cycle space of  $G$  as a list of fundamental cycles in  $G$ , with each cycle represented as a list of vertices. Furthermore,  $|B| = |E| - |V| + \kappa(G)$ , where  $\kappa(G)$  is the number of connected components of  $G$ . Every cycle  $C$  in  $G$  such that  $C \notin B$  can be obtained from cycles in  $B$  using only [symmetric differences](#).

The strategy is to construct a spanning tree  $T$  of  $G$  using depth-first search and look for edges in  $E$  which do not belong to the tree. For each non-tree edge  $e$  there is a unique fundamental cycle  $C_e$  consisting of  $e$  together with the path in  $T$  connecting the endpoints of  $e$ . The vertices of  $C_e$  are easily obtained from the search data. The complexity of this algorithm is  $O(|V| + |E|)$ .

```
> G:=graph(trail(1,2,3,4,5,2,6))
```

an undirected unweighted graph with 6 vertices and 6 edges

```
> C:=fundamental_cycle(G)
```

an undirected unweighted graph with 4 vertices and 4 edges

```
> edges(C)
```

```
[[4, 5], [2, 5], [3, 4], [2, 3]]
```

Given a tree graph  $G$  and adding an edge from the complement  $G^c$  to  $G$  one obtains a 1-tree graph.

```
> G:=random_tree(25)
```

an undirected unweighted graph with 25 vertices and 24 edges

```
> ed:=choice(edges(graph_complement(G)))
```

```
[3, 8]
```

```
> G:=add_edge(G,ed)
```

an undirected unweighted graph with 25 vertices and 25 edges

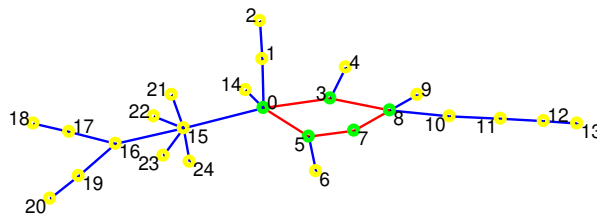
```
> C:=fundamental_cycle(G)
```

an undirected unweighted graph with 5 vertices and 5 edges

```
> edges(C)
```

```
[[5, 7], [0, 5], [7, 8], [3, 8], [0, 3]]
```

```
> draw_graph(highlight_subgraph(G,C),spring)
```

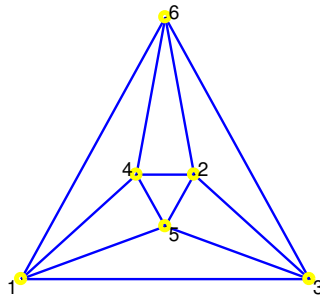


In the next example, a cycle basis of octahedral graph is computed.

```
> G:=graph("octahedron")
```

an undirected unweighted graph with 6 vertices and 12 edges

```
> draw_graph(G)
```



```
> cycle_basis(G)
```

```
[[6, 3, 1], [5, 4, 6, 3, 1], [4, 6, 3, 1], [5, 4, 6, 3], [2, 5, 4, 6, 3], [2, 5, 4, 6], [2, 5, 4]]
```

Given a tree graph  $T$ , one can create a graph with cycle basis cardinality equal to  $k$  by simply adding  $k$  randomly selected edges from the complement  $T^c$  to  $T$ .

```
> tree1:=random_tree(15)
```

an undirected unweighted graph with 15 vertices and 14 edges

```
> G1:=add_edge(tree1,rand(3,edges(graph_complement(tree1))))
```

an undirected unweighted graph with 15 vertices and 17 edges

```
> tree2:=random_tree(12)
```

an undirected unweighted graph with 12 vertices and 11 edges

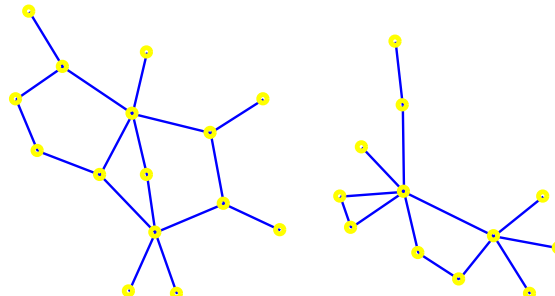
```
> G2:=add_edge(tree2,rand(2,edges(graph_complement(tree2))))
```

an undirected unweighted graph with 12 vertices and 13 edges

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

an undirected unweighted graph with 27 vertices and 30 edges

```
> draw_graph(G, spring, labels=false)
```



```
> nops(cycle_basis(G))
```

5

```
> number_of_edges(G)-number_of_vertices(G)+nops(connected_components(G))
```

### 1.8.5 Finding cycles in digraphs

```
find_cycles(G)
find_cycles(G,length=k)
find_cycles(G,length=l..u)
```

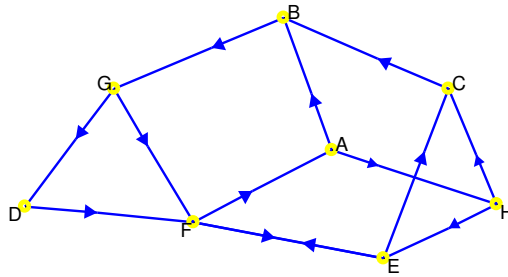
The command `find_cycles` is used for finding cycles (elementary circuits) in directed graphs. It takes a digraph  $G(V, E)$  as its first argument. If it is the only input given, `find_cycles` returns the list of all cycles in  $G$  where each cycle is output as a list of its vertices. If an optional second argument `length=k` resp. `length=l..u` is given, where  $k, l$  and  $u$  are positive integers, only cycles of length  $k$  resp. of length between  $l$  and  $u$  (inclusive) are returned.

The strategy is to use TARJAN's algorithm for enumerating elementary circuits in a digraph [72]. The algorithm runs in  $O(|V||E|(C+1))$  time, where  $C$  is the number of cycles in  $G$ .

```
> purge(A,B,C,D,E,F,G,H) ;;
> DG:=digraph(%{[A,B],[A,H],[B,G],[C,B],[D,F],[E,C],[E,F],[F,A],[F,E],[G,D],[G,F],[H,C],[H,E]})
```

a directed unweighted graph with 8 vertices and 13 arcs

```
> draw_graph(DG, spring)
```



```
> find_cycles(DG)
[[A, H, E, F], [A, H, E, C, B, G, F], [A, H, E, C, B, G, D, F], [A, H, C, B, G, F], [A, H, C, B, G, D, F], [A, B, G, F], [A, B, G, D, F], [B, G, F, E, C], [B, G, D, F, E, C], [F, E]]
```

```
> find_cycles(DG,length=4)
```

```
[[A, H, E, F], [A, B, G, F]]
```

```
> find_cycles(DG,length=6..7)
```

```
[[A, H, E, C, B, G, F], [A, H, C, B, G, F], [A, H, C, B, G, D, F], [B, G, D, F, E, C]]
```

## 1.9 Operations on graphs

### 1.9.1 Graph complement

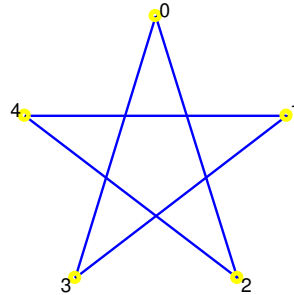
```
graph_complement(G)
```

The command `graph_complement` is used for constructing [complement graphs](#). It takes a graph  $G(V, E)$  as its only argument and returns the complement graph  $G^c(V, E^c)$  of  $G$ , where  $E^c$  is the largest set containing only edges/arcs not present in  $G$ .

```
> G:=graph_complement(cycle_graph(5))
```

an undirected unweighted graph with 5 vertices and 5 edges

```
> draw_graph(G)
```



## 1.9.2 Graph switching

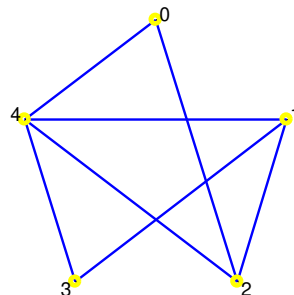
```
seidel_switch(G,L)
```

The command `seidel_switch` is used for Seidel [switching in graphs](#). It takes 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. The edges whose endpoints are both in the set, or both not in the set, are not changed.

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

an undirected unweighted graph with 5 vertices and 7 edges

```
> draw_graph(S)
```



```
> purge(A,B,C,D,E,F,X,Y) ;
```

```
> G:=graph([A,B,C,D,E,F,X,Y],%{[A,B],[B,C],[B,X],[B,Y],[C,D],[C,Y],[D,X],[E,Y],[F,Y],[X,Y]})
```

an undirected unweighted graph with 8 vertices and 10 edges

```
> G:=highlight_edges(G,[[X,B],[X,D],[Y,B],[Y,C],[Y,E],[Y,F],[X,Y]],[green$6,red]);
```

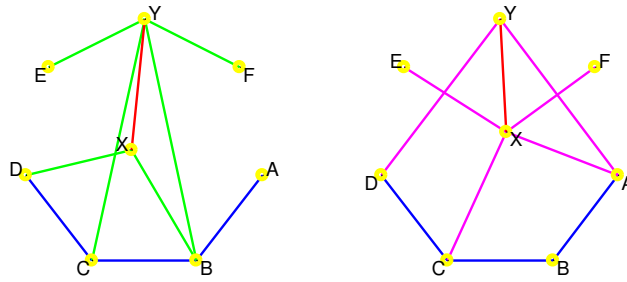
```
> H:=seidel_switch(G,[X,Y])
```

an undirected unweighted graph with 8 vertices and 10 edges

```
> H:=highlight_edges(H,[[X,A],[X,C],[X,E],[X,F],[Y,A],[Y,D],[X,Y]],[magenta$6,red]);
```

```
> draw_graph(G,circle=[Y,F,A,B,C,D,E],[0,0],size=[1,0]);
draw_graph(H,circle=[Y,F,A,B,C,D,E],[1.5,0],size=[1,0]);
```





### 1.9.3 Transposing graphs

`reverse_graph(G)`

The command `reverse_graph` is used for reversing arc directions in digraphs. It takes a graph  $G(V, E)$  as its only argument and returns the reverse graph  $G^T(V, E')$  of  $G$  where  $E' = \{vu : uv \in E\}$ , 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)
```

```
[[2, 1], [3, 2], [4, 2], [5, 4]]
```

### 1.9.4 Union of graphs

`graph_union(G1, G2, ..., Gn)`

The command `graph_union` is used for constructing unions of graphs. It takes a sequence of graphs  $G_k(V_k, E_k)$  for  $k = 1, 2, \dots, n$  as its argument and returns the graph  $G(V, E)$  where  $V = V_1 \cup V_2 \cup \dots \cup V_n$  and  $E = E_1 \cup E_2 \cup \dots \cup E_n$ .

```
> 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)
```

```
[[1, 2], [1, 3], [2, 3]]
```

### 1.9.5 Disjoint union of graphs

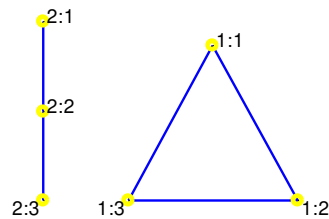
`disjoint_union(G1,G2,...,Gn)`

The command `disjoint_union` is used for constructing a **disjoint union** of graphs. It takes a sequence of graphs  $G_k(V_k, E_k)$  for  $k = 1, 2, \dots, n$  as its only 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 `graph_union` subsequently. As all vertices and edges are labeled differently, it follows  $|V| = \sum_{k=1}^n |V_k|$  and  $|E| = \sum_{k=1}^n |E_k|$ .

```
> G:=disjoint_union(cycle_graph([1,2,3]),path_graph([1,2,3]))
```

an undirected unweighted graph with 6 vertices and 5 edges

```
> draw_graph(G)
```



### 1.9.6 Joining two graphs

`graph_join(G,H)`

The command `graph_join` is used for joining two graphs together. It takes two graphs  $G$  and  $H$  as its arguments and returns the graph  $G + H$  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  $H$ .

```
> G:=path_graph(2)
```

an undirected unweighted graph with 2 vertices and 1 edge

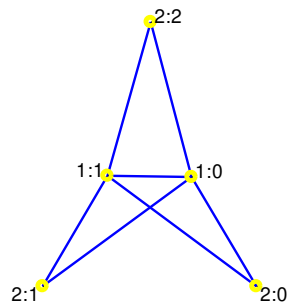
```
> H:=graph(3)
```

an undirected unweighted graph with 3 vertices and 0 edges

```
> GH:=graph_join(G,H)
```

an undirected unweighted graph with 5 vertices and 7 edges

```
> draw_graph(GH, spring)
```



### 1.9.7 Power graphs

`graph_power(G,k)`

The command `graph_power` is used for computing powers of graphs. It takes two arguments, a graph  $G(V, E)$  and a positive integer  $k$ . It 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  $G$ :

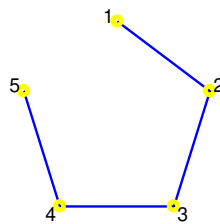
$$A_k = \sum_{i=1}^k A^i.$$

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

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

an undirected unweighted graph with 5 vertices and 4 edges

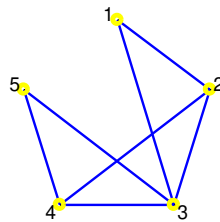
```
> draw_graph(G,circle)
```



```
> P2:=graph_power(G,2)
```

an undirected unweighted graph with 5 vertices and 7 edges

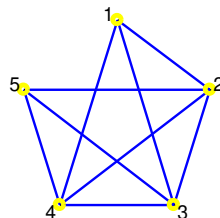
```
> draw_graph(P2,circle)
```



```
> P3:=graph_power(G,3)
```

an undirected unweighted graph with 5 vertices and 9 edges

```
> draw_graph(P3,circle)
```



### 1.9.8 Graph products

`cartesian_product(G1,G2,...,Gn)`

`tensor_product(G1,G2,...,Gn)`

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

`cartesian_product` takes a sequence of graphs  $G_k(V_k, E_k)$  for  $k = 1, 2, \dots, n$  as its argument and returns the Cartesian product  $G_1 \times G_2 \times \dots \times G_n$  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  $v_1:v_2$  where  $v_1 \in V_1$  and  $v_2 \in V_2$ , such that  $(u_1:v_1, u_2:v_2) \in E$  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  $v_2$ .

`tensor_product` takes a sequence of graphs  $G_k(V_k, E_k)$  for  $k = 1, 2, \dots, n$  as its argument and returns the tensor product  $G_1 \times G_2 \times \dots \times G_n$  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  $v_1:v_2$  where  $v_1 \in V_1$  and  $v_2 \in V_2$ , such that  $(u_1:v_1, u_2:v_2) \in E$  if and only if  $u_1$  is adjacent to  $u_2$  **and**  $v_1$  is adjacent to  $v_2$ .

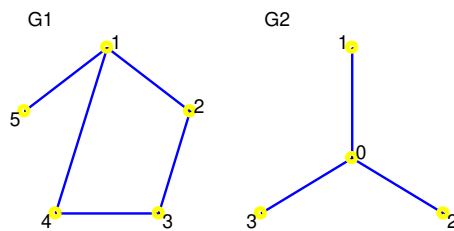
```
> G1:=graph(trail(1,2,3,4,1,5))
```

an undirected unweighted graph with 5 vertices and 5 edges

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

an undirected unweighted graph with 4 vertices and 3 edges

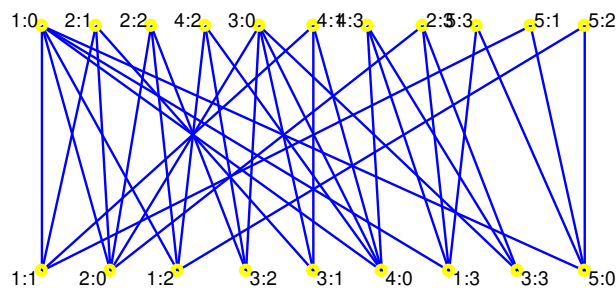
```
> draw_graph(G1,circle,[0,0],size=[0,1],title="G1");
draw_graph(G2,[1.5,0],size=[0,1],title="G2")
```



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

an undirected unweighted graph with 20 vertices and 35 edges

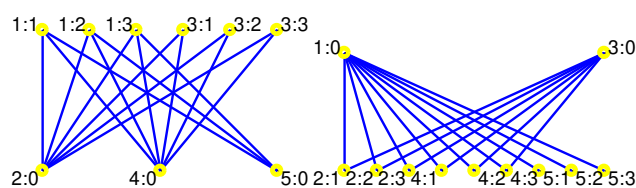
```
> draw_graph(G)
```



```
> T:=tensor_product(G1,G2)
```

an undirected unweighted graph with 20 vertices and 30 edges

```
> draw_graph(T)
```



### 1.9.9 Transitive closure graph

`transitive_closure(G, <weighted>)`

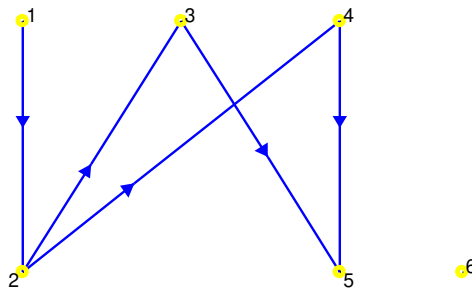
The command `transitive_closure` is used for constructing [transitive closure graphs](#). It takes one or two arguments, a graph  $G(V, E)$  and optionally the argument `weighted`. The command returns the transitive closure  $T(V, E')$  of the input graph  $G$  by connecting  $u \in V$  to  $v \in V$  in  $T$  if and only if there is a path from  $u$  to  $v$  in  $G$ . If  $G$  is directed, then  $T$  is also directed. When `weighted` is specified,  $T$  is weighted such that the weight of edge  $v w \in E'$  is equal to the length (or cost, if  $G$  is weighted) of the shortest path from  $v$  to  $w$  in  $G$ .

The lengths/weights of the shortest paths are obtained by the command `allpairs_distance` if  $G$  is weighted resp. the command `vertex_distance` if  $G$  is unweighted. Therefore  $T$  is constructed in at most  $O(|V|^3)$  time if `weighted` is specified and in  $O(|V||E|)$  time otherwise.

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

a directed unweighted graph with 6 vertices and 5 arcs

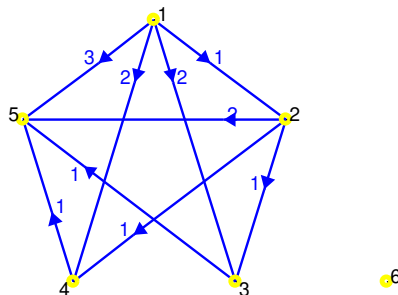
```
> draw_graph(G)
```



```
> T:=transitive_closure(G,weighted)
```

a directed weighted graph with 6 vertices and 9 arcs

```
> draw_graph(T)
```



### 1.9.10 Line graph

`line_graph(G)`

The command `line_graph` is used for constructing [line graphs](#) [34, p. 10]. It takes a graph  $G(V, E)$  as its only argument and returns the corresponding line graph  $L(G)$  with  $|E|$  distinct line graph vertices, one vertex for each edge in  $E$ . If  $G$  is undirected, then two vertices  $v_1$  and  $v_2$  in  $L(G)$  are adjacent if and only if the corresponding edges  $e_1, e_2 \in E$  have a common endpoint. If  $G$  is directed, then  $v_1$  and  $v_2$  are adjacent if and only if the corresponding arcs  $e_1$  and  $e_2$  form a directed path  $(e_1, e_2)$ , i.e. if the head of  $e_1$  coincides with the tail of  $e_2$ .

The vertices in  $L(G)$  are labeled with strings in form `v-w`, where  $e = vw \in E$ .

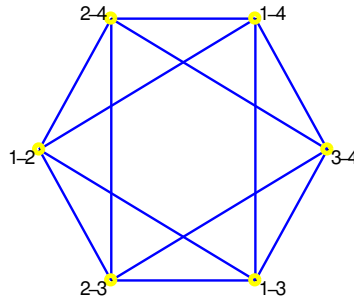
```
> K4:=complete_graph([1,2,3,4])
```

an undirected unweighted graph with 4 vertices and 6 edges

```
> L:=line_graph(K4)
```

an undirected unweighted graph with 6 vertices and 12 edges

```
> draw_graph(L, spring)
```



### 1.9.11 Plane dual graph

```
plane_dual(G)
plane_dual(F)
is_planar(G, <F>)
```

The command `plane_dual` is used for constructing the **dual graph** of an undirected biconnected **planar graph**. To determine whether a graph is planar [34, p. 12] use the command `is_planar`.

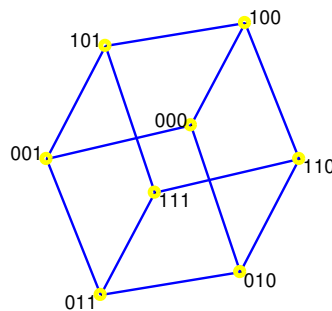
`plane_dual` takes a biconnected<sup>1.1</sup> planar graph  $G(V, E)$  or the list  $F$  of faces of a planar embedding of  $G$  as its only argument and returns the graph  $H$  with faces of  $G$  as its vertices. Two vertices in  $H$  are adjacent if and only if the corresponding faces share an edge in  $G$ . The algorithm runs in  $O(|V|^2)$  time.

`is_planar` takes one or two arguments, the input graph  $G$  and optionally an unassigned identifier  $F$ . It returns `true` if  $G$  is planar and `false` otherwise. If the second argument is given and  $G$  is planar and biconnected, the list of faces of  $G$  is stored to  $F$ . Each face is represented as a list of its vertices. The strategy is to use the algorithm of DEMOUCRON et al. [33, p. 88], which runs in  $O(|V|^2)$  time.

```
> H:=hypercube_graph(3)
```

an undirected unweighted graph with 8 vertices and 12 edges

```
> draw_graph(H, spring)
```



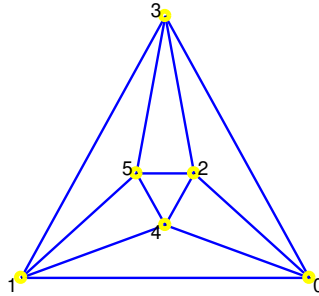
1.1. The concept of dual graph is normally defined for multigraphs. Every planar multigraph has the corresponding dual multigraph; moreover, the dual of the latter is equal to the former. Since GIAC generally does not support multigraphs, a more specialized definition suitable for simple graphs is used; hence the requirement that the input graph is biconnected.

The cube has six faces, hence its plane dual graph  $D$  has six vertices. Also, every face obviously shares an edge with exactly four other faces, so the degree of each vertex in  $D$  is equal to 4.

```
> D:=plane_dual(H)
```

an undirected unweighted graph with 6 vertices and 12 edges

```
> draw_graph(D,planar)
```



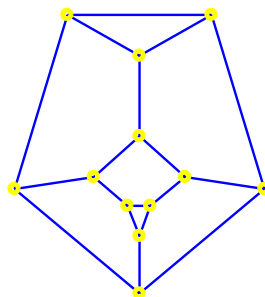
```
> is_planar(graph("petersen"))
```

false

```
> is_planar(graph("duerer"))
```

true

```
> draw_graph(graph("duerer"),planar,labels=false)
```



In the next example, a graph isomorphic to  $D$  is obtained when passing a list of faces of  $H$  to `plane_dual`. The order of vertices is determined by the order of faces.

```
> purge(F):: is_planar(H,F); F
```

“Done”, true,  $\begin{pmatrix} \text{“011”} & \text{“001”} & \text{“000”} & \text{“010”} \\ \text{“000”} & \text{“001”} & \text{“101”} & \text{“100”} \\ \text{“110”} & \text{“010”} & \text{“000”} & \text{“100”} \\ \text{“011”} & \text{“010”} & \text{“110”} & \text{“111”} \\ \text{“111”} & \text{“110”} & \text{“100”} & \text{“101”} \\ \text{“101”} & \text{“001”} & \text{“011”} & \text{“111”} \end{pmatrix}$

```
> is_isomorphic(plane_dual(F),D)
```

true

### 1.9.12 Truncating planar graphs

```
truncate_graph(G)
```

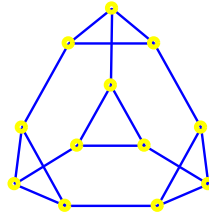
The command `truncate_graph` performs [truncation](#) of biconnected planar graphs. It takes a biconnected planar graph  $G(V, E)$  as its only argument and returns the graph obtained by truncating the respective polyhedron, i.e. by “cutting off” its vertices. The resulting graph has  $2|E|$  vertices and  $3|E|$  edges. The procedure of truncating a graph by subdividing its edges is described in [5].

The algorithm requires computing a planar embedding of  $G$ , which is done by applying DEMOURON’s algorithm. Hence its complexity is  $O(|V|^2)$ .

```
> G:=truncate_graph(graph("tetrahedron"))
```

an undirected unweighted graph with 12 vertices and 18 edges

```
> draw_graph(G, spring, labels=false)
```



Truncating the plane dual of  $G$  represents the **leapfrog operation** on  $G$ , which can be used for constructing [fullerene graphs](#) [5]. By performing the leapfrog operation on a fullerene graph one obtains a larger fullerene. For example, the dual of the Errera graph is a fullerene (see [here](#)); hence by truncating Errera graph (i.e. the dual of its dual) one obtains a fullerene.

```
> G:=truncate_graph(graph("errera"))
```

an undirected unweighted graph with 90 vertices and 135 edges

```
> purge(F) ;; is_planar(G,F)
```

“Done”, true

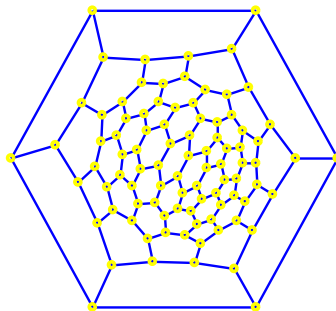
Now  $F$  contains a list of faces of the graph  $G$ . Since  $G$  is a fullerene, every face is a 5- or 6-cycle.

```
> set[op(apply(length,F))]
```

{5, 6}

When drawing fullerenes, it is recommended to use the [circular method](#) which usually produces best results. Any face of the planar embedding of a given fullerene be chosen as the outer face, as in the example below.

```
> draw_graph(G, circle=rand(F))
```



As an another example, the  $C_{180}$  fullerene is obtained by performing two leapfrog operations on the dodecahedral graph [65].

```
> G:=truncate_graph(plane_dual(graph("dodecahedron")))
```



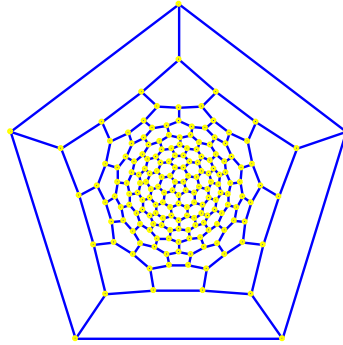
an undirected unweighted graph with 60 vertices and 90 edges

```
> C180:=truncate_graph(plane_dual(G))
```

an undirected unweighted graph with 180 vertices and 270 edges

In order to obtain a symmetric drawing of  $C_{180}$ , a 5-edge face is used as the outer face.

```
> purge(F); is_planar(C180,F);
for f in F do if length(f)==5 then break; fi; od;;
draw_graph(C180,circle=f)
```



## 1.10 Random graphs

### 1.10.1 Random general graphs

```
random_graph(n|L,p|m)
random_digraph(n|L,p|m)
random_graph(n|L,[p0,p1,...])
random_graph(n|L,f)
random_graph(n|L,d,k)
```

The commands `random_graph` and `random_digraph` are used for generating general (di)graphs at random according to various models, including the [preferential attachment](#). Both commands take two arguments: a positive integer  $n$  or a list of labels  $L$  of length  $n$ . The second argument is a positive real number  $p < 1$  or a positive integer  $m$ . The return value is a (di)graph on  $n$  vertices (with elements of  $L$  as vertex labels) selected uniformly at random, i.e. a (di)graph in which each edge/arc is present with probability  $p$  or which contains exactly  $m$  edges/arcs chosen uniformly at random ([Erdős–Rényi model](#)).

Erdős–Rényi model is implemented according to BATAGELJ and BRANDES [6, algorithms 1 and 2]. The corresponding algorithms run in linear time and are suitable for generating large graphs.

`random_graph` can also generate graphs with respect to a given probability distribution of vertex degrees if the second argument is a discrete probability density function given as a list of probabilities or weights  $[p_0, p_1, \dots, p_{n-1}]$  or as a weight function  $f: \mathbb{N} \cup \{0\} \rightarrow [0, +\infty)$  such that  $f(i) = p_i$  for  $i = 0, 1, \dots, n-1$ . Trailing zeros in the list of weights, if present, may be omitted. The numbers  $p_i$  are automatically scaled by  $1/\sum_{i=1}^{n-1} p_i$  to achieve the sum of 1 and a graph with that precise distribution of vertex degrees is generated at random using the algorithm described in [58, p. 2567] with some modifications. First, a degree sequence  $d$  is generated randomly by drawing samples from the given distribution and repeating the process until a graphic sequence is obtained. Then the algorithm for constructing a feasible solution from  $d$  [38] is applied. Finally, the edges of that graph are randomized by choosing suitable pairs of non-incident edges and “rewiring” them without changing the degree sequence. Two edges  $uv$  and  $wz$  can be rewired in at most two ways, becoming either  $uz$  and  $wv$  or  $uw$  and  $vz$  (if these edges are not in the graph already). Letting  $m$  denote the number of edges, at most

$$N = \left\lceil \left( \log_2 \frac{m}{m-1} \right)^{-1} \right\rceil < m$$

such choices is made, assuring that the probability of rewiring each edge at least once is larger than  $1/2$ . The total complexity of this algorithm is  $O(n^2 \log n)$ .

Additionally, to support generation of realistic networks, `random_graph` can be used with integer parameters  $d > 0$  and  $k \geq 0$  as the second and the third argument, respectively, in which case a preferential attachment rule is applied in the following way. For  $n \geq 2$ , the resulting graph  $G(V, E)$  initially contains two vertices  $v_1, v_2$  and one edge  $v_1 v_2$ . For each  $i = 3, \dots, n$ , the vertex  $v_i$  is added to  $V$  along with edges  $v_i v_j$  for  $\min\{i-1, d\}$  mutually different values of  $j$ , which are chosen at random in the set  $\{1, 2, \dots, i-1\}$  with probability

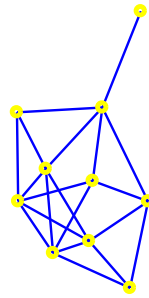
$$p_j = \frac{\deg v_j}{\sum_{r=1}^{i-1} \deg v_r}.$$

Subsequently, additional at most  $k$  random edges connecting the neighbors of  $v_i$  to each other are added to  $E$ , allowing the user to control the `clustering coefficient` of  $G$ . This method is due to SCHANK and WAGNER [68, Algorithm 2, p. 271]. The time complexity of the implementation is  $O(n^2 d + n k)$ .

```
> G:=random_graph(10,0.5)
```

an undirected unweighted graph with 10 vertices and 20 edges

```
> draw_graph(G, spring, labels=false)
```



```
> G:=random_graph(1000,0.05)
```

an undirected unweighted graph with 1000 vertices and 24845 edges

```
> is_connected(G)
```

true

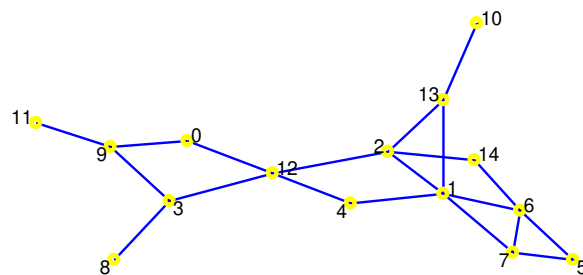
```
> minimum_degree(G), maximum_degree(G)
```

28, 71

```
> G:=random_graph(15,20)
```

an undirected unweighted graph with 15 vertices and 20 edges

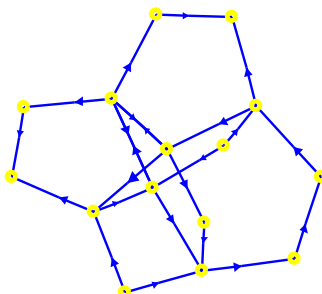
```
> draw_graph(G, spring)
```



```
> DG:=random_digraph(15,0.1)
```

a directed unweighted graph with 15 vertices and 23 arcs

```
> draw_graph(DG,labels=false,spring)
```



In the following example, a random graph is generated such that the degree of each vertex is drawn from  $\{0, 1, \dots, 10\}$  according to weights specified in the table below.

degree	0	1	2	3	4	5	6	7	8	9	10
weight	0	0	9	7	0	5	4	3	0	1	1

That is, the degrees are generated with probabilities  $0, 0, \frac{3}{10}, \frac{7}{30}, 0, \frac{1}{6}, \frac{2}{15}, \frac{1}{10}, 0, \frac{1}{30}, \frac{1}{30}$ , respectively.

```
> G:=random_graph(10000,[0,0,9,7,0,5,4,3,0,1,1])
```

an undirected unweighted graph with 10000 vertices and 21469 edges

5.413 sec

```
> frequencies(degree_sequence(G))
```

2	0.3028
3	0.2287
5	0.1619
6	0.1324
7	0.1037
9	0.0327
10	0.0378

In the example below, a random graph is generated such that the vertex degrees are distributed according to the following weight function:

$$f(k) = \begin{cases} 0, & k=0, \\ k^{-3/2} e^{-k/3}, & k \geq 1. \end{cases}$$

```
> G:=random_graph(10000,k->when(k<1,0,k^-1.5*exp(-k/3)))
```

an undirected unweighted graph with 10000 vertices and 8013 edges

```
> length(connected_components(G))
```

2278

The command line below computes the average size of a connected component in  $G$ .

```
> round(mean(apply(length,connected_components(G))))
```

4

The next example demonstrates how to generate random graphs with adjustable clustering coefficient.

```
> G1:=random_graph(10000,5,10)
```

an undirected unweighted graph with 10000 vertices and 105349 edges

```
> clustering_coefficient(G1)
```

0.468517214584

```
> G2:=random_graph(10000,5,20)
```

an undirected unweighted graph with 10000 vertices and 121729 edges

```
> clustering_coefficient(G2)
```

0.615949324773

```
> G3:=random_graph(10000,10,5)
```

an undirected unweighted graph with 10000 vertices and 143378 edges

```
> clustering_coefficient(G3)
```

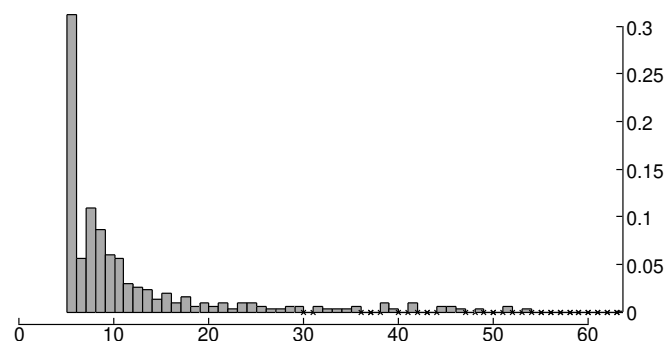
0.114122321952

The distribution of vertex degrees in a graph generated with preferential attachment rule roughly obeys the power law in its tail, as shown in the example below.

```
> G:=random_graph(300,5,2)
```

an undirected unweighted graph with 300 vertices and 1889 edges

```
> histogram(degree_sequence(G))
```



### 1.10.2 Random bipartite graphs

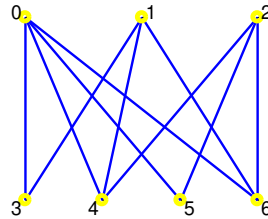
```
random_bipartite_graph(n,p|m)
random_bipartite_graph([a,b],p|m)
```

The command `random_bipartite_graph` is used for generating **bipartite graphs** at random. It takes two arguments. The first argument is either a positive integer  $n$  or a list of two positive integers  $a$  and  $b$ . The second argument is either a positive integer  $m$  or a positive real number  $p < 1$ . The command returns a random bipartite graph on  $n$  vertices (or with two partitions of sizes  $a$  and  $b$ ) in which each possible edge is present with probability  $p$  (or  $m$  edges are inserted at random).

```
> G:=random_bipartite_graph([3,4],0.5)
```

an undirected unweighted graph with 7 vertices and 10 edges

```
> draw_graph(G)
```



```
> G:=random_bipartite_graph(30,60)
```

an undirected unweighted graph with 30 vertices and 60 edges

### 1.10.3 Random trees

```
random_tree(n|V)
random_tree(n|V,d)
random_tree(n|V,root<=v)
```

The command `random_tree` is used for generating **tree graphs** at random. It takes one or two arguments: a positive integer  $n$  or a list  $V = \{v_1, v_2, \dots, v_n\}$  and optionally an integer  $d \geq 2$  or the option `root<=v`, where  $v \in V$ . It returns a random tree  $T(V, E)$  on  $n$  vertices such that:

- if the second argument is omitted, then  $T$  is uniformly selected among all unrooted unlabeled trees on  $n$  vertices,
- if  $d$  is given as the second argument, then  $\Delta(T) \leq d$ , where  $\Delta(T)$  is the maximum vertex degree in  $T$ ,
- if `root[=v]` is given as the second argument, then  $T$  is uniformly selected among all rooted unlabeled trees on  $n$  vertices. If  $v$  is specified then the vertex labels in  $V$  (required) will be assigned to vertices in  $T$  such that  $v$  is the first vertex in the list returned by the command `vertices`.

Rooted unlabeled trees are generated uniformly at random using RANRUT algorithm [59, p. 274]. The root of a tree  $T$  generated this way, if not specified as  $v$ , is always the first vertex in the list returned by `vertices`. The average time complexity of RANRUT algorithm is  $O(n \log n)$  [4].

Unrooted unlabeled trees, also called **free** trees, are generated uniformly at random using WILF's algorithm<sup>1.2</sup> [85], which is based on RANRUT algorithm and runs in about the same time as RANRUT itself.

Trees with bounded maximum degree are generated using a simple algorithm which starts with an empty tree and adds edges at random one at a time. It is much faster than RANRUT but selects trees in a non-uniform manner. To force the use of this algorithm even without vertex degree limit (for example, when  $n$  is very large), one can set  $d = +\infty$ .

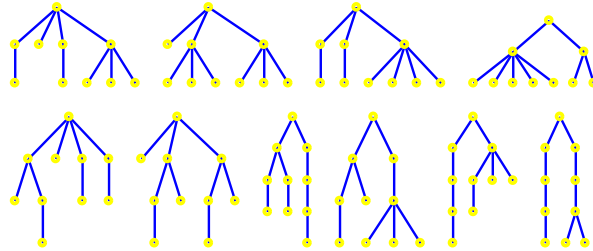
1.2. The original publication of WILF's algorithm has a minor flaw in the procedure **Free** [85, p. 207]. In the formula  $p = \binom{1+a_n/2}{2} / a_n$  in step (T1) the denominator  $a_n$  stands for the number of all rooted unlabeled trees on  $n$  vertices. However, one should divide by the number  $t_n$  of all *unrooted* unlabeled trees instead, which can be obtained from  $a_1, a_2, \dots, a_n$  by applying the formula in [61, p. 589]. This implementation includes the correction.

The command line below creates a forest containing 10 randomly selected free trees on 10 vertices.

```
> G:=disjoint_union(apply(random_tree,[10$10]))
```

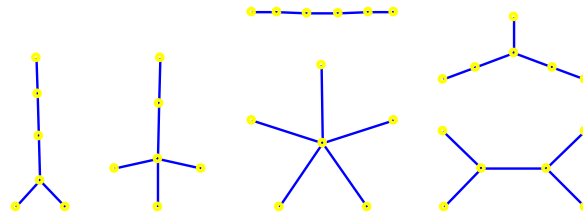
an undirected unweighted graph with 100 vertices and 90 edges

```
> draw_graph(G,tree,labels=false)
```



The following example demonstrates the uniformity of random generation of free trees. Letting  $n=6$ , there are exactly 6 distinct free trees on 6 vertices, created by the next command line.

```
> trees:=[star_graph(5),path_graph(6),graph(trail(1,2,3,4),trail(5,4,6)),
graph(%{[1,2],[2,3],[2,4],[4,5],[4,6]}),graph(trail(1,2,3,4),trail(3,5,6)),
graph(trail(1,2,3,4),trail(5,3,6))];
> draw_graph(disjoint_union(trees),spring,labels=false)
```



Now, generating a random free tree on 6 nodes always produces one of the above six graphs, which is determined by using the command `is_isomorphic`. 1200 trees are generated in total and the number of occurrences of `trees[k]` is stored in `hits[k]` for every  $k=1,2,\dots,6$  (note that in `xcas` mode it is actually  $k=0,\dots,5$ ).

```
> hits:= [0$6];
> for k from 1 to 1200 do
  T:=random_tree(6);
  for j from 0 to 5 do
    if is_isomorphic(T,trees[j]) then hits[j]++; fi;
  od;
od;;
> hits
```

[186, 208, 221, 186, 189, 210]

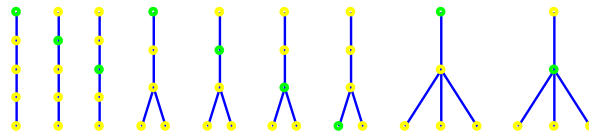
To show that the algorithm also selects rooted trees on  $n$  vertices with equal probability, one can reproduce the example in [59, p. 281], in which  $n=5$ . First, all distinct rooted trees on 5 vertices are created and stored in `trees`; there are exactly nine of them. Their root vertices are highlighted to be distinguishable. Then, 4500 rooted trees on 5 vertices are generated at random, highlighting the root vertex in each of them. As in the previous example, the variable `hits[k]` records how many of them are isomorphic to `trees[k]`.

```

> trees:=[
  highlight_vertex(graph(trail(1,2,3,4,5)),1),
  highlight_vertex(graph(trail(1,2,3,4,5)),2),
  highlight_vertex(graph(trail(1,2,3,4,5)),3),
  highlight_vertex(graph(trail(1,2,3),trail(4,3,5)),1),
  highlight_vertex(graph(trail(1,2,3),trail(4,3,5)),2),
  highlight_vertex(graph(trail(1,2,3),trail(4,3,5)),3),
  highlight_vertex(graph(trail(1,2,3),trail(4,3,5)),4),
  highlight_vertex(graph(trail(1,2,3),trail(4,2,5)),1),
  highlight_vertex(graph(trail(1,2,3),trail(4,2,5)),2)
];

> draw_graph(disjoint_union(trees),labels=false)

```



```

> hits:=[0$9]::;

> for k from 1 to 4500 do
  T:=random_tree(5,root);
  HT:=highlight_vertex(T,vertices(T)[0]);
  for j from 0 to 8 do
    if is_isomorphic(HT,trees[j]) then hits[j]++; fi;
  od;
od;

> hits

```

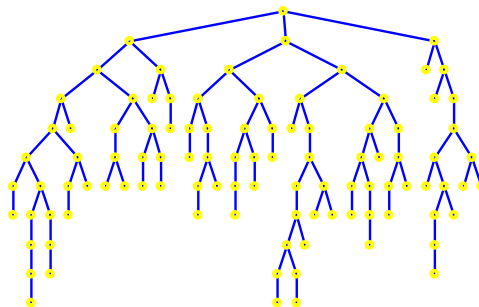
[505, 561, 457, 496, 487, 517, 489, 500, 488]

In the following example, a random tree on 100 vertices with maximum degree at most 3 is drawn.

```

> draw_graph(random_tree(100,3))

```



#### 1.10.4 Random planar graphs

`random_planar_graph( $n|L,p,\langle k \rangle$ )`

The command `random_planar_graph` is used for generating random planar graphs. It takes two or three arguments, a positive integer  $n$  or a list  $L$  of length  $n$ , a positive real number  $p < 1$ , and optionally an integer  $k \in \{0, 1, 2, 3\}$  (by default,  $k = 1$ ). The command returns a random  $k$ -connected planar graph on  $n$  vertices (using the elements of  $L$  as vertex labels).

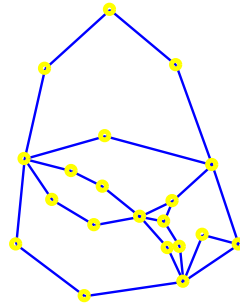
The result is obtained by first generating a random maximal planar graph and then attempting to remove each edge with probability  $p$ , maintaining the  $k$ -connectivity of the graph (if  $k = 0$ , the graph may be disconnected). The running time is  $O(n^{\lceil 1+k/2 \rceil})$ .

Generating a biconnected planar graph:

```
> G:=random_planar_graph(20,0.8,2)
```

an undirected unweighted graph with 20 vertices and 27 edges

```
> draw_graph(G,planar,labels=false)
```

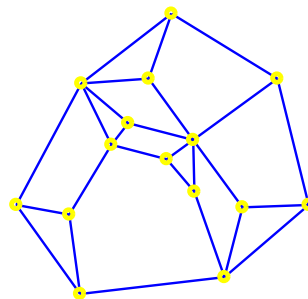


Generating a triconnected planar graph:

```
> G:=random_planar_graph(15,0.9,3)
```

an undirected unweighted graph with 15 vertices and 26 edges

```
> draw_graph(G,planar,labels=false)
```



Generating a disconnected planar graph with high probability:

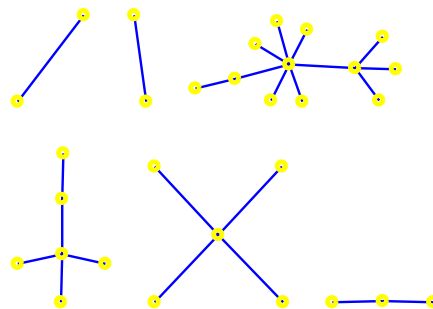
```
> G:=random_planar_graph(30,0.9,0)
```

an undirected unweighted graph with 30 vertices and 24 edges

```
> is_forest(G)
```

true

```
> draw_graph(G,spring,labels=false)
```



By default, a connected planar graph is generated, like in the following example.



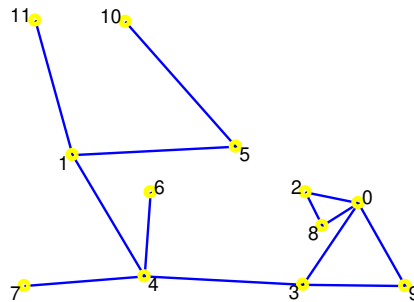
```
> G:=random_planar_graph(12,0.618)
```

an undirected unweighted graph with 12 vertices and 13 edges

```
> is_connected(G)
```

true

```
> draw_graph(G,planar)
```



### 1.10.5 Random graphs from a given degree sequence

`random_sequence_graph(L)`

The command `random_sequence_graph` is used for generating random undirected graphs from degree sequences. It takes a degree sequence  $L$  (a list of nonnegative integers) as its only argument and returns an asymptotically uniform random graph with the degree sequence equal to  $L$  using the algorithm developed by BAYATI et al. [8].

The algorithm slows down quickly and uses  $O(|L|^2)$  of auxiliary space, so it is best used for up to several hundreds of vertices.

```
> s:=[1,3,3,2,1,2,2,2,3,3]
```

[1, 3, 3, 2, 1, 2, 2, 2, 3, 3]

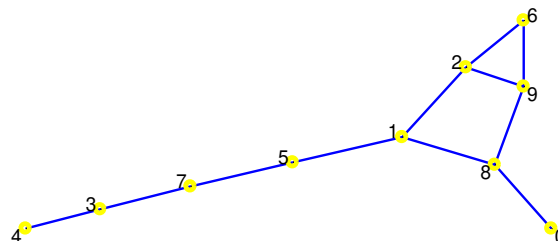
```
> is_graphic_sequence(s)
```

true

```
> G:=random_sequence_graph(s)
```

an undirected unweighted graph with 10 vertices and 11 edges

```
> draw_graph(G,spring)
```



### 1.10.6 Random regular graphs

`random_regular_graph(n|L,d,<connected>)`

The command `random_regular_graph` is used for generating random [regular graphs](#). It takes two mandatory arguments, a positive integer  $n$  (or a list  $L$  of length  $n$ ) and a nonnegative integer  $d$ . Optionally, the argument `connected` may be appended, forcing the generated graph to be connected. The command creates  $n$  vertices (using elements of  $L$  as vertex labels) and returns a random  $d$ -regular (connected) graph on these vertices.

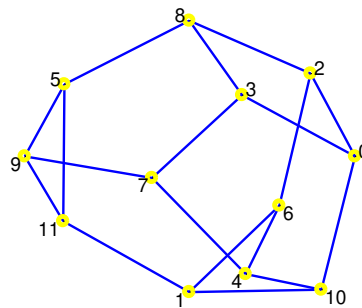
Note that a  $d$ -regular graph on  $n$  vertices exists if and only if  $n > d + 1$  and  $nd$  is even. If these conditions are not met, `random_regular_graph` returns an error.

The strategy is to use the algorithm developed by STEGER and WORMALD [70, algorithm 2]. The runtime is negligible for  $n \leq 100$ . However, for  $n > 200$  the algorithm is considerably slower. Graphs are generated with approximately uniform probability, which means that for  $n \rightarrow \infty$  and  $d$  not growing so quickly with  $n$  the probability distribution converges to uniformity.

```
> G:=random_regular_graph(12,3)
```

an undirected unweighted graph with 12 vertices and 18 edges

```
> draw_graph(G, spring)
```



### 1.10.7 Random tournaments

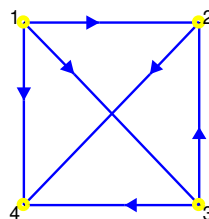
`random_tournament(n|V)`

The command `random_tournament` is used for generating random [tournaments](#). It takes a positive integer  $n$  or a list  $V$  of length  $n$  as its only argument and returns a random tournament on  $n$  vertices. If  $V$  is specified, its elements are used to label the vertices.

```
> G:=random_tournament([1,2,3,4])
```

a directed unweighted graph with 4 vertices and 6 arcs

```
> draw_graph(G)
```



### 1.10.8 Random network graphs

`random_network(a,b,<p>,<opts>)`

The command `random_network` is used for generating random [networks](#). It takes two to four arguments: a positive integer  $a$ , a positive integer  $b$ , an optional real number  $p$  such that  $0 < p \leq 1$  (by default  $p = 0.5$ ) and optionally a sequence of options `opts`. The supported options are `acyclic<=true|false>` and `weights=a..b`.

The command returns a network graph with  $a^2 b$  vertices which is composed as follows (the method of generating the network skeleton is due to GOLDFARB and GRIGORIADIS [35]).

Firstly, grid graphs  $F_1, F_2, \dots, F_b$  (called **frames**), each of them with  $a \times a$  vertices, are generated. If the option `acyclic<=true>` is used (by default is `acyclic=false`), then an acyclic orientation is computed for each frame using st-ordering (see Section 4.9.3) with two opposite corners of the frame as source and sink, otherwise all vertices in the frame are connected to their neighbors (forth and back). In addition, for each  $k < b$  the vertices of  $F_k$  are connected one to one with the vertices of the next frame  $F_{k+1}$  using a random permutation of those vertices. The first vertex of the first frame is the source and the last vertex of the last frame is the sink of the network (some arcs may have to be removed to achieve that). Finally, the removal of each arc is attempted with probability  $1 - p$  (unless its removal disconnects the network), making each arc present with probability  $p$ .

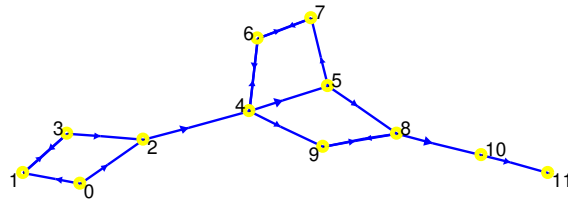
if the option `weights=a..b` is specified, arc weights in the network are randomized in the interval  $[a, b] \subset \mathbb{R}$ . If  $a, b$  are integers, the weights are also integers.

The command below creates a random network, consisting of 3 frames of size  $2 \times 2$ , in which each arc is present with the probability 0.8.

```
> N1:=random_network(2,3,0.8)
```

a directed unweighted graph with 12 vertices and 18 arcs

```
> draw_graph(N1, spring)
```



```
> is_network(N1)
```

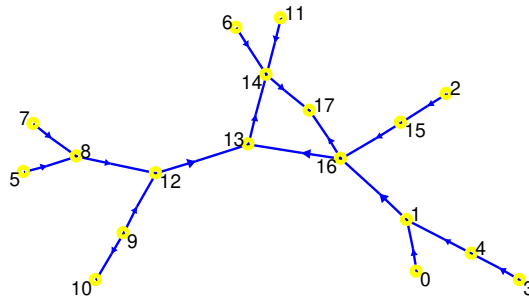
[0], [11]

In the next example, passing the option `acyclic` forces the output graph to be acyclic.

```
> N2:=random_network(3,2,0.62,acyclic)
```

a directed unweighted graph with 18 vertices and 18 arcs

```
> draw_graph(N2, spring)
```



```
> is_network(N2)
```

[0, 2, 3, 5, 6, 7, 9, 11], [10, 17]

```
> is_acyclic(N2)
```

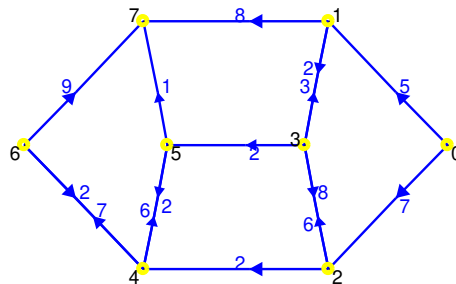
true

Arc weights can be randomized, as demonstrated in the following example.

```
> N3:=random_network(2,2,0.75,weights=1..9)
```

a directed weighted graph with 8 vertices and 15 arcs

```
> draw_graph(N3,spring)
```



### 1.10.9 Randomizing edge weights

```
assign_edge_weights(G,a..b)
```

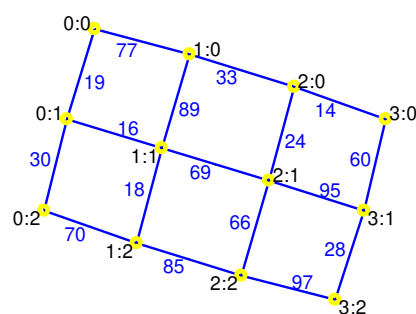
```
assign_edge_weights(G,m,n)
```

The command `assign_edge_weights` is used for assigning weights to edges of graphs at random. It takes two or three arguments: a graph  $G(V, E)$  and an interval  $a .. b$  of real numbers or a sequence of two positive integers  $m$  and  $n$ . The command operates such that for, each edge  $e \in E$ , the weight of  $e$  is chosen uniformly from the real interval  $[a, b)$  or from the set of integers lying between  $m$  and  $n$ , including both  $m$  and  $n$ . After assigning weights to all edges, a modified copy of  $G$  is returned.

```
> G:=assign_edge_weights(grid_graph(4,3),1,99)
```

an undirected weighted graph with 12 vertices and 17 edges

```
> draw_graph(G,spring)
```



# Chapter 2

## Modifying graphs

### 2.1 Promoting to directed and weighted graphs

#### 2.1.1 Converting edges to arcs

```
make_directed(G,⟨W⟩)
```

The command `make_directed` is used for promoting undirected graphs to directed ones. It takes one or two arguments, an undirected graph  $G(V, E)$  and optionally a numerical square matrix  $W = [a_{ij}]$  of order  $|V|$ . Every edge  $v_i v_j \in E$  is replaced with the pair of arcs  $v_i v_j$  and  $v_j v_i$ . If matrix  $W$  is specified, its elements  $w_{ij}$  and  $w_{ji}$  are assigned as weights of these arcs, respectively. Thus a directed (weighted) copy of  $G$  is constructed and subsequently returned.

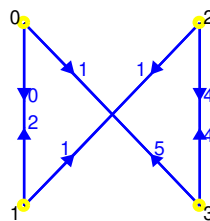
```
> G:=make_directed(cycle_graph(4))
```

a directed unweighted graph with 4 vertices and 8 arcs

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

a directed weighted graph with 4 vertices and 8 arcs

```
> draw_graph(WG)
```



#### 2.1.2 Assigning weight matrix to unweighted graphs

```
make_weighted(G,⟨W⟩)
```

The command `make_weighted` is used for promoting unweighted graphs to weighted ones. It takes one or two arguments, an unweighted graph  $G(V, E)$  and optionally a square matrix  $W = [w_{ij}]$  of order  $|V|$ . If the matrix specification is omitted, a square matrix of ones is assumed. Then a copy of  $G$  is returned in which each edge/arc  $v_i v_j \in E$  gets the element  $w_{ij}$  in  $W$  assigned as its weight. If  $G$  is undirected, it is assumed that  $W$  is a symmetric matrix.

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

an undirected unweighted graph with 3 vertices and 3 edges

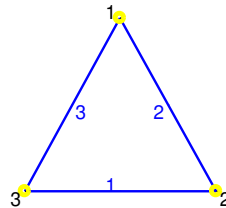
```
> W:=[[0,2,3],[2,0,1],[3,1,0]]
```

$$\begin{pmatrix} 0 & 2 & 3 \\ 2 & 0 & 1 \\ 3 & 1 & 0 \end{pmatrix}$$

```
> H:=make_weighted(G,W)
```

an undirected weighted graph with 3 vertices and 3 edges

```
> draw_graph(H)
```



## 2.2 Modifying vertices of a graph

### 2.2.1 Adding and removing vertices

```
add_vertex(G,v|L)
```

```
delete_vertex(G,v|L)
```

The commands `add_vertex` and `delete_vertex` are used for adding new vertices to graphs and for removing existing vertices from graphs, respectively.

`add_vertex` takes 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.

`delete_vertex` takes 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  $L$  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.

```
> K5:=complete_graph([1,2,3,4,5])
```

an undirected unweighted graph with 5 vertices and 10 edges

```
> add_vertex(K5,6)
```

an undirected unweighted graph with 6 vertices and 10 edges

```
> add_vertex(K5,[a,b,c])
```

an undirected unweighted graph with 8 vertices and 10 edges

Note that vertices already present in  $G$  will not be added. For example:

```
> add_vertex(K5,[4,5,6])
```

an undirected unweighted graph with 6 vertices and 10 edges

```
> delete_vertex(K5,2)
```

an undirected unweighted graph with 4 vertices and 6 edges

```
> delete_vertex(K5,[2,3])
```

an undirected unweighted graph with 3 vertices and 3 edges

### 2.2.2 Contracting subgraphs

```
contract_subgraph(G,S,<lab>)
```

The command `contract_subgraph` is used for contracting subgraphs into single vertices. It takes two mandatory arguments, a graph  $G(V, E)$  and a set (or list)  $S \subset V$ . It returns a copy of  $G$  with all the vertices in  $S$  merged into a single vertex. The neighborhood of that vertex is the union of the neighborhoods of all of merged vertices. The argument `lab`, or the list of labels of merged vertices if `lab` is omitted, becomes the label of the new vertex.

Edge attributes and directions from  $G$  are kept in the resulting graph, as well as the attributes for vertices in  $V \setminus S$ .

```
> C6:=cycle_graph(6)
```

an undirected unweighted graph with 6 vertices and 6 edges

```
> H:=contract_subgraph(C6,[0,1,5],a)
```

an undirected unweighted graph with 4 vertices and 4 edges

```
> vertices(H)
```

$[a, 2, 3, 4]$

```
> edges(H)
```

$[[2, a], [4, a], [2, 3], [3, 4]]$

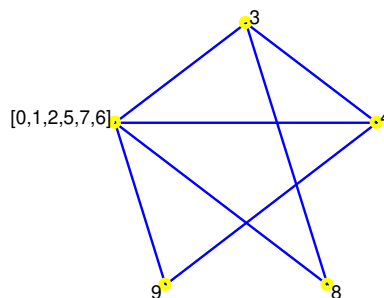
```
> P:=graph("petersen")
```

an undirected unweighted graph with 10 vertices and 15 edges

```
> H:=contract_subgraph(P,[0,1,2,5,7,6])
```

an undirected unweighted graph with 5 vertices and 7 edges

```
> draw_graph(H)
```



## 2.3 Modifying edges of a graph

### 2.3.1 Adding and removing edges

```
add_edge(G,e|E|T)
add_arc(G,e|E|T)
delete_edge(G,e|E|T)
delete_arc(G,e|E|T)
```

The commands `add_edge` or `add_arc` and `delete_edge` or `delete_arc` are used for adding new edges to graphs and for removing existing edges from graphs, respectively.

`add_edge` takes two arguments, an undirected graph  $G$  and an edge  $e$  or a list of edges  $E$  or a trail of edges  $T$  (entered as a list of vertices), and returns the copy of  $G$  with the specified edges inserted. Edge insertion implies that its endpoints will be created if they are not already present in  $G$ . The command `add_arc` works similarly to `add_edge` but applies only to directed graphs. Note that the order of endpoints in an arc is relevant. When adding edge to a weighted graph, its weight should be specified alongside its endpoints, or it will be assumed that it equals to 1.

`delete_edge` and `delete_arc` both take two arguments, the input graph  $G$  and an edge  $e$  or a list of edges  $E$  or a trail of edges  $T$ . It returns a copy of  $G$  in which the specified edges are removed. Note that this operation does not change the set of vertices of  $G$ .

*Examples.*

```
> C4:=cycle_graph(4)
```

an undirected unweighted graph with 4 vertices and 4 edges

```
> add_edge(C4,[1,3])
```

an undirected unweighted graph with 4 vertices and 5 edges

```
> add_edge(C4,[1,3,5,7])
```

an undirected unweighted graph with 6 vertices and 7 edges

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

a directed unweighted graph with 4 vertices and 6 arcs

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

an undirected weighted graph with 4 vertices and 3 edges

```
> K33:=relabel_vertices(complete_graph(3,3),[A,B,C,D,E,F])
```

an undirected unweighted graph with 6 vertices and 9 edges

```
> has_edge(K33,[A,D])
```

true

```
> delete_edge(K33,[A,D])
```

an undirected unweighted graph with 6 vertices and 8 edges

Note that the original input graph is not changed.

```
> has_edge(K33,[B,D])
```

true



```
> delete_edge(K33, [[A,D], [B,D]])
```

a undirected unweighted graph with 6 vertices and 7 edges

```
> DG:=digraph(trail(1,2,3,4,5,2,4))
```

a directed unweighted graph with 5 vertices and 6 arcs

```
> delete_arc(DG, [[2,3], [4,5], [5,2]])
```

a directed unweighted graph with 5 vertices and 3 arcs

```
> delete_arc(DG, [3,4,5,2])
```

a directed unweighted graph with 5 vertices and 3 arcs

### 2.3.2 Accessing and modifying edge weights

`set_edge_weight(G,e,(w))`

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

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

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

*Examples.*

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

a undirected weighted graph with 3 vertices and 2 edges

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

6

### 2.3.3 Contracting edges

`contract_edge(G,e)`

The command `contract_edge` is used for [contracting edges](#) in undirected graphs. It takes two arguments, an undirected graph  $G(V, E)$  and an edge  $e = vw \in E$ , and merges  $v$  and  $w$  to a single vertex, deleting the edge  $e$ . The resulting vertex inherits the label of  $v$ . The modified copy of  $G$  is returned.

*Examples.*

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

a undirected unweighted graph with 5 vertices and 10 edges

```
> contract_edge(K5, [1,2])
```

a undirected unweighted graph with 4 vertices and 6 edges

To contract a set  $\{e_1, e_2, \dots, e_k\} \subset E$  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 `fold1` command. In the following example, the complete graph  $K_5$  is obtained from Petersen graph by edge contraction.

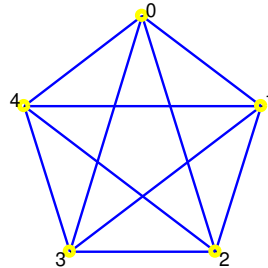
```
> P:=graph("petersen")
```

an undirected unweighted graph with 10 vertices and 15 edges

```
> G:=foldl(contract_edge,P,[0,5],[1,6],[2,7],[3,8],[4,9])
```

an undirected unweighted graph with 5 vertices and 10 edges

```
> draw_graph(G)
```



### 2.3.4 Subdividing edges

`subdivide_edges(G,e|S,r)`

The command `subdivide_edges` is used for [graph subdivision](#). It takes two or three arguments: a graph  $G(V, E)$ , a single edge/arc  $e \in E$  or a list of edges/arcs  $S \subset E$  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 nonnegative integers. The resulting graph, which is homeomorphic to  $G$ , is returned.

If the endpoints of the edge being subdivided have valid coordinates, the coordinates of the inserted vertices will be computed accordingly.

*Examples.*

```
> G:=graph("petersen")
```

an undirected unweighted graph with 10 vertices and 15 edges

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

an undirected unweighted graph with 11 vertices and 16 edges

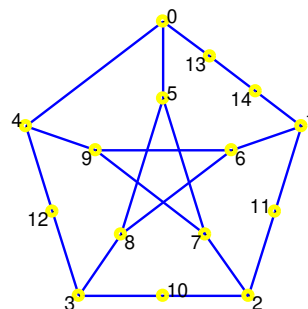
```
> G:=subdivide_edges(G,[[1,2],[3,4]])
```

an undirected unweighted graph with 13 vertices and 18 edges

```
> G:=subdivide_edges(G,[0,1],2)
```

an undirected unweighted graph with 15 vertices and 20 edges

```
> draw_graph(G)
```



## 2.4 Using attributes

### 2.4.1 Graph attributes

```
set_graph_attribute(G,tag1=value1,tag2=value2,...)
set_graph_attribute(G,[tag1=value1,tag2=value2,...])
set_graph_attribute(G,[tag1,tag2,...],[value1,value2,...])
get_graph_attribute(G,tag1,tag2,...)
get_graph_attribute(G,[tag1,tag2,...])
list_graph_attributes(G)
discard_graph_attribute(G,tag1,tag2,...)
discard_graph_attribute(G,[tag1,tag2,...])
```

The graph structure maintains a set of attributes as tag-value pairs which can be accessed and/or modified by using the commands `set_graph_attribute`, `get_graph_attribute`, `list_graph_attributes` and `discard_graph_attribute`.

The command `set_graph_attribute` is used for modifying the existing graph attributes or adding new ones. It takes two arguments, a graph  $G$  and a sequence or list of graph attributes in form `tag=value` where `tag` is a 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  $G$ .

The previously set graph attribute values can be fetched with the command `get_graph_attribute` which takes 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 an 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 command `list_graph_attributes` which takes  $G$  as its only argument.

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

Two tags being used by the CAS commands are `directed` and `weighted`, so it is not advisable to overwrite their values using this command; use the `make_directed`, `make_weighted` and `underlying_graph` commands instead. Another attribute used internally is `name`, which holds the name of the respective graph (as a string).

*Examples.*

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

a directed unweighted graph with 3 vertices and 3 arcs

```
> G:=set_graph_attribute(G,"name"="C3","message"="this is some text")
```

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

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

"this is some text"

```
> list_graph_attributes(G)
```

["directed"=true,"weighted"=false,"name"="C3","message"="this is some text"]

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

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

```
> list_graph_attributes(G)
```

```
[“directed”=true, “weighted”=false, “name”=“C3”]
```

### 2.4.2 Vertex attributes

```
set_vertex_attribute(G,v,tag1=value1,tag2=value2,...)
set_vertex_attribute(G,v,[tag1=value1,tag2=value2,...])
set_vertex_attribute(G,v,[tag1,tag2,...],[value1,value2,...])
get_vertex_attribute(G,v,tag1,tag2,...)
get_vertex_attribute(G,v,[tag1,tag2,...])
list_vertex_attributes(G,v)
discard_vertex_attribute(G,v,tag1,tag2,...)
discard_vertex_attribute(G,v,[tag1,tag2,...])
```

For every vertex of a graph, the list of attributes in form of tag-value pairs is maintained, which can be accessed/modified by using the commands `set_vertex_attribute`, `get_vertex_attribute`, `list_vertex_attributes` and `discard_vertex_attribute`.

The command `set_vertex_attribute` is used for modifying the existing vertex attributes or adding new ones. It takes 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 a 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 takes three arguments:  $G$ ,  $v$  and a sequence or list of tags. The corresponding values will be returned in a sequence or list, respectively. If an attribute is not set, `undef` is returned as its value.

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

The command `discard_vertex_attribute` is used for discarding attribute(s) assigned to some vertex  $v \in V$ . It takes three arguments:  $G$ ,  $v$  and a sequence or list of tags to be cleared, and returns the modified copy of  $G$ .

The attributes `label`, `color`, `shape` and `pos` are also used internally. These hold the vertex label, color, shape and coordinates in a drawing, respectively. If the color is not set for a vertex, the latter is drawn in yellow. The shape attribute may have one of the following values: `square`, `triangle`, `diamond`, `star` or `plus`. If the shape attribute is not set or has a different value, the circled shape is applied when drawing the vertex.

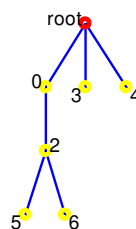
```
> T:=complete_binary_tree(2)
```

an undirected unweighted graph with 7 vertices and 6 edges

```
> T:=set_vertex_attribute(T,1,"label"="root","color"=red)
```

an undirected unweighted graph with 7 vertices and 6 edges

```
> draw_graph(T,tree="root")
```



A vertex may also hold custom attributes.

```
> T:=set_vertex_attribute(T,"root","depth"=3,"shape"=square)
```

an undirected unweighted graph with 15 vertices and 14 edges

```
> list_vertex_attributes(T,"root")
```

```
["label"="root", "color"=red, "shape"="square", "depth"=3]
```

```
> T:=discard_vertex_attribute(T,"root","color")
```

an undirected unweighted graph with 15 vertices and 14 edges

```
> list_vertex_attributes(T,"root")
```

```
["label"="root", "shape"="square", "depth"=3]
```

### 2.4.3 Edge attributes

```
set_edge_attribute(G,e,tag1=value1,tag2=value2,...)
set_edge_attribute(G,e,[tag1=value1,tag2=value2,...])
set_edge_attribute(G,e,[tag1,tag2,...],[value1,value2,...])
get_edge_attribute(G,e,tag1,tag2,...)
get_edge_attribute(G,e,[tag1,tag2,...])
list_edge_attributes(G,e)
discard_edge_attribute(G,e,tag1,tag2,...)
discard_edge_attribute(G,e,[tag1,tag2,...])
```

For every edge of a graph, the list of attributes in form of key-value pairs is maintained, which can be accessed and/or modified by using the commands `set_edge_attribute`, `get_edge_attribute`, `list_edge_attributes` and `discard_edge_attribute`.

The command `set_edge_attribute` is used for modifying the existing edge attributes or adding new ones. It takes 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 a 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 takes 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 command `list_edge_attributes` which takes two arguments,  $G$  and  $e$ .

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

The attributes `weight`, `color`, `style`, `pos` and `temp` are also used internally. They hold the edge weight, color, line style, the coordinates of the weight label anchor (and also the coordinates of the arrow) and `true` if the edge is temporary. If the color attribute is not set for an edge, the latter is drawn in blue, unless it is a temporary edge, in which case it is drawn in light gray. The style attribute may have one of the following values: `dashed`, `dotted` or `bold`. If the style attribute is not set or has a different value, the solid line style is applied when drawing the edge.

```
> T:=cycle_graph(5)
```

an undirected unweighted graph with 5 vertices and 5 edges

```
> T:=set_edge_attribute(T,[1,2],"cost"=12.8,"message"="this is some text")
```

an undirected unweighted graph with 5 vertices and 5 edges

```
> list_edge_attributes(T, [1,2])
```

```
["cost"=12.8, "message"="this is some text"]
```

```
> T:=discard_edge_attribute(T, [1,2], "message")
```

an undirected unweighted graph with 5 vertices and 5 edges

```
> T:=set_edge_attribute(T, [1,2], "style"="dotted", "color"="magenta")
```

an undirected unweighted graph with 5 vertices and 5 edges

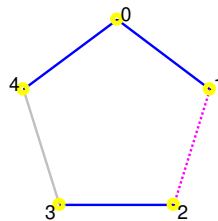
```
> list_edge_attributes(T, [1,2])
```

```
["color"=magenta, "style"="dotted", "cost"=12.8]
```

```
> T:=set_edge_attribute(T, [3,4], "temp"=true)
```

an undirected unweighted graph with 5 vertices and 5 edges

```
> draw_graph(T)
```



# Chapter 3

## Import and export

### 3.1 Importing graphs

#### 3.1.1 Loading graphs from DOT and LST files

`import_graph(filename, <opts>)`

The command `import_graph` is used for importing a graph from text file in `dot` format. It takes a string `filename` as its only argument and returns the graph constructed from instructions written in the file `filename`, or an error. The passed string should contain the path to a file in DOT or LST format. The format is recognized from the extension: the DOT format is associated with extensions `.dot` and `.gv`<sup>3.1</sup>, while the LST format is associated with `.lst`.

If a relative path to the file is specified, i.e. if it does not contain a leading forward slash in Linux, 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`.

In MS WINDOWS, paths must be entered using either the forward slash (e.g. in `C:/Users/You/path/to/file.dot`) or double backslash (e.g. in `C:\\Users\\You\\path\\to\\file.dot`) as the directory separator.

When importing graphs in DOT format, the following optional arguments may be given in a sequence `opts`.

- `style=true|false` — import or discard style-related attributes, including color, shape, style, and position (by default, `style=true`).
- `eval=labels|weights` or `eval=labels+weights` — parse labels and/or weights of the vertices and edges, entered as strings in the file, to the corresponding GIAC expressions. By default, no parsing of edge weights and vertex labels is performed.

Optional arguments are ignored when importing a file in LST format.

For example, assume that the following files exist in the directory `path/to/dot/`.

`example.dot`:

```
graph "ExampleGraph" {  
  a [label="Foo"];  
  b [shape=square,color=red];  
  a -- b [style=bold];  
  b -- c [color=green];  
  b -- d [style=dashed];  
}
```

`octahedron.lst`:

```
1: 3 4 5 6  
2: 3 4 5 6  
3: 5 6
```

---

<sup>3.1</sup> Although it is recommended to use `.gv` as the extension for `dot` files to avoid a certain confusion between different file types, GIAC uses the `.dot` extension because it coincides with the format name. This may change in the future.

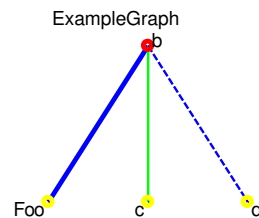
4: 5 6

Now we load these files using `import_graph` and draw the imported graphs.

```
> G:=import_graph("path/to/dot/example.dot")
```

ExampleGraph: an undirected unweighted graph with 4 vertices and 3 edges

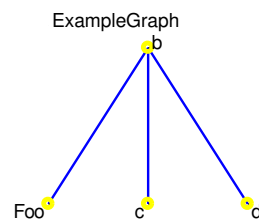
```
> draw_graph(G,tree="b")
```



```
> G:=import_graph("path/to/dot/example.dot",style=false)
```

ExampleGraph: an undirected unweighted graph with 4 vertices and 3 edges

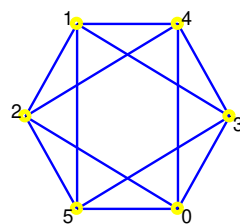
```
> draw_graph(G,tree="b")
```



```
> H:=import_graph("path/to/dot/octahedron.lst")
```

an undirected unweighted graph with 6 vertices and 12 edges

```
> draw_graph(H, spring)
```



```
> is_isomorphic(H,graph("octahedron"))
```

true

### 3.1.2 The DOT file format specification

GIAC has a basic support for the [DOT language](#). Each dot file must correspond to exactly one graph and should consist of a single instance of the following environment:

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



Keywords **strict** and **name** may be omitted, as indicated by the question marks. The former is used for differentiating between simple graphs (strict) and multigraphs (non-strict). Since GIAC 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 must end with the semicolon (;) and has one of the forms given in Table 3.1.

syntax	creates
<code>vertex_name [attributes]?</code>	isolated vertices
<code>V1 &lt;edgeop&gt; V2 &lt;edgeop&gt; ... &lt;edgeop&gt; V<sub>k</sub> [attributes]?</code>	edges and trails
<code>graph [attributes]</code>	graph attributes

**Table 3.1.** Syntax for creating vertices, edges, and graph attributes in the DOT language.

Here, **attributes** is a comma-separated list of tag-value pairs in form **tag=value**, and **<edgeop>** equals to **--** for undirected graphs and **->** for directed graphs. Each of **V1**, **V2** etc. is either a vertex name or a set of vertex names in the form **{vertex\_name1 vertex\_name2 ...}**. If a set of vertices is specified, each vertex in that set is connected to the neighbor operands. A vertex will be created if it does not exist yet.

Lines beginning with **#** are ignored. C-like comments are supported as well.

Using DOT syntax it is easy to specify a graph using adjacency lists. For example, the following is the contents of a file which defines the octahedral graph.

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

Also see the example in Section 3.1.1.

### 3.1.3 The **lst** file format specification

The LST file format is a practical way to save an undirected graph as the sequence of adjacency lists. Unlike the DOT format, it does not support attributes, including vertex labels and edge weights. This format is supported by e.g. [The House of Graphs](#).

Each line of a file in LST format has the following syntax:

```
v: a1 a2 a3 ...
```

Here,  $v$  is a vertex index and  $a_i$  are its neighbors' indices. Hence this line represents the adjacency list of  $v$  (possibly empty, i.e. with no indices after the colon). It is enough to enter adjacencies with respect to the upper triangle of the adjacency matrix, i.e. one can list only the neighbors with indices  $a_j > v$  on each line. Each vertex must be specified somewhere in the file, either as  $v$  or  $a$ .

Note that indices must be 1-based, while the labels in the imported graph are mode-aware (0-based in **xcas** mode and 1-based in **maple** mode) but follow the order specified in the file. For an example of **lst** file, see **octahedron.lst** in Section 3.1.1.

## 3.2 Exporting graphs

```
export_graph(G,filename,<opts>)
```

The command `export_graph` is used for saving graphs to disk in DOT/LST or L<sup>A</sup>T<sub>E</sub>X format. It takes two mandatory arguments, a graph  $G$  and a string `filename`, and writes  $G$  to the file specified by `filename`. The argument `filename` should be a string containing a path to the desired destination file (which is created if it does not exist). The remark on relative paths in Section 3.1.1 applies here as well.

If only two arguments are provided, the extension `.dot/.gv` or `.lst` must exist in `filename`. In the former case the graph is output in DOT format, while in the latter case it is output in LST format (it is thereby required that  $G$  is undirected, and all attributes will be stripped).

The optional argument `opts` is a sequence which can include the following arguments.

- `style=true|false` — if `style` is set to `true` (the default), then the style-related attributes of  $G$  are exported to the file, including color, shape, style, and position. Otherwise, these attributes are discarded.
- `latex(<params>)` — the drawing of  $G$  (obtained by calling the `draw_graph` command) is saved to the L<sup>A</sup>T<sub>E</sub>X file indicated by `filename` (the extension `.tex` may be omitted, in which case it is appended automatically). Optionally, one can specify a parameter or a list of parameters `params` which will be passed to `draw_graph`.

`export_graph` returns 1 on success and 0 on failure.

```
> G:=graph("diamond")
```

an undirected unweighted graph with 4 vertices and 5 edges

```
> G:=set_edge_attribute(G,[0,2],"style"=dashed);
```

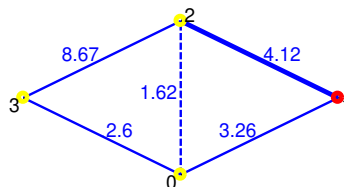
```
> G:=set_edge_attribute(G,[1,2],"style"=bold);
```

```
> G:=set_vertex_attribute(G,1,"color"=red);
```

```
> G:=assign_edge_weights(G,1..10)
```

an undirected weighted graph with 4 vertices and 5 edges

```
> draw_graph(G)
```



```
> export_graph(G,"path/to/diamond.dot")
```

1

The following is the contents of the exported file `diamond.dot`.

```
graph {
  graph [directed=false,weighted=true];
  0 [label=0,pos="1.4300725153,0.430159709003"];
  0 -- 1 [weight=3.26368919434];
  0 -- 2 [weight=1.6176089556,style=dashed];
  0 -- 3 [weight=2.60382712772];
  1 [label=1,color=red,pos="2.430159709,0.894229765084"];
  1 -- { 0 };
  1 -- 2 [weight=4.1175966193,style=bold];
  2 [label=2,pos="1.43051338931,1.3605143449"];
  2 -- { 0 1 };
  2 -- 3 [weight=8.66874152562];
```

```

3 [label=3,pos="0.430159709003,0.894229765084"];
3 -- { 0 2 };
}

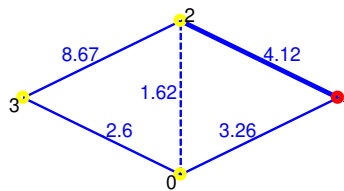
```

The exported file can be imported back to GIAC with the `import_graph` command. By drawing the imported graph, we see that all attributes are interpreted correctly, including the vertex positions generated by the `graph` constructor.

```
> H:=import_graph("path/to/diamond.dot")
```

an undirected weighted graph with 4 vertices and 5 edges

```
> draw_graph(H)
```



If the `style=false` option is used with `export_graph`, all style-related attributes are discarded.

```
> export_graph(G,"path/to/diamond.dot",style=false)
```

1

Now the contents of `diamond.dot` is as follows.

```

graph {
  graph [directed=false,weighted=true];
  0 [label=0];
  0 -- 1 [weight=3.26368919434];
  0 -- 2 [weight=1.6176089556];
  0 -- 3 [weight=2.60382712772];
  1 [label=1];
  1 -- { 0 };
  1 -- 2 [weight=4.1175966193];
  2 [label=2];
  2 -- { 0 1 };
  2 -- 3 [weight=8.66874152562];
  3 [label=3];
  3 -- { 0 2 };
}

```

One can use `export_graph` to obtain graph drawings using the GRAPHVIZ software. In this example, we construct a network, export it to DOT file, and create a layout using `dot`.

```
> V:=[A,B,C,D,E,F,G,H,I,J,K,L,M];;
```

```
> purge(op(V));;
```

```
> net:=digraph(V,%{[A,B],[B,C],[B,D],[C,H],[D,E],[D,F],[D,G],[E,H],[F,H],
  [G,H],[H,I],[H,J],[I,K],[J,L],[K,M],[L,M]}%);
```

a directed unweighted graph with 13 vertices and 16 arcs

```
> net:=relabel_vertices(net,["Excavate","Lay foundation","Rough plumbing",
  "Frame","Finish exterior","Install HVAC","Rough electric","Sheet rock",
  "Install cabinets","Paint","Final plumbing","Final electric","Install
  flooring"]);
```

a directed unweighted graph with 13 vertices and 16 arcs

```
> export_graph(net,"path/to/net.dot")
```

1

Now we enter the following command line in a terminal:

```
dot -Tpdf net.dot -o net_layout.pdf
```

The result is saved to `net_layout.pdf`. The drawing is shown in Figure 3.1. By default, `dot` spreads the graph vertically; if a horizontally oriented layout is desired, then one can set the graph attribute `rankdir` to `LR` before calling `export_graph`.

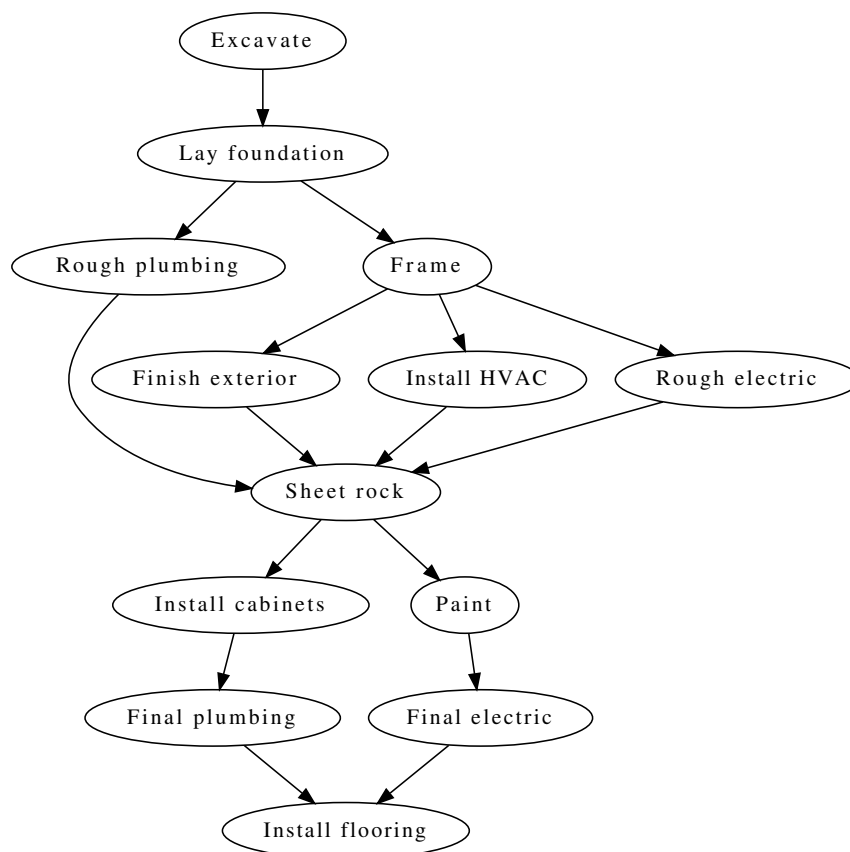
In the following example, we create a  $\text{L}^{\text{A}}\text{T}_{\text{E}}\text{X}$  drawing of the Sierpiński sieve graph  $ST_3^5$ .

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

an undirected unweighted graph with 123 vertices and 243 edges

```
> export_graph(G,"st53.tex",latex=[spring,size=[1,0],labels=false])
```

1



**Fig. 3.1.** A network graph drawn by GRAPHVIZ (`dot`).

# Chapter 4

## Graph properties

### 4.1 Basic properties

#### 4.1.1 Determining the type of a graph

```
is_directed(G)  
is_weighted(G)
```

The commands `is_directed` and `is_weighted` are used for determining the type of a graph: whether is it directed or not resp. weighted or not. Both commands take a graph  $G$  as their only argument. `is_directed` resp. `is_weighted` returns `true` if  $G$  is directed resp. weighted, else it returns `false`.

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

an undirected unweighted graph with 5 vertices and 6 edges

```
> is_directed(G)
```

false

```
> is_directed(make_directed(G))
```

true

```
> is_weighted(G)
```

false

```
> is_weighted(make_weighted(G,randmatrix(5,5,99)))
```

true

#### 4.1.2 Listing vertices and edges

```
vertices(G)  
graph_vertices(G)  
edges(G,⟨weights⟩)  
number_of_vertices(G)  
number_of_edges(G)
```

The command `vertices` or `graph_vertices` resp. `edges` is used for extracting the set of vertices resp. the set of edges from a graph. To obtain the number of vertices resp. the number of edges, use the `number_of_vertices` resp. the `number_of_edges` command.

`vertices` or `graph_vertices` takes a graph  $G(V, E)$  as its only argument and returns the set of vertices  $V$  in the same order in which they were created.

`edges` takes one or two arguments, a graph  $G(V, E)$  and optionally the argument `weights`. This command returns the set of edges  $E$  (in a non-meaningful order). If `weights` is specified, each edge is paired with the corresponding weight (in this case  $G$  must be a weighted graph).

`number_of_vertices` resp. `number_of_edges` takes the input graph  $G(V, E)$  as its only argument and returns  $|V|$  resp.  $|E|$ .

```
> G:=hypercube_graph(3)
```

an undirected unweighted graph with 8 vertices and 12 edges

```
> vertices(G)
```

```
["000","001","010","011","100","101","110","111"]
```

```
> number_of_vertices(G), number_of_edges(G)
```

```
8, 12
```

```
> H:=digraph([[0,2.32,0,0.25],[0,0,0,1.32],[0,0.50,0,0],[0.75,0,3.34,0]])
```

a directed weighted graph with 4 vertices and 6 arcs

```
> edges(H)
```

```
[[0,1],[0,3],[1,3],[2,1],[3,0],[3,2]]
```

```
> edges(H,weights)
```

```
[[[0,1],2.32],[[0,3],0.25],[[1,3],1.32],[[2,1],0.5],[[3,0],0.75],[[3,2],3.34]]
```

### 4.1.3 Equality of graphs

`graph_equal(G1,G2)`

Two graphs are considered **equal** if they are both (un)weighted and (un)directed and if the commands `vertices` and `edges` give the same results for both graphs. To determine whether two graphs are equal use the command `graph_equal`. It takes two arguments, graphs  $G_1$  and  $G_2$ , and returns **true** if  $G_1$  is equal to  $G_2$  with respect to the above definition. Otherwise, it returns **false**.

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

an undirected unweighted graph with 3 vertices and 2 edges

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

an undirected unweighted graph with 3 vertices and 2 edges

```
> graph_equal(G1,G2)
```

```
false
```

```
> G3:=graph(trail(1,2,3))
```

an undirected unweighted graph with 3 vertices and 2 edges

```
> graph_equal(G1,G3)
```

```
true
```

```
> G4:=digraph(trail(1,2,3))
```

a directed unweighted graph with 3 vertices and 2 arcs

```
> graph_equal(G1,G4)
```

```
false
```

#### 4.1.4 Vertex degrees

```
vertex_degree(G,v)
vertex_in_degree(G,v)
vertex_out_degree(G,v)
degree_sequence(G)
minimum_degree(G)
maximum_degree(G)
```

The command `vertex_degree` is used for computing the degree of a vertex, i.e. counting the vertices adjacent to it. The related specialized commands are `vertex_out_degree`, `vertex_in_degree`, `degree_sequence`, `minimum_degree` and `maximum_degree`.

`vertex_degree` takes two arguments, a graph  $G(V, E)$  and a vertex  $v \in V$ . It returns the number of edges in  $E$  which are incident to  $v$ .

When dealing with directed graphs, one can also use the specialized command `vertex_out_degree` resp. `vertex_in_degree` which takes the same arguments as `vertex_degree` but returns the number of arcs  $vw \in E$  resp. the number of arcs  $wv \in E$ , where  $w \in V$ .

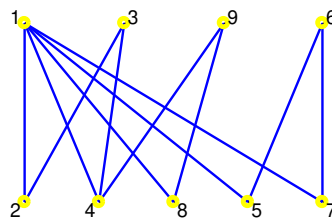
To obtain the list of degrees of all vertices  $v \in V$ , use the command `degree_sequence` which returns the list of degrees of vertices from  $V$  in the same order as returned by the command `vertices`. If  $G$  is a digraph, arc directions are ignored.

To compute the minimum vertex degree  $\delta(G)$  and the maximum vertex degree  $\Delta(G)$  in an undirected graph  $G$ , use the commands `minimum_degree` and `maximum_degree`, respectively.

```
> G:=graph(trail(1,2,3,4,1,5,6,7,1,8,9,4))
```

an undirected unweighted graph with 9 vertices and 11 edges

```
> draw_graph(G)
```



```
> vertex_degree(G,1)
```

5

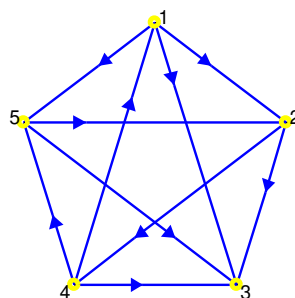
```
> degree_sequence(G)
```

[5, 2, 2, 3, 2, 2, 2, 2, 2]

```
> T:=random_tournament([1,2,3,4,5])
```

a directed unweighted graph with 5 vertices and 10 arcs

```
> draw_graph(T)
```



```
> vertex_out_degree(T,1)
```

3

```
> vertex_in_degree(T,5)
```

2

The command line below shows that Petersen graph is cubic (3-regular).

```
> P:=graph("petersen")
```

an undirected unweighted graph with 10 vertices and 15 edges

```
> minimum_degree(P), maximum_degree(P)
```

3,3

```
> is_regular(P,3)
```

true

#### 4.1.5 Regular graphs

`is_regular(G,⟨d⟩)`

The command `is_regular` is used for determining whether a graph is **regular**. It takes one or two arguments, a graph  $G(V, E)$  and optionally a nonnegative integer or an unassigned identifier  $d$ . If  $G$  is undirected, the return value is **true** if  $\delta_G = \Delta_G$ , i.e. if the minimal vertex degree is equal to the maximal vertex degree in  $G$ , otherwise **false** is returned. If  $G$  is a digraph, it is also required for each vertex  $v \in V$  to have the same in- and out-degree. If the second argument is given,  $G$  is tested for  $d$ -regularity in case  $d$  is an integer, otherwise  $\Delta_G$  is written to  $d$  in case the latter is an identifier and  $G$  is regular.

The complexity of the algorithm is  $O(|V|)$ .

```
> G:=graph("petersen")
```

an undirected unweighted graph with 10 vertices and 15 edges

```
> is_regular(G,d)
```

true

```
> d
```

3

```
> is_regular(G,2)
```

false

```
> is_regular(graph("groetzsch"))
```

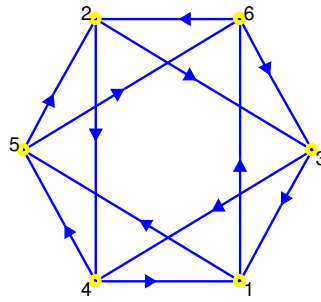
false

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

a directed unweighted graph with 6 vertices and 12 arcs

```
> draw_graph(G, spring)
```





```
> is_regular(G,4)
```

```
true
```

```
> H:=add_arc(delete_arc(G,[5,6]),[6,5])
```

```
a directed unweighted graph with 6 vertices and 12 arcs
```

```
> is_regular(H,4)
```

```
false
```

```
> is_regular(underlying_graph(H))
```

```
true
```

#### 4.1.6 Strongly regular graphs

`is_strongly_regular(G,⟨srg⟩)`

The command `is_strongly_regular` is used for determining whether a graph is **strongly regular**. It takes one or two arguments, a graph  $G(V, E)$  and optionally an unassigned identifier `srg`. It returns `true` if  $G$  is regular and there are integers  $\lambda$  and  $\mu$  such that every two adjacent vertices resp. non-adjacent vertices in  $V$  have exactly  $\lambda$  resp.  $\mu$  common neighbors. Otherwise, it returns `false`. If the second argument is given, the list  $[k, \lambda, \mu]$ , where  $k$  is the degree of  $G$ , is stored to `srg`.

The complexity of the algorithm is  $O(k |V|^2)$ .

```
> G:=graph("clebsch")
```

```
an undirected unweighted graph with 16 vertices and 40 edges
```

```
> is_regular(G)
```

```
true
```

```
> is_strongly_regular(G)
```

```
true
```

```
> H:=graph("shrikhande")
```

```
an undirected unweighted graph with 16 vertices and 48 edges
```

```
> purge(s); is_strongly_regular(H,s)
```

```
"Done", true
```

```
> s
```

[6, 2, 2]

```
> is_strongly_regular(cycle_graph(5))
```

true

```
> is_strongly_regular(cycle_graph(6))
```

false

#### 4.1.7 Vertex adjacency

```
has_edge(G, [u,v])
has_arc(G, [u,v])
neighbors(G, <v>)
departures(G, <v>)
arrivals(G, <v>)
```

The command **has\_edge** is used for determining whether two vertices in an undirected graph are adjacent. For digraphs, there is an analogous command **has\_arc**.

The command **neighbors** is used for obtaining the list of vertices in a graph that are adjacent to the particular vertex or the complete adjacency structure of the graph, in sparse form.

The command **departures** resp. **arrivals** is used for obtaining all neighbors of a vertex  $v$  in a digraph which are the heads resp. the tails of the corresponding arcs.

**has\_edge** takes two arguments, an undirected graph  $G(V, E)$  and a list  $[u, v]$  where  $u, v \in V$ . The command returns **true** if  $uv \in E$  and **false** otherwise. The syntax for **has\_arc** is the same, except now  $G$  is required to be directed. Note, however, that the order of vertices  $u$  and  $v$  matters in digraphs. The worst-case complexity of both algorithms is  $O(\log |V|)$ .

**neighbors** takes one or two arguments, a graph  $G(V, E)$  and optionally a vertex  $v \in V$ . It returns the list of vertices adjacent to  $v$ , if given. Otherwise, it returns the list of lists of neighbors for all vertices in  $V$ , in order of **vertices**( $G$ ). Note that edge directions are ignored in case  $G$  is a digraph.

**departures** resp. **arrivals** takes one or two arguments, a digraph  $G(V, E)$  and optionally a vertex  $v \in V$ , and returns the list  $L_v$  containing all vertices  $w \in V$  for which  $vw \in E$  resp.  $wv \in E$ . If  $v$  is omitted, the list of lists  $L_v$  for each  $v \in V$  is returned.

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

an undirected unweighted graph with 5 vertices and 5 edges

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

true

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

true

```
> has_edge(G, [1,3])
```

false

```
> D:=digraph(trail(1,2,3,4,5,2,1))
```

a directed unweighted graph with 5 vertices and 6 arcs

```
> has_arc(D, [1,2])
```

true

```
> has_arc(D,[2,1])
```

true

```
> has_arc(D,%{1,2%})
```

true

```
> has_arc(D,[4,5])
```

true

```
> has_arc(D,[5,4])
```

false

```
> has_arc(D,%{4,5%})
```

false

```
> neighbors(G,3)
```

```
[2,4]
```

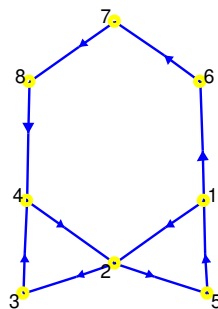
```
> neighbors(G)
```

```
[[2],[1,3,5],[2,4],[3,5],[2,4]]
```

```
> G:=digraph(trail(1,2,3,4,2,5,1,6,7,8,4))
```

a directed unweighted graph with 8 vertices and 10 arcs

```
> draw_graph(G,spring)
```



```
> departures(G,2); arrivals(G,2); departures(G,1); arrivals(G,1)
```

```
[3,5],[1,4],[2,6],[5]
```

### 4.1.8 Tournament graphs

`is_tournament(G)`

The command `is_tournament` is used for determining whether a graph is a [tournament](#). It takes a graph  $G(V, E)$  as its only argument and returns `true` if  $G$  is directed and for each pair of vertices  $u, v \in V$  it is either  $uv \in E$  or  $vu \in E$ , i.e. there is exactly one arc between  $u$  and  $v$ . Otherwise, it returns `false`.

```
> T1:=digraph(%{[1,2],[2,3],[3,1]%})
```

a directed unweighted graph with 3 vertices and 3 arcs

```
> is_tournament(T1)
```

true

```
> T2:=digraph(%{[1,2],[2,3],[3,1],[1,3]%})
```

a directed unweighted graph with 3 vertices and 4 arcs

```
> is_tournament(T2)
```

false

### 4.1.9 Bipartite graphs

`is_bipartite(G,⟨P⟩)`

The command `is_bipartite` is used for determining if a graph is **bipartite**. It takes one or two arguments, a graph  $G(V, E)$  and optionally an unassigned identifier  $P$ . It returns **true** if there is a partition of  $V$  into two sets  $S$  and  $T$  such that every edge from  $E$  connects a vertex in  $S$  to one in  $T$ . Otherwise, it returns **false**. If the second argument is given and  $G$  is bipartite, the partition of  $V$  is stored to  $P$  as a list of two lists of vertices, the first one containing the vertices from  $S$  and the second one containing vertices from  $T$ .

```
> K32:=complete_graph(3,2)
```

an undirected unweighted graph with 5 vertices and 6 edges

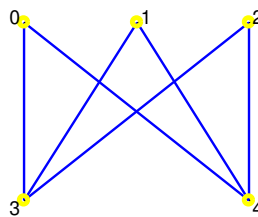
```
> is_bipartite(K32,bp)
```

true

```
> bp
```

[[0, 1, 2], [3, 4]]

```
> draw_graph(K32,bipartite)
```



```
> adjacency_matrix(K32)
```

$$\begin{pmatrix} 0 & 0 & 0 & 1 & 1 \\ 0 & 0 & 0 & 1 & 1 \\ 0 & 0 & 0 & 1 & 1 \\ 1 & 1 & 1 & 0 & 0 \\ 1 & 1 & 1 & 0 & 0 \end{pmatrix}$$

```
> C5:=cycle_graph(5)
```

an undirected unweighted graph with 5 vertices and 5 edges

```
> is_bipartite(G)
```

false

#### 4.1.10 Edge incidence

```
incident_edges(G,v|L)
```

The command `incident_edges` is used for obtaining edges incident to a given vertex in a graph. It takes two arguments, a graph  $G(V, E)$  and a vertex  $v \in V$  or a list of vertices  $L \subset V$ , and returns the list of edges  $e_1, e_2, \dots, e_k \in E$  such that each of them has  $v$  as one of its endpoints.

Note that edge directions are ignored when  $G$  is a digraph. To obtain only outgoing or incoming edges, use the commands `departures` and `arrivals`, respectively.

```
> G:=cycle_graph([1,2,3,4,5])
```

an undirected unweighted graph with 5 vertices and 5 edges

```
> incident_edges(G,1)
```

[[1, 2], [1, 5]]

```
> incident_edges(G,[2,4,5])
```

[[1, 2], [1, 5], [2, 3], [3, 4], [4, 5]]

```
> G:=random_tournament([1,2,3,4,5])
```

a directed unweighted graph with 5 vertices and 10 arcs

```
> incident_edges(G,2)
```

[[2, 1], [2, 3], [2, 4], [2, 5]]

## 4.2 Algebraic properties

### 4.2.1 Adjacency matrix

```
adjacency_matrix(G)
```

The command `adjacency_matrix` is used for obtaining the `adjacency matrix` of a graph. It takes a graph  $G(V, E)$ , where  $V = \{v_1, v_2, \dots, v_n\}$ , as its only argument and returns the square matrix  $A = [a_{ij}]$  of order  $n$  such that, for  $i, j = 1, 2, \dots, n$ ,

$$a_{ij} = \begin{cases} 1, & \text{if the set } E \text{ contains edge/arc } v_i v_j, \\ 0, & \text{otherwise.} \end{cases}$$

Note that  $\text{tr}(A) = 0$ . Also, the adjacency matrix of an undirected graph is always symmetric.

```
> G:=graph("octahedron")
```

an undirected unweighted graph with 6 vertices and 12 edges

```
> A:=adjacency_matrix(G)
```

$$\begin{pmatrix} 0 & 0 & 1 & 1 & 1 & 1 \\ 0 & 0 & 1 & 1 & 1 & 1 \\ 1 & 1 & 0 & 0 & 1 & 1 \\ 1 & 1 & 0 & 0 & 1 & 1 \\ 1 & 1 & 1 & 1 & 0 & 0 \\ 1 & 1 & 1 & 1 & 0 & 0 \end{pmatrix}$$

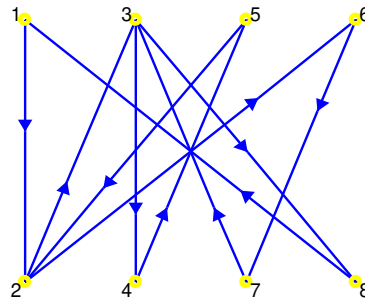
```
> transpose(A)==A
```

```
true
```

```
> D:=digraph(trail(1,2,3,4,5,2,6,7,3,8,1))
```

a directed unweighted graph with 8 vertices and 10 arcs

```
> draw_graph(D)
```



```
> A:=adjacency_matrix(D)
```

$$\begin{pmatrix} 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{pmatrix}$$

```
> transpose(A)==A
```

```
false
```

### 4.2.2 Laplacian matrix

```
laplacian_matrix(G,⟨normal⟩)
```

The command `laplacian_matrix` is used for computing the [Laplacian matrix](#) of a graph. It takes a graph  $G(V, E)$ , where  $V = \{v_1, v_2, \dots, v_n\}$ , and returns the matrix  $L = D - A$ , where  $A$  is the (weighted) adjacency matrix of  $G$  and

$$D = \begin{pmatrix} \deg(v_1) & 0 & \cdots & 0 \\ 0 & \deg(v_2) & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & \deg(v_n) \end{pmatrix}.$$

The number  $\deg(v)$  is computed by summing weights of all edges incident to  $v$  (in unweighted graphs, all edge weights are assumed to be equal to 1). The option `normal` may be passed as the second argument. In that case, the [normalized Laplacian](#)

$$L^{\text{sym}} := I - D^{-1/2} A D^{-1/2}$$

of  $G$  is returned.

```
> G:=path_graph(4)
```

an undirected unweighted graph with 4 vertices and 3 edges

```
> A:=adjacency_matrix(G)
```

$$\begin{pmatrix} 0 & 1 & 0 & 0 \\ 1 & 0 & 1 & 0 \\ 0 & 1 & 0 & 1 \\ 0 & 0 & 1 & 0 \end{pmatrix}$$

```
> L:=laplacian_matrix(G)
```

$$\begin{pmatrix} 1 & -1 & 0 & 0 \\ -1 & 2 & -1 & 0 \\ 0 & -1 & 2 & -1 \\ 0 & 0 & -1 & 1 \end{pmatrix}$$

```
> diag(degree_sequence(G))-A==L
```

true

```
> laplacian_matrix(G,normal)
```

$$\begin{pmatrix} 1 & -\frac{1}{\sqrt{2}} & 0 & 0 \\ -\frac{1}{\sqrt{2}} & 1 & -\frac{1}{2} & 0 \\ 0 & -\frac{1}{2} & 1 & -\frac{1}{\sqrt{2}} \\ 0 & 0 & -\frac{1}{\sqrt{2}} & 1 \end{pmatrix}$$

The smallest eigenvalue of the Laplacian matrix of an undirected graph is always zero. Moreover, its multiplicity is equal to the number of connected components in the corresponding graph [34, p. 280].

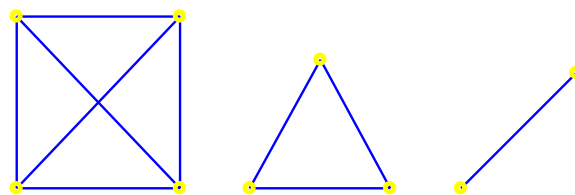
```
> sort(eigenvals(L))
```

$0, -\sqrt{2} + 2, 2, \sqrt{2} + 2$

```
> H:=disjoint_union(complete_graph(4),cycle_graph(3),path_graph(2))
```

an undirected unweighted graph with 9 vertices and 10 edges

```
> draw_graph(H,labels=false)
```



```
> eigenvals(laplacian_matrix(H))
```

```
0, 0, 0, 4, 4, 4, 3, 3, 2
```

Therefore, the multiplicity of zero eigenvalue is equal to 3. Indeed, that is also the number of connected components in  $H$ :

```
> nops(connected_components(H))
```

```
3
```

### 4.2.3 Incidence matrix

```
incidence_matrix(G)
```

The command `incidence_matrix` is used for obtaining the **incidence matrix** of a graph. It takes a graph  $G(V, E)$ , where  $V = \{v_1, v_2, \dots, v_n\}$  and  $E = \{e_1, e_2, \dots, e_m\}$ , as its only argument and returns the  $n \times m$  matrix  $B = [b_{ij}]$  such that, for all  $i = 1, 2, \dots, n$  and  $j = 1, 2, \dots, m$ ,

$$b_{ij} = \begin{cases} 1, & \text{if the vertex } v_i \text{ is incident to the edge } e_j, \\ 0, & \text{otherwise} \end{cases}$$

if  $G$  is undirected resp.

$$b_{ij} = \begin{cases} 1, & \text{if the vertex } v_i \text{ is the head of the arc } e_j, \\ -1, & \text{if the vertex } v_i \text{ is the tail of the arc } e_j, \\ 0, & \text{otherwise} \end{cases}$$

if  $G$  is directed.

```
> K4:=complete_graph([1,2,3,4])
```

an undirected unweighted graph with 4 vertices and 6 edges

```
> edges(K4)
```

```
[[1, 2], [1, 3], [1, 4], [2, 3], [2, 4], [3, 4]]
```

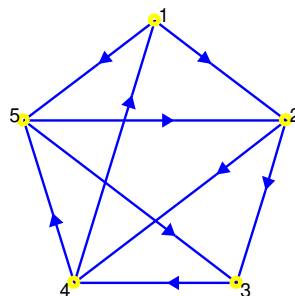
```
> incidence_matrix(K4)
```

$$\begin{pmatrix} 1 & 1 & 1 & 0 & 0 & 0 \\ 1 & 0 & 0 & 1 & 1 & 0 \\ 0 & 1 & 0 & 1 & 0 & 1 \\ 0 & 0 & 1 & 0 & 1 & 1 \end{pmatrix}$$

```
> DG:=digraph(trail(1,2,3,4,5,3),trail(1,5,2,4,1))
```

a directed unweighted graph with 5 vertices and 9 arcs

```
> draw_graph(DG)
```





```
> edges(DG)
```

```
[[1, 2], [1, 5], [2, 3], [2, 4], [3, 4], [4, 1], [4, 5], [5, 2], [5, 3]]
```

```
> incidence_matrix(DG)
```

$$\begin{pmatrix} -1 & -1 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 1 & 0 & -1 & -1 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 1 & 0 & -1 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 1 & 1 & -1 & -1 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 1 & -1 & -1 \end{pmatrix}$$

#### 4.2.4 Weight matrix

```
weight_matrix(G)
```

The command `weight_matrix` is used for obtaining the weight matrix of a [weighted graph](#). It takes a graph  $G(V, E)$ , where  $V = \{v_1, v_2, \dots, v_n\}$ , as its only argument and returns the square matrix  $M = [m_{ij}]$  of order  $n$  such that  $m_{ij}$  equals zero if  $v_i$  and  $v_j$  are not adjacent and the weight of the edge  $v_i v_j$  otherwise, for all  $i, j = 1, 2, \dots, n$ .

Note that  $\text{tr}(M) = 0$ . Also, the weight matrix of an undirected graph is always symmetric.

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

an undirected weighted graph with 5 vertices and 4 edges

```
> weight_matrix(G)
```

$$\begin{pmatrix} 0 & 1 & 0 & 0 & 0 \\ 1 & 0 & 2 & 0 & 4 \\ 0 & 2 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 3 \\ 0 & 4 & 0 & 3 & 0 \end{pmatrix}$$

#### 4.2.5 Characteristic polynomial

```
graph_charpoly(G,⟨x⟩)
```

```
charpoly(G,⟨x⟩)
```

The command `graph_charpoly` or `charpoly` is used for obtaining the [characteristic polynomial](#) of an undirected graph. It takes one or two arguments, an undirected graph  $G(V, E)$  and optionally a value or symbol  $x$ . The command returns  $p(x)$ , where  $p$  is the characteristic polynomial of the adjacency matrix of  $G$ .

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

an undirected unweighted graph with 3 vertices and 2 edges

```
> charpoly(G,x)
```

$$x^3 - 2x$$

```
> charpoly(G,3)
```

```
> G:=graph("shrikhande")
```

an undirected unweighted graph with 16 vertices and 48 edges

```
> charpoly(G,x)
```

$$x^{16} - 48x^{14} - 64x^{13} + 768x^{12} + 1536x^{11} - 5888x^{10} - 15360x^9 + 23040x^8 + 81920x^7 - 36864x^6 - 245760x^5 - 32768x^4 + 393216x^3 + 196608x^2 - 262144x - 196608$$

## 4.2.6 Graph spectrum

`graph_spectrum(G)`

The command `graph_spectrum` is used for computing [graph spectra](#). It takes a graph  $G$  as its only argument and returns the list in which every element is an eigenvalue of the adjacency matrix of  $G$  paired with its multiplicity.

```
> C5:=cycle_graph(5)
```

an undirected unweighted graph with 5 vertices and 5 edges

```
> gs:=graph_spectrum(C5)
```

$$\begin{pmatrix} 2 & 1 \\ \frac{\sqrt{5}-1}{2} & 2 \\ -\frac{\sqrt{5}-1}{2} & 2 \end{pmatrix}$$

```
> p:=charpoly(C5,x)
```

$$x^5 - 5x^3 + 5x - 2$$

```
> expand(roots(p))==expand(gs)
```

true

The above result indicates that `gs` and `roots(p)` are equal.

## 4.2.7 Seidel spectrum

`seidel_spectrum(G)`

The command `seidel_spectrum` is used for computing [Seidel spectra](#). It takes a graph  $G(V, E)$  as its only argument and returns the list in which every element is an eigenvalue of the [Seidel adjacency matrix](#)  $S$  paired with its multiplicity. The matrix  $S$ , which can be interpreted as the difference of the adjacency matrices of  $G$  and its complement  $G^c$ , is computed as  $J - I - 2A$ , where  $J$  is all-one  $n \times n$  matrix,  $I$  is the identity matrix of order  $n$ ,  $A$  is the adjacency matrix of  $G$  and  $n = |V|$ .

```
> seidel_spectrum(graph("clebsch"))
```

$$\begin{pmatrix} -3 & 10 \\ 5 & 6 \end{pmatrix}$$

```
> seidel_spectrum(graph("levi"))
```

$$\begin{pmatrix} -5 & 9 \\ -1 & 10 \\ 3 & 9 \\ 5 & 1 \\ 23 & 1 \end{pmatrix}$$

### 4.2.8 Integer graphs

`is_integer_graph(G)`

The command `is_integer_graph` is used for determining whether a graph is an [integral graph](#). It takes a graph  $G$  as its only argument and returns `true` if the [spectrum](#) of  $G$  consists only of integers. Otherwise, it returns `false`.

```
> G:=graph("levi")
```

an undirected unweighted graph with 30 vertices and 45 edges

```
> is_integer_graph(G)
```

true

```
> factor(charpoly(G,x))
```

$$x^{10}(x-3)(x-2)^9(x+2)^9(x+3)$$

```
> graph_spectrum(G)
```

$$\begin{pmatrix} -3 & 1 \\ -2 & 9 \\ 0 & 10 \\ 2 & 9 \\ 3 & 1 \end{pmatrix}$$

## 4.3 Graph isomorphism

### 4.3.1 Isomorphic graphs

`is_isomorphic(G1,G2,<m>)`

The command `is_isomorphic` is used for determining whether two graphs are [isomorphic](#). It takes two or three arguments: a graph  $G_1(V_1, E_1)$ , a graph  $G_2(V_2, E_2)$  and optionally an unassigned identifier  $m$ . The command returns `true` if  $G_1$  and  $G_2$  are isomorphic and `false` otherwise. If the third argument is given and  $G_1$  and  $G_2$  are isomorphic, the list of pairwise matching of vertices in  $G_1$  and  $G_2$ , representing the isomorphism between the two graphs, is stored to  $m$ .

Note that the algorithm takes vertex colors into account. Namely, only vertices sharing the same color can be mapped to each other. Vertex colors can be set by calling the [highlight\\_vertex](#) command.

This command, as well as the commands [canonical\\_labeling](#) and [graph\\_automorphisms](#) described later in this section, is using the NAUTY library [55], which is one of the fastest implementations for graph isomorphism. If NAUTY is not available, `is_isomorphic` uses ULLMANN's algorithm [80] as a fallback.

```
> is_isomorphic(graph("petersen"),kneser_graph(5,2))
```

true

In the following example,  $G_1$  and  $G_3$  are isomorphic while  $G_1$  and  $G_2$  are not isomorphic.

```
> G1:=graph(trail(1,2,3,4,5,6,1,3))
```

an undirected unweighted graph with 6 vertices and 7 edges

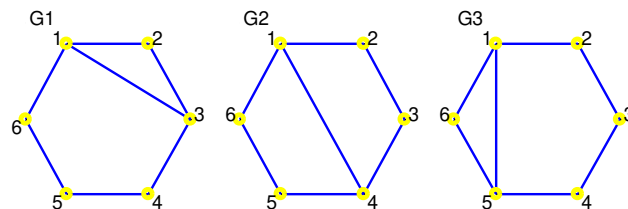
```
> G2:=graph(trail(1,2,3,4,5,6,1,4))
```

an undirected unweighted graph with 6 vertices and 7 edges

```
> G3:=graph(trail(1,2,3,4,5,6,1,5))
```

an undirected unweighted graph with 6 vertices and 7 edges

```
> draw_graph(G1,circle,[0,0],size=[1,0],title="G1");
draw_graph(G2,circle,[1.3,0],size=[1,0],title="G2");
draw_graph(G3,circle,[2.6,0],size=[1,0],title="G3");
```



```
> is_isomorphic(G1,G2)
```

false

```
> is_isomorphic(G1,G3)
```

true

```
> purge(mapping):: is_isomorphic(G1,G3,mapping):: mapping
```

"Done", "Done", [1 = 5, 2 = 6, 3 = 1, 4 = 2, 5 = 3, 6 = 4]

```
> H1:=highlight_vertex(G1,5):: H3:=highlight_vertex(G3,5)::
```

"Done", "Done"

```
> is_isomorphic(H1,H3)
```

false

```
> H1:=highlight_vertex(H1,1):: H3:=highlight_vertex(H3,3)::
```

"Done", "Done"

```
> is_isomorphic(H1,H3)
```

true

In the following example,  $D_1$  and  $D_3$  are isomorphic while  $D_1$  and  $D_2$  are not isomorphic.

```
> D1:=digraph(trail(1,2,3,1,4,5))
```

a directed unweighted graph with 5 vertices and 5 arcs

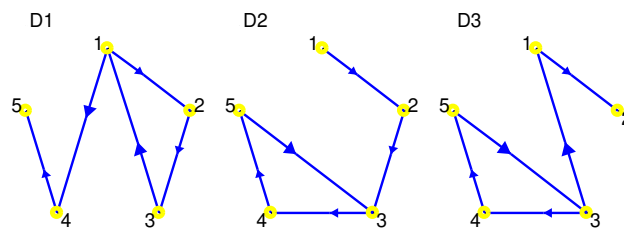
```
> D2:=digraph(trail(1,2,3,4,5,3))
```

a directed unweighted graph with 5 vertices and 5 arcs

```
> D3:=digraph([1,2,3,4,5],trail(3,4,5,3,1,2))
```

a directed unweighted graph with 5 vertices and 5 arcs

```
> draw_graph(D1,circle,[0,0],size=[1,0],title="D1");
draw_graph(D2,circle,[1.3,0],size=[1,0],title="D2");
draw_graph(D3,circle,[2.6,0],size=[1,0],title="D3");
```



```
> is_isomorphic(D1,D2)
```

false

```
> is_isomorphic(D1,D3)
```

true

Isomorphism testing with NAUTY is very fast and can be used for large graphs, as in the example below.

```
> G:=random_graph(10000,0.01)
```

an undirected unweighted graph with 10000 vertices and 498793 edges

```
> H:=permute_vertices(G,shuffle)
```

an undirected unweighted graph with 10000 vertices and 498793 edges

```
> vertices(G)==vertices(H)
```

false

```
> is_isomorphic(G,H)
```

true

1.567 sec

To make the edge structures of  $G$  and  $H$  slightly different, a random edge from  $H$  is “misplaced”.

```
> ed:=edges(H)[rand(number_of_edges(H))]
```

[4826,5144]

```
> has_edge(H,[4826,5145])
```

false

```
> H:=add_edge(delete_edge(H,ed),[4826,5145])
```

an undirected unweighted graph with 10000 vertices and 498793 edges

```
> is_isomorphic(G,H)
```

false

1.678 sec

### 4.3.2 Canonical labeling

`canonical_labeling(G)`

Graph isomorphism testing in NAUTY is based on computing the canonical labeling for the input graphs. The **canonical labeling** of  $G$  is a particular ordering of the vertices of  $G$ . Rearranging the vertices with respect to that ordering produces the **canonical representation** of  $G$ . Two graphs are isomorphic if and only if their canonical representations share the same edge structure.

The command `canonical_labeling` is used for computing the canonical labeling as a permutation. One can reorder the vertices by using this permutation with the `isomorphic_copy` command.

`canonical_labeling` takes a graph  $G(V, E)$  as its only argument and returns the permutation representing the canonical labeling of  $G$ . Note that the colors of the vertices are taken into account.

In the next example it is demonstrated how to prove that  $G_1$  and  $G_3$  are isomorphic by comparing their canonical representations  $C_1$  and  $C_3$  with the `graph_equal` command. Before testing  $C_1$  and  $C_3$  for equality, their vertices have to be relabeled so that the command `vertices` gives the same result for both graphs.

```
> L1:=canonical_labeling(G1)
```

[4, 3, 5, 1, 2, 0]

```
> L3:=canonical_labeling(G3)
```

[2, 1, 3, 5, 0, 4]

```
> C1:=relabel_vertices(isomorphic_copy(G1,L1),[1,2,3,4,5,6])
```

an undirected unweighted graph with 6 vertices and 7 edges

```
> C3:=relabel_vertices(isomorphic_copy(G3,L3),[1,2,3,4,5,6])
```

an undirected unweighted graph with 6 vertices and 7 edges

```
> graph_equal(C1,C3)
```

true

### 4.3.3 Graph automorphisms

`graph_automorphisms(G)`

The command `graph_automorphisms` is used for finding generators of the `automorphism` group of a graph. It takes a graph  $G$  as its only argument and returns a list containing the generators of  $\text{Aut}(G)$ , the automorphism group of  $G$  (see [34, p. 4] and [10, p. 115]). Each generator is given as a list of cycles, which can be turned to a permutation by calling the command `cycles2permu`.

Note that vertex colors are taken into account. Only vertices sharing the same color can be mapped to each other. The color of a vertex can be set by calling the command `highlight_vertex`.

```
> g:=graph_automorphisms(graph("petersen"))
```

```
[[[3, 7], [4, 5], [8, 9]], [[2, 6], [3, 8], [4, 5], [7, 9]], [[1, 4], [2, 3], [6, 9], [7, 8]], [[0, 1], [2, 4], [5, 6], [7, 9]]]
```

```
> cycles2permu(g[2])
```

```
[0, 4, 3, 2, 1, 5, 9, 8, 7, 6]
```

```
> G:=graph("petersen")
```

```
an undirected unweighted graph with 10 vertices and 15 edges
```

```
> G:=highlight_vertex(G,4)
```

```
an undirected unweighted graph with 10 vertices and 15 edges
```

```
> graph_automorphisms(G)
```

```
[[[2, 6], [3, 9], [7, 8]], [[1, 5], [2, 7], [3, 9], [6, 8]], [[0, 3], [1, 2], [5, 8], [6, 7]]]
```

In the above result, all permutations map the vertex 4 to itself, because it is the single green-colored vertex in  $G$  (it cannot be mapped to any other vertex because colors do not match).

Frucht graph (see the page 32) is an example of a graph with automorphism group containing only the identity, so the set of its generators is empty:

```
> graph_automorphisms(graph("frucht"))
```

```
[]
```

#### 4.3.4 Test for isomorphism against subgraphs

```
is_subgraph_isomorphic(G1,G2,<opts>)
```

The command `is_subgraph_isomorphic` is used for checking whether a graph is isomorphic to a subgraph of another graph. It takes two mandatory arguments, graphs  $G_1(V_1, E_1)$  and  $G_2(V_2, E_2)$ , which are either both undirected or both directed. If  $G_1$  or  $G_2$  is a weighted graph, the edge weights are ignored. The command returns `true` if  $G_1$  is isomorphic to a subgraph  $S$  of  $G_2$ , else it returns `false`. A sequence of optional arguments may be passed as the third argument `opts`. The following options are supported:

- `induced_subgraph` —  $S$  must be an induced subgraph of  $G_2$ .
- `unassigned identifier` — a destination to which  $S$  is stored.

The strategy is to use ULLMANN's backtracking algorithm [80] with improvements by ČIBEJ and MIHELIC [17]. The implementation is space-efficient but may perform slower on regular graphs.

In the first example we show that the flower snark  $J_5$  contains a 5- and 6-cycle.

```
> J5:=flower_snark(5)
```

```
an undirected unweighted graph with 20 vertices and 30 edges
```

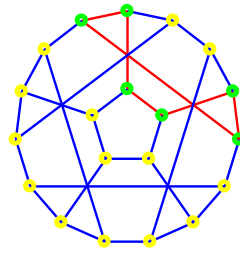
```
> is_subgraph_isomorphic(cycle_graph(5),J5)
```

```
true
```

```
> purge(S); is_subgraph_isomorphic(cycle_graph(6),J5,S)
```

```
"Done", true
```

```
> draw_graph(highlight_subgraph(J5,S),labels=false)
```

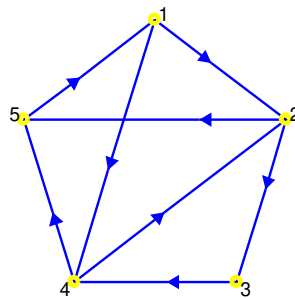


In the example below we find 3-cycle in a directed graph.

```
> G:=digraph(trail(1,2,3,4,5,1,4,2,5))
```

a directed unweighted graph with 5 vertices and 8 arcs

```
> draw_graph(G)
```



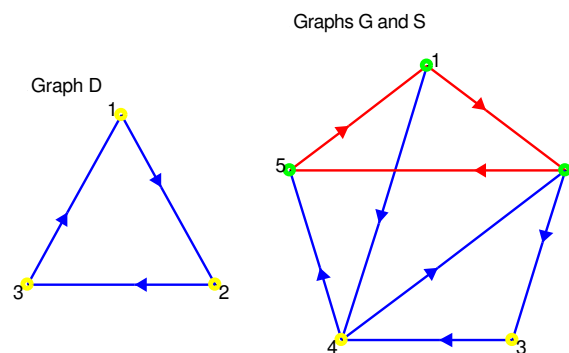
```
> D:=digraph([1,2,3],trail(1,2,3,1))
```

a directed unweighted graph with 3 vertices and 3 arcs

```
> purge(S):: is_subgraph_isomorphic(D,G,S)
```

"Done", true

```
> draw_graph(D, [0,0.2], size=[0,0.62], title="Graph D");  
> draw_graph(highlight_subgraph(G,S), [1,0], size=[0,1], title="Graphs G and S");
```



In the following example, we verify that the Sylvester graph is a subgraph of the Hoffman-Singleton graph.

```
> HS:=graph("hoffman-singleton")
```

an undirected unweighted graph with 50 vertices and 175 edges

```
> G:=graph("sylvester")
```



an undirected unweighted graph with 36 vertices and 90 edges

```
> is_subgraph_isomorphic(G,HS)
```

true

The source graph may also be sought only among induced subgraphs of the destination graph, as in the example below.

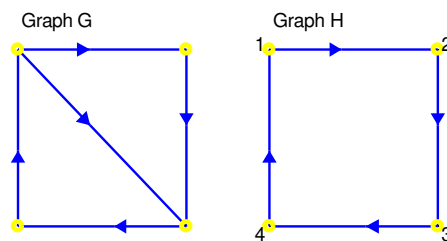
```
> G:=digraph(trail(1,2,3,4,1,3))
```

a directed unweighted graph with 4 vertices and 5 arcs

```
> H:=digraph(trail(1,2,3,4,1))
```

a directed unweighted graph with 4 vertices and 4 arcs

```
> draw_graph(G,[0,0],size=[1,0],labels=false,title="Graph G");
draw_graph(H,[1.5,0],size=[1,0],circle=[1,2,3,4],title="Graph H")
```



```
> is_subgraph_isomorphic(H,G)
```

true

```
> is_subgraph_isomorphic(H,G,induced_subgraph)
```

false

### 4.3.5 Recognizing special graphs

```
identify_graph(G,⟨haar_graph=<n>⟩)
```

The command `identify_graph` is used for testing a graph for isomorphism against special graphs known to GIAC. It takes a graph  $G$  as its mandatory argument and returns the list of special graphs which are isomorphic to  $G$ . Each entry in the list is a list comprised of the respective constructor and a sequence of parameters.

The optional argument `haar_graph=<n>`, where  $n$  is an integer between 0 and 64 (by default  $n = 25$ ), is used for setting an upper limit for the number of vertices in each partition of a Haar graph. Haar graphs with more than  $2n$  vertices will not be tested for an isomorphism. If  $n = 0$ , then Haar graphs are not tested at all. This is also equivalent to setting `haar_graph=false`.

Note that `identify_graph` outputs only the lowest index of an isomorphic Haar graph.

```
> G:=graph("petersen")
```

an undirected unweighted graph with 10 vertices and 15 edges

```
> identify_graph(G)
```

```
[[kneser_graph, 5, 2], [odd_graph, 3], [petersen_graph, 5, 2], [graph, "petersen"]]
```

```
> G:=petersen_graph(16,7)
```

an undirected unweighted graph with 32 vertices and 48 edges

```
> identify_graph(G)
```

```
[[petersen_graph, 16, 7], [haar_graph, 32786]]
```

In the following example, we remove an edge together with all incident vertices from the Hoffman-Singleton graph. The remaining graph is isomorphic to the Sylvester graph, as discovered by `identify_graph`.

```
> G:=graph("hoffman-singleton")
```

an undirected unweighted graph with 50 vertices and 175 edges

```
> ed:=choice(edges(G))
```

```
[36, 37]
```

```
> H:=delete_vertex(G,concat(ed,neighbors(G,ed[0]),neighbors(G,ed[1])))
```

an undirected unweighted graph with 36 vertices and 90 edges

```
> identify_graph(H)
```

```
[[graph, "sylvester"]]
```

## 4.4 Graph polynomials

### 4.4.1 Tutte polynomial

```
tutte_polynomial(G,⟨x,y⟩)
```

The command `tutte_polynomial` is used for computing [Tutte polynomials](#). It takes one or three arguments, an undirected graph  $G(V, E)$  and optionally two variables or values  $x$  and  $y$ . It returns the bivariate Tutte polynomial<sup>4.1</sup>  $T_G$  of  $G$  or the value  $T_G(x, y)$  if the optional arguments are given. If  $G$  is weighted, it is treated as a multigraph: the weight  $w$  of an edge  $e$ , which must be a positive integer, is interpreted as the multiplicity of  $e$ , for each  $e \in E$ . Note, however, that loops are not supported.

The strategy is to apply the recursive definition of Tutte polynomial [36] together with the vorder heuristic proposed by HAGGARD et al. [37] and improved by MONAGAN [56]. The subgraphs appearing in the computation tree are cached and reused when possible, pruning the tree significantly. Subgraphs are stored (and compared) in their canonical form, for which the NAUTY library is used.

Note that finding Tutte polynomials is NP-hard in general, hence the problem becomes intractable for larger and/or denser graphs.

```
> K4:=complete_graph(4)
```

an undirected unweighted graph with 4 vertices and 6 edges

---

4.1. See [36], [10, p. 97] and [11, p. 335].

```
> tutte_polynomial(K4,x,y)
```

$$x^3 + 3x^2 + 4xy + 2x + y^3 + 3y^2 + 2y$$

```
> tutte_polynomial(K4,x,1)
```

$$x^3 + 3x^2 + 6x + 6$$

```
> G:=graph("petersen")
```

an undirected unweighted graph with 10 vertices and 15 edges

```
> f:=tutte_polynomial(G)
```

$$y^6 + 9y^5 + 10y^4x + 35y^4 + 15y^3x^2 + 65y^3x + 75y^3 + 30y^2x^3 + 105y^2x^2 + 171y^2x + 84y^2 + 12yx^5 + 70yx^4 + 170yx^3 + 240yx^2 + 168yx + 36y + x^9 + 6x^8 + 21x^7 + 56x^6 + 114x^5 + 170x^4 + 180x^3 + 120x^2 + 36x$$

This result coincides with that in [10, p. 103], which is supposed to be correct. Alternatively, it can be verified by applying the recursive definition with an arbitrary edge  $e \in E$ , as below.

```
> ed:=edges(G)[0]
```

$$[0, 1]$$

```
> Gdelete:=delete_edge(G,ed)
```

an undirected unweighted graph with 10 vertices and 14 edges

```
> Gcontract:=contract_edge(G,ed)
```

an undirected unweighted graph with 9 vertices and 14 edges

```
> expand(f-tutte_polynomial(Gdelete)-tutte_polynomial(Gcontract))
```

$$0$$

The value  $T_G(1, 1)$  is equal to the number of spanning forests in  $G$  [11, p. 345]—in this case, the number of spanning trees in Petersen graph. For verification, the same number is computed by using the specialized command `number_of_spanning_trees`, which uses a different (much faster) algorithm.

```
> tutte_polynomial(G,1,1)
```

$$2000$$

```
> number_of_spanning_trees(G)
```

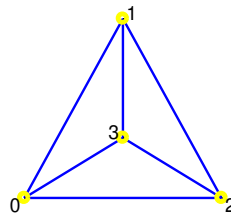
$$2000$$

For a graph  $G$  and its dual  $G^*$  the following relation holds:  $T_G(x, y) = T_{G^*}(y, x)$ . Therefore, if  $T_G(x, y) = T_G(y, x)$  then  $G$  and  $G^*$  are isomorphic (since Tutte polynomial is a graph invariant). A simple example of such graph is tetrahedral graph. Since it is planar and biconnected, its dual can be determined by using the command `plane_dual`.

```
> G:=graph("tetrahedron")
```

an undirected unweighted graph with 4 vertices and 6 edges

```
> draw_graph(G)
```



```
> is_biconnected(G) and is_planar(G)
```

```
true
```

```
> H:=plane_dual(G)
```

an undirected unweighted graph with 4 vertices and 6 edges

```
> T:=tutte_polynomial(G)
```

$$x^3 + 3x^2 + 4xy + 2x + y^3 + 3y^2 + 2y$$

```
> expand(T-subst(T, [x,y], [y,x]))
```

```
0
```

```
> is_isomorphic(G,H)
```

```
true
```

Multiple edges can be specified as edge weights.

```
> M:=make_weighted(G)
```

an undirected weighted graph with 4 vertices and 6 edges

```
> M:=set_edge_weight(set_edge_weight(M, [0,1], 2), [2,3], 3)
```

an undirected weighted graph with 4 vertices and 6 edges

```
> edges(M, weights)
```

```
[[[0, 1], 2], [[0, 2], 1], [[0, 3], 1], [[1, 2], 1], [[1, 3], 1], [[2, 3], 3]]
```

```
> tutte_polynomial(M, x, y)
```

$$x^3 + x^2y^2 + 2x^2y + 3x^2 + 3xy^3 + 6xy^2 + 6xy + 2x + y^6 + 3y^5 + 6y^4 + 7y^3 + 5y^2 + 2y$$

#### 4.4.2 Chromatic polynomial

`chromatic_polynomial(G, <t>)`

The command `chromatic_polynomial`, is used for computing [chromatic polynomials](#). It takes one or two arguments, an undirected unweighted graph  $G(V, E)$  and optionally a variable or value  $t$ . It returns the chromatic polynomial  $P_G$  of  $G$  or the value  $P_G(t)$  if the second argument is given.

$P_G$  and the [Tutte polynomial](#)  $T_G$  satisfy the following relation (see [36] and [11, p. 346]):

$$P_G(t) = (-1)^{|V| - \kappa(G)} t^{\kappa(G)} T_G(1 - t, 0), \quad (4.1)$$

where  $\kappa(G)$  is the number of connected components of  $G$ . `chromatic_polynomial` uses (4.1) to compute  $P_G$ .

The value  $P_G(k)$ , where  $k > 0$  is an integer, is equal to the number of all distinct  $k$ -colorings of vertices in  $G$ . As shown in the example below, Petersen graph cannot be colored by using only two colors, but is 3-colorable with 120 distinct colorings (all using the same three colors).

```
> P:=chromatic_polynomial(graph("petersen"),x)
```

$$x(x-2)(x-1)(x^7-12x^6+67x^5-230x^4+529x^3-814x^2+775x-352)$$

```
> subs(P,x=2)
```

0

```
> subs(P,x=3)
```

120

### 4.4.3 Flow polynomial

`flow_polynomial(G,⟨x⟩)`

The command `flow_polynomial` is used for computing [flow polynomials](#). It takes one or two arguments, an undirected unweighted graph  $G(V, E)$  and optionally a variable or value  $x$ . It returns the flow polynomial  $Q_G$  of  $G$  or the value  $Q_G(x)$  if the second argument is given.

$Q_G$  and the [Tutte polynomial](#)  $T_G$  satisfy the following relation (see [36] and [10, p. 110]):

$$Q_G(x) = (-1)^{|E|-|V|+\kappa(G)} T_G(0, 1-x), \quad (4.2)$$

where  $\kappa(G)$  is the number of connected components of  $G$ . `flow_polynomial` uses (4.2) to compute  $Q_G$ .

The value  $Q_G(k)$ , where  $k > 0$  is an integer, is equal to the number of all nowhere-zero  $k$ -flows in  $G$ . In such flows, the total flow  $f_v$  entering and leaving vertex  $v$  is congruent modulo  $k$ , hence  $f_v \in \{1, 2, \dots, k-1\}$  for all  $v \in V$  [11, p. 347]. As shown in the example below, Petersen graph has zero 4-flows and 240 5-flows.

```
> Q:=flow_polynomial(graph("petersen"))
```

$$x^6-15x^5+95x^4-325x^3+624x^2-620x+240$$

```
> Q | x=4
```

0

```
> Q | x=5
```

240

### 4.4.4 Reliability polynomial

`reliability_polynomial(G,⟨p⟩)`

The command `reliability_polynomial` is used for computing [reliability polynomials](#). It takes one or two arguments, an undirected graph  $G(V, E)$  and optionally a variable or value  $p$ . It returns the all-terminal reliability polynomial  $R_G$  of  $G$  or the value  $R_G(p)$  if the second argument is given. If  $G$  is weighted, it is treated as a multigraph: the weight  $w$  of an edge  $e$ , which must be a positive integer, is interpreted as the multiplicity of  $e$ , for each  $e \in E$ .

$R_G$  and the [Tutte polynomial](#)  $T_G$  satisfy the following relation [56]:

$$R_G(p) = (1-p)^{|V|-\kappa(G)} p^{|E|-|V|+\kappa(G)} T_G(1, p^{-1}), \quad (4.3)$$

where  $\kappa(G)$  is the number of connected components of  $G$ . `reliability_polynomial` uses (4.3) to compute  $R_G$ .

If  $G$  is a connected network, then the value  $R_G(p)$ , where  $p \in [0, 1]$ , is equal to the probability that  $G$  does not fail (i.e. stays connected) after removing each edge with probability  $p$  [34, pp. 354–355].

In the following example, it is clear that the graph  $G$  will stay connected with probability  $(1-p)^2$  if each of its two edges is removed with probability  $p$ .

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

an undirected unweighted graph with 3 vertices and 2 edges

```
> R:=reliability_polynomial(G,p)
```

$$p^2 - 2p + 1$$

```
> factor(R)
```

$$(p - 1)^2$$

Adding a new edge should increase the reliability of  $G$ , since the latter is connected. Indeed, the difference  $S - R$  below is positive for  $0 < p < 1$ .

```
> S:=reliability_polynomial(add_edge(G,[1,3]),p)
```

$$2p^3 - 3p^2 + 1$$

```
> factor(S-R)
```

$$2p(p - 1)^2$$

Multiple edges can be specified as edge weights.

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

an undirected weighted graph with 3 vertices and 3 edges

```
> factor(reliability_polynomial(M))
```

$$(x - 1)^2 (2x^2 + 2x + 1)$$

The following graph represents the ARPANET (early internet) in December 1970.

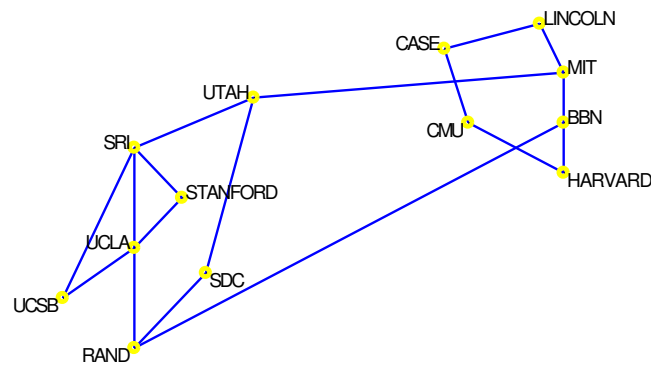
```
> V:=["MIT","LINCOLN","CASE","CMU","HARVARD","BBN","UCSB","UCLA","STANFORD",
    "SRI","RAND","UTAH","SDC"];;
> A:=graph(V, trail("BBN","HARVARD","CMU","CASE","LINCOLN","MIT","UTAH","SRI",
    "STANFORD","UCLA","UCSB","SRI","UCLA","RAND","BBN","MIT"), trail("RAND","SDC",
    "UTAH"))
```

an undirected unweighted graph with 13 vertices and 17 edges

```
> Arpanet:=set_vertex_positions(A,[[1.0,1.0],[0.9,1.2],[0.5,1.1],[0.6,0.8],[1.0,
    0.6],[1.0,0.8],[-1.1,0.1],[-0.8,0.3],[-0.6,0.5],[-0.8,0.7],[-0.8,-0.1],[-0.3,
    0.9],[-0.5,0.2]])
```

an undirected unweighted graph with 13 vertices and 17 edges

```
> draw_graph(Arpanet)
```



If we were allowed to add a single edge to ARPANET in order to improve its reliability, which choice would be optimal? Below is the analysis for an edge from Stanford to CMU.

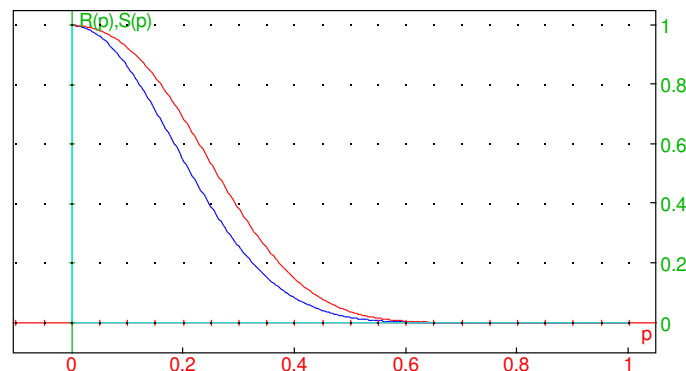
```
> R:=reliability_polynomial(Arpanet,p)
```

$$(p-1)^{12} (280 p^5 + 310 p^4 + 186 p^3 + 63 p^2 + 12 p + 1)$$

```
> S:=reliability_polynomial(add_edge(Arpanet,["STANFORD","CMU"]),p)
```

$$(p-1)^{12} (976 p^6 + 1118 p^5 + 703 p^4 + 276 p^3 + 72 p^2 + 12 p + 1)$$

```
> labels=["p","R(p),S(p)"]; plot([R,S],p=0..1,color=[blue,red])
```



The improvement is defined as the area enclosed by the two curves.

```
> improvement:=integrate(S-R,p=0..1)
```

$$\frac{443879}{10581480}$$

```
> evalf(improvement)
```

$$0.0419486688063$$

## 4.5 Connectivity

### 4.5.1 Connected, biconnected and triconnected graphs

```
is_connected(G)
is_biconnected(G)
is_triconnected(G)
```

The commands `is_connected`, `is_biconnected` and `is_triconnected` are used for determining if a graph is `connected`, `biconnected` or `triconnected` (`3-connected`), respectively. Each of these commands takes a graph  $G(V, E)$  as its only argument and returns `true` if  $G$  possesses the required level of connectivity. Otherwise, it returns `false`.

If  $G$  is directed, the edge directions are simply ignored (the commands operate on the underlying graph of  $G$ ).

The strategy for checking 1- and 2-connectivity is to use `depth-first search` (see [33, p. 20] and [73]). Both algorithms run in  $O(|V| + |E|)$  time. The algorithm for checking 3-connectivity is, however, less efficient: it works by choosing a vertex  $v \in V$  and checking if the subgraph induced by  $V \setminus \{v\}$  is biconnected, moving on to the next vertex if so, and repeating the process until all vertices are visited exactly once or a non-biconnected subgraph is found for some  $v$ . In the latter case the input graph is not triconnected. The complexity of this algorithm is hence  $O(|V||E|)$ .

```
> G:=graph_complement(complete_graph(2,3,4))
```

an undirected unweighted graph with 9 vertices and 10 edges

```
> is_connected(G)
```

false

```
> C:=connected_components(G)
```

[[0, 1], [2, 3, 4], [5, 6, 7, 8]]

```
> H:=induced_subgraph(G,C[2])
```

an undirected unweighted graph with 4 vertices and 6 edges

```
> is_connected(H)
```

true

```
> is_biconnected(path_graph(5))
```

false

```
> is_biconnected(cycle_graph(5))
```

true

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

true

```
> is_triconnected(cycle_graph(5))
```

false

## 4.5.2 Connected and biconnected components

`connected_components(G)`

`biconnected_components(G)`

The commands `connected_components` and `biconnected_components` are used for decomposing a graph into `connected` and `biconnected components`, respectively. Both commands take a graph  $G(V, E)$  as its only argument and return the minimal partition  $\{V_1, V_2, \dots, V_k\}$  of  $V$  such that the subgraph  $G_i \subset G$  induced by  $V_i$  is connected resp. biconnected for each  $i = 1, 2, \dots, k$ . The partition is returned as a list of lists  $V_1, V_2, \dots, V_k$ .



If  $G$  is directed, the edge directions are simply ignored (the commands operate on the underlying graph of  $G$ ).

The connected components of  $G$  are readily obtained by depth-first search in  $O(|V| + |E|)$  time. To find the biconnected components of  $G$ , TARJAN's algorithm is used [73], which also runs in linear time.

```
> G:=graph_complement(complete_graph(3,5,7))
```

an undirected unweighted graph with 15 vertices and 34 edges

```
> is_connected(G)
```

false

```
> C:=connected_components(G)
```

```
[[0, 1, 2], [3, 4, 5, 6, 7], [8, 9, 10, 11, 12, 13, 14]]
```

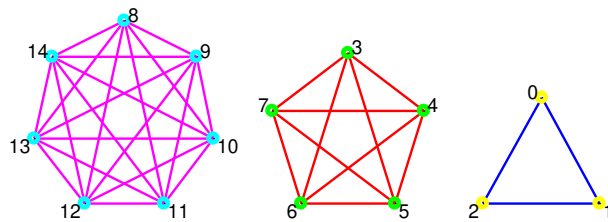
```
> G:=highlight_subgraph(G,induced_subgraph(G,C[1]))
```

an undirected unweighted graph with 15 vertices and 34 edges

```
> G:=highlight_subgraph(G,induced_subgraph(G,C[2]),magenta,cyan)
```

an undirected unweighted graph with 15 vertices and 34 edges

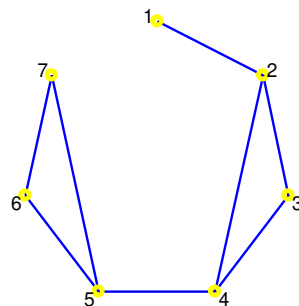
```
> draw_graph(G)
```



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

an undirected unweighted graph with 7 vertices and 8 edges

```
> draw_graph(H)
```



```
> is_biconnected(H)
```

false

```
> biconnected_components(H)
```

`[[5, 6, 7], [4, 5], [2, 3, 4], [1, 2]]`

### 4.5.3 Vertex connectivity

`vertex_connectivity(G)`

The command `vertex_connectivity` is used for computing **vertex connectivity** in undirected graphs. It takes an undirected connected graph  $G(V, E)$  as its only argument and returns the largest integer  $k$  for which  $G$  is  $k$ -vertex-connected, meaning that  $G$  remains connected after removing fewer than  $k$  vertices from  $V$ .

The strategy is to use the algorithm by ESFAHANIAN and HAKIMI [25], which is based on the maximum-flow computing approach by EVEN [27, Section 6.2]. The algorithm makes  $|V| - \delta - 1 + \frac{\delta(\delta-1)}{2}$  calls to `maxflow` command, where  $\delta$  is the minimum vertex degree in  $G$ .

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

3

```
> vertex_connectivity(graph("clebsch"))
```

5

```
> G:=random_planar_graph(1000,0.5,2)
```

an undirected unweighted graph with 1000 vertices and 1865 edges

```
> is_biconnected(G)
```

true

```
> vertex_connectivity(G)
```

2

2.582 sec

### 4.5.4 Graph rank

`graph_rank(G, <S>)`

The command `graph_rank` is used for computing **graph rank**. It takes one or two arguments, a graph  $G(V, E)$  and optionally a set of edges  $S \subset E$  (by default  $S = E$ ), and returns  $|V| - k$  where  $k$  is the number of connected components of the spanning subgraph of  $G$  with edge set  $S$ .

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

an undirected unweighted graph with 5 vertices and 3 edges

```
> graph_rank(G)
```

3

```
> graph_rank(G,[[1,2],[3,4]])
```

2

### 4.5.5 Articulation points

`articulation_points(G)`

The command `articulation_points` is used for obtaining the set of **articulation points** (cut-vertices) of a graph. It takes a graph  $G(V, E)$  as its only argument and returns the list of articulation points of  $G$ . A vertex  $v \in V$  is an **articulation point** of  $G$  if the removal of  $v$  increases the number of connected components of  $G$ .

The articulation points of  $G$  are found by depth-first search in  $O(|V| + |E|)$  time [33].

```
> articulation_points(path_graph([1,2,3,4]))
```

```
[2, 3]
```

```
> length(articulation_points(cycle_graph(1,2,3,4)))
```

```
0
```

### 4.5.6 Strongly connected components

```
strongly_connected_components(G)
```

```
is_strongly_connected(G)
```

The command `strongly_connected_components` is used for decomposing digraphs into **strongly connected components**. A digraph  $H$  is **strongly connected** if for each pair  $(v, w)$  of distinct vertices in  $H$  there is a directed path from  $v$  to  $w$  in  $H$ . The command `is_strongly_connected` can be used to determine whether a graph is strongly connected.

`strongly_connected_components` takes a digraph  $G(V, E)$  as its only argument and returns the minimal partition  $\{V_1, V_2, \dots, V_k\}$  of  $V$  such that the subgraph  $G_i \subset G$  induced by  $V_i$  is strongly connected for each  $i = 1, 2, \dots, k$ . The result is returned as a list of lists  $V_1, V_2, \dots, V_k$ .

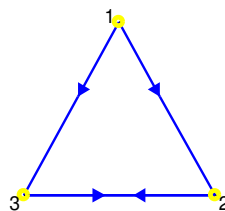
`is_strongly_connected` takes a digraph  $G$  as its only argument and returns `true` if  $G$  has exactly one strongly connected component and `false` otherwise.

The strategy is to use TARJAN's algorithm for strongly connected components [73], which runs in  $O(|V| + |E|)$  time.

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

a directed unweighted graph with 3 vertices and 4 arcs

```
> draw_graph(G)
```



```
> is_connected(G)
```

```
true
```

```
> is_strongly_connected(G)
```

```
false
```

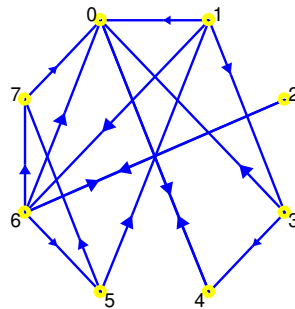
```
> strongly_connected_components(G)
```

```
[[2, 3], [1]]
```

```
> G:=random_digraph(8,15)
```

a directed unweighted graph with 8 vertices and 15 arcs

```
> draw_graph(G)
```



```
> strongly_connected_components(G)
```

```
[[0, 4], [3], [7], [1, 2, 5, 6]]
```

### 4.5.7 Edge connectivity

`edge_connectivity(G)`

The command `edge_connectivity` is used for computing the [edge connectivity](#) of an undirected graph. It takes an undirected connected graph  $G(V, E)$  as its only argument and returns the largest integer  $k$  for which  $G$  is  $k$ -edge connected, meaning that  $G$  remains connected after fewer than  $k$  edges are removed from  $E$ .

The strategy is to apply MATULA's algorithm [77, Section 13.3.1], which constructs a dominating set  $D \subset V$  and calls `maxflow` command  $|D| - 1$  times.

```
> G:=cycle_graph([1,2,3,4,5])
```

an undirected unweighted graph with 5 vertices and 5 edges

```
> edge_connectivity(G)
```

```
2
```

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

an undirected unweighted graph with 5 vertices and 10 edges

```
> edge_connectivity(K5)
```

```
4
```

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

```
3
```

```
> edge_connectivity(graph("clebsch"))
```

```
5
```

### 4.5.8 Edge cuts

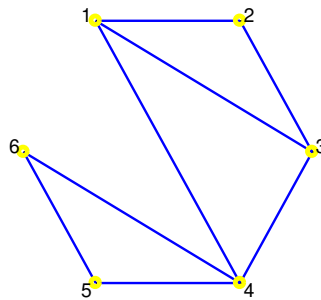
`is_cut_set(G,L)`

The command `is_cut_set` is used for determining whether a particular subset of edges of a graph is an [edge cut](#). It takes two arguments, a graph  $G(V, E)$  and a set  $L \subset E$ , and returns `true` if the graph  $G'(V, E \setminus L)$  has more connected components than  $G$ . Otherwise, it returns `false`.

```
> G:=graph(trail(1,2,3,4,5,6,4,1,3))
```

an undirected unweighted graph with 6 vertices and 8 edges

```
> draw_graph(G)
```



```
> E:=[[1,4],[3,4]]
```

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

```
> is_cut_set(G,E)
```

true

```
> is_connected(delete_edge(G,E))
```

false

### 4.5.9 Two-edge-connected graphs

```
is_two_edge_connected(G)
```

```
two_edge_connected_components(G)
```

The command `is_two_edge_connected` is used for determining whether an undirected graph is [two-edge-connected](#). The command `two_edge_connected_components` is used for splitting a graph into components having this property. It takes an undirected graph  $G(V, E)$  as its only argument and returns `true` if  $G$  has no bridges, i.e. edges which removal increases the number of connected components of  $G$ .

`two_edge_connected_components` takes an undirected graph  $G(V, E)$  and returns the list of two-edge-connected components of  $G$ , each of them represented by the list of its vertices. To obtain a component as a graph, use the [induced\\_subgraph](#) command.

The strategy for finding bridges [74] is similar to finding [articulation points](#). Once the bridges of  $G$  are found, it is easy to split  $G$  into two-edge-connected components by removing the bridges and returning the list of [connected components](#) of the resulting graph. Both algorithms run in  $O(|V| + |E|)$  time.

```
> is_two_edge_connected(cycle_graph(4))
```

true

```
> is_two_edge_connected(path_graph(4))
```

false

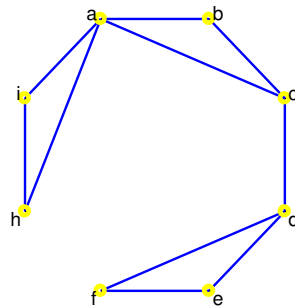
```
> G:=graph(%{"a","b"},["b","c"],["a","c"],["d","e"],["e","f"],["d","f"],["c","d"],["a","h"],["a","i"],["h","i"]%})
```

an undirected unweighted graph with 8 vertices and 10 edges

```
> is_two_edge_connected(G)
```

false

```
> draw_graph(G)
```



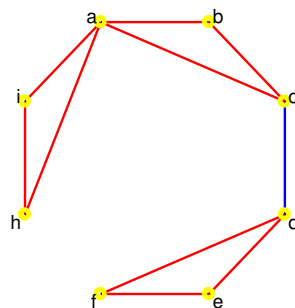
```
> C:=two_edge_connected_components(G)
```

```
[[["a","b","c","h","i"],["d","e","f"]]
```

To visualize the bridges of  $G$ , one can highlight the edges of each component. The non-highlighted edges are the bridges.

```
> for c in C do G:=highlight_edges(G,edges(induced_subgraph(G,c))); od;;
```

```
> draw_graph(G)
```



## 4.6 Trees

### 4.6.1 Tree graphs

```
is_tree(G)
```

The command `is_tree` is used for determining whether a graph is a [tree](#). It takes a graph  $G(V, E)$  as its only argument and returns `true` if  $G$  is undirected, connected and  $|V| = |E| + 1$ . Otherwise, it returns `false`.

The most expensive step is to determine whether  $G$  is connected. The condition  $|V| = |E| + 1$  is checked first, hence the algorithm runs in  $O(|V|)$  time.

```
> is_tree(complete_binary_tree(3))
```

```
true
```

```
> is_tree(cycle_graph(5))
```

```
false
```

### 4.6.2 Forest graphs

`is_forest(G)`

The command `is_forest` is used for determining whether a graph is a *forest*. It takes the a  $G(V, E)$  as its only argument and returns `true` if each connected component of  $G$  is a tree. Otherwise, it returns `false`.

The algorithm runs in  $O(|V| + |E|)$  time.

```
> F:=disjoint_union(apply(random_tree,[k$(k=10..30)]))
```

an undirected unweighted graph with 420 vertices and 399 edges

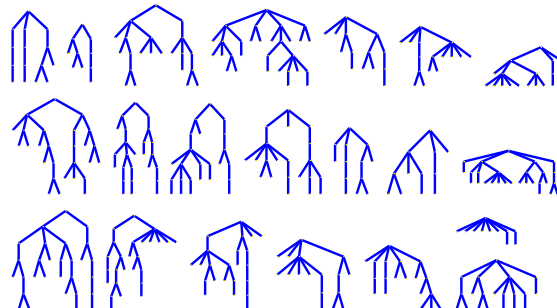
```
> is_connected(F)
```

```
false
```

```
> is_forest(F)
```

```
true
```

```
> draw_graph(F)
```



### 4.6.3 Height of a tree

`tree_height(G, <r>)`

The command `tree_height` is used for determining either the height of a tree with respect to the specified root node or the minimal height. It takes a tree graph  $G(V, E)$  as its first argument and optionally a vertex  $r \in V$ , which is used as the root node. The command returns the the length of the longest path in  $T$  that has the node  $r$  as one of its endpoints. If  $r$  is not specified, the return value is a sequence comprised of the minimal tree height and an expression `root=r0`, where  $r_0 \in V$  is the first vertex such that  $G$  has the minimal height with respect to  $r_0$ .

The strategy for given  $r$  is to start a depth-first search from the root node and look for the deepest node. Therefore the algorithm runs in  $O(|V|)$  time. If  $r$  is not given, then  $r_0$  is determined by pointers moving from leaf nodes inwards and combining them as they meet, until at most two pointers remain, pointing to the admissible vertices. This algorithm requires  $O(|V|)$  time as well.

```
> G:=random_tree(1000)
```

an undirected unweighted graph with 1000 vertices and 999 edges

```
> r:=choice(vertices(G))
```

953

```
> tree_height(G,r)
```

88

```
> tree_height(G)
```

46, root = 189

#### 4.6.4 Prüfer sequences

`pruefer_code(L|T)`

The command `pruefer_code` is used for converting a tree into a [Prüfer sequence](#) and vice versa. It takes a Prüfer encoding  $L$  or a tree graph  $T$  as its only argument and returns a tree corresponding to  $L$  resp. the Prüfer encoding of  $T$ . The argument  $L$  must be a list of integers between 0 and  $|L| + 1$  (inclusive) in modes with 0-based indices (such as `xcas` mode) resp. between 1 and  $|L| + 2$  in modes with 1-based indices (such as `maple` mode). Encodings output by `pruefer_code` are also mode-aware.

The strategy is to use linear-time implementations<sup>4.2</sup> of the encoding/decoding algorithm [50].

The following examples were entered in `xcas` mode (0-based indices).

```
> T:=pruefer_code([5,6,0,4,1,2,10,3,8,11])
```

an undirected unweighted graph with 12 vertices and 11 edges

```
> is_tree(T)
```

true

```
> G:=graph(%{[1,8],[2,3],[2,7],[4,6],[5,6],[6,7],[6,8],[7,9],[8,10]%})
```

an undirected unweighted graph with 10 vertices and 9 edges

```
> is_tree(G)
```

true

```
> pruefer_code(G)
```

[1, 2, 4, 6, 6, 4, 6, 1]

```
> R:=random_tree(100)
```

an undirected unweighted graph with 100 vertices and 99 edges

```
> code:=pruefer_code(R);
```

```
> is_isomorphic(R,pruefer_code(code))
```

true

---

4.2. See [https://cp-algorithms.com/graph/pruefer\\_code.html](https://cp-algorithms.com/graph/pruefer_code.html).

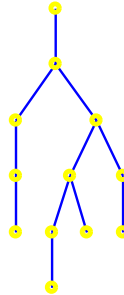


`pruefer_code` can be used for fast uniform random sampling of labeled trees. Namely, for  $n > 2$ , each sequence of length  $n - 2$  in alphabet of  $n$  symbols corresponds to a unique labeled tree on  $n$  vertices. Thus the number of labeled trees on  $n$  vertices equals to  $n^{n-2}$  (also by Cayley's formula). It is hence enough to select a sequence at random and convert it to its associated tree by using `pruefer_code`. In the following example we generate a tree on 10 vertices.

```
> L:=randvector(10,12)
```

```
[3, 10, 6, 2, 4, 5, 3, 8, 8, 2]
```

```
> draw_graph(pruefer_code(L),labels=false)
```



In `maple` mode (or any other mode with 1-based indices) one should add 1 to each element of  $L$  before passing it to `pruefer_code`.

For generating unlabeled trees uniformly at random, see Section 1.10.3.

#### 4.6.5 Lowest common ancestor of a pair of nodes

```
lowest_common_ancestor(G,r,u,v)
```

```
lowest_common_ancestor(G,r,[[u1,v1],[u2,v2],...,[uk,vk]])
```

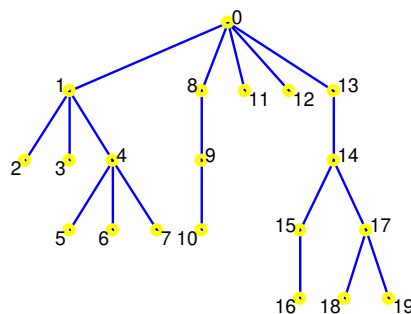
The command `lowest_common_ancestor` is used for computing the **lowest common ancestor** (LCA) of a pair of nodes in a tree or for each element of a list of such pairs. It takes two mandatory arguments, a tree graph  $G(V, E)$  and the root node  $r \in V$ . There are two possibilities for specifying the nodes to operate on: either the nodes  $u, v \in V$  are given as the third and the fourth argument, or a list of pairs of nodes  $(u_1, v_1), (u_2, v_2), \dots, (u_k, v_k)$ , where  $u_i, v_i \in V$  and  $u_i \neq v_i$  for  $i = 1, 2, \dots, k$ , is given as the third argument. The command returns the LCA of  $u$  and  $v$  or the list containing LCA of every pair of nodes  $u_i, v_i$  for  $i = 1, 2, \dots, k$ . Note that this is much faster than calling `lowest_common_ancestor`  $k$  times with a single pair of vertices each time.

The strategy is to use TARJAN's offline LCA algorithm [75], which runs in nearly linear time.

```
> G:=random_tree(20)
```

an undirected unweighted graph with 20 vertices and 19 edges

```
> draw_graph(G)
```



```
> lowest_common_ancestor(G,0,16,17)
```

14

```
> lowest_common_ancestor(G,0,[[5,6],[7,8],[15,18]])
```

[4,0,14]

### 4.6.6 Arborescence graphs

`is_arborescence(G)`

The command `is_arborescence` is used for determining whether a directed unweighted graph is an **arborescence** (which is the digraph form of a rooted tree). It takes a digraph  $G(V, E)$  as its only argument and returns **true** if there is a vertex  $u \in V$  such that for any other  $v \in V$  there is exactly one directed path from  $u$  to  $v$ . Otherwise, it returns **false**.

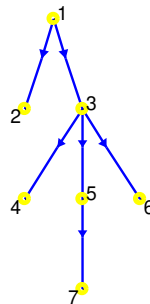
```
> T:=digraph(%{[1,2],[1,3],[3,4],[3,5],[3,6],[5,7]})
```

a directed unweighted graph with 7 vertices and 6 arcs

```
> is_arborescence(T)
```

true

```
> draw_graph(T)
```



## 4.7 Networks

### 4.7.1 Network graphs

`is_network(G,⟨s,t⟩)`

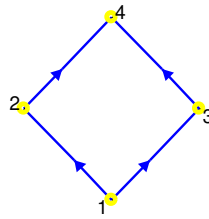
The command `is_network` is used for determining whether a graph is a **flow network**. In this context, a flow network is directed, connected graph with at least one vertex with in-degree 0 (the **source**) and at least one vertex with out-degree 0 (the **sink**).

`is_network` takes one or three arguments, a digraph  $G(V, E)$  and optionally the source vertex  $s$  and the sink vertex  $t$ . If these vertices are given, the command returns **true** if  $G$  is a network with respect to  $s, t$  and **false** otherwise. If the graph  $G$  is given as the only argument, the command returns a sequence of two objects, the list of all sources in  $G$  and the list of all sinks in  $G$ , respectively. If one of these lists is empty, then  $G$  is implicitly not a network (both lists are empty if  $G$  is not connected).

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

a directed unweighted graph with 4 vertices and 4 arcs

```
> draw_graph(N, spring)
```



```
> is_network(N, 1, 4)
```

true

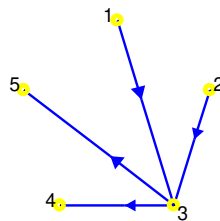
```
> is_network(N, 2, 3)
```

false

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

a directed unweighted graph with 5 vertices and 4 arcs

```
> draw_graph(G, circle)
```



```
> is_network(G)
```

[1, 2], [4, 5]

### 4.7.2 Maximum flow

```
maxflow(G, s, t, <M>)
```

The command `maxflow` is used for computing the [maximum flow](#) in a network. It takes three or four arguments: a network graph  $G(V, E)$ , the source  $s \in V$ , the sink  $t \in V$  and optionally an unassigned identifier  $M$ . It returns the optimal value for the maximum flow problem for the network  $(G, s, t)$ . If the fourth argument is given, an optimal flow is written to  $M$  in form of a matrix.

The strategy is to use the algorithm of EDMONDS and KARP [24], which solves the maximum flow problem in  $O(|V| |E|^2)$  time.

```
> A:=[0,1,0,4,0,0],[0,0,1,0,3,0],[0,1,0$3,1],[0,0,3,0,1,0],[0$3,1,0,4],[0$6]]
```

$$\begin{pmatrix} 0 & 1 & 0 & 4 & 0 & 0 \\ 0 & 0 & 1 & 0 & 3 & 0 \\ 0 & 1 & 0 & 0 & 0 & 1 \\ 0 & 0 & 3 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 & 0 & 4 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{pmatrix}$$

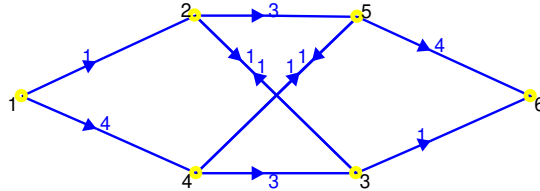
```
> N:=digraph([1,2,3,4,5,6],A)
```

a directed weighted graph with 6 vertices and 10 arcs

```
> is_network(N)
```

[1], [6]

```
> draw_graph(N, spring)
```



```
> purge(M) ;; maxflow(N, 1, 6, M)
```

“Done”, 4

```
> M
```

$$\begin{pmatrix} 0 & 1 & 0 & 3 & 0 & 0 \\ 0 & 0 & 0 & 0 & 2 & 0 \\ 0 & 1 & 0 & 0 & 0 & 1 \\ 0 & 0 & 2 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 3 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{pmatrix}$$

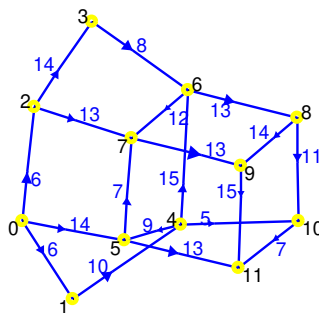
```
> N:=random_network(2,3,0.9,acyclic,weights=5..15)
```

a directed weighted graph with 12 vertices and 19 arcs

```
> is_network(N)
```

[0], [11]

```
> purge(pos) ;; draw_graph(N, spring, pos)
```



```
> purge(M) ;; maxflow(N, 0, 11, M)
```

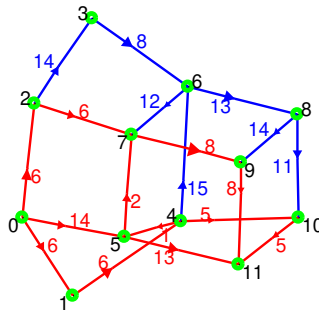
“Done”, 26

To visualize the optimal flow  $F$ , one can use the `highlight_subgraph` command with the option `weights` to display the actual flow in the highlighted edges. Non-highlighted edges have zero flow. Note that we use vertex positions generated in the above drawing.

```
> flow:=set_vertex_positions(highlight_subgraph(N,digraph(vertices(N),M),
weights),pos)
```

a directed weighted graph with 12 vertices and 19 arcs

```
> draw_graph(flow)
```



### 4.7.3 Minimum cut

```
minimum_cut(G,s,t)
```

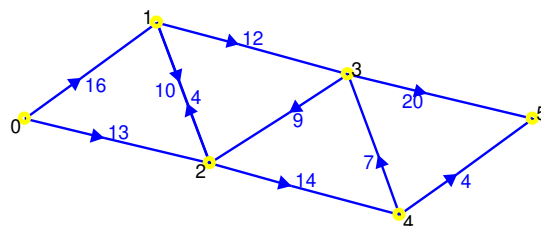
The command `minimum_cut` is used for obtaining [minimum cuts](#) in networks. It takes three arguments, a digraph  $G(V, E)$  and two vertices  $s, t \in V$  such that  $(G, s, t)$  is a network with source  $s$  and sink  $t$ . The returned value is a list of edges in  $E$  representing a minimum cut in the network.

The strategy is to apply the command `maxflow`, which finds a maximal flow, and to run depth-first search on the corresponding residual graph to find a  $S, T$  partition of  $V$ . The minimum cut is then the set of all arcs  $vw \in E$  such that  $v \in S$  and  $w \in T$ . The algorithm runs in  $O(|V||E|^2)$  time.

```
> G:=digraph(%{[[0,1],16],[[0,2],13],[[1,2],10],[[1,3],12],[[2,1],4],[[2,4],14],
[[3,2],9],[[3,5],20],[[4,3],7],[[4,5],4]}%)
```

a directed weighted graph with 6 vertices and 10 arcs

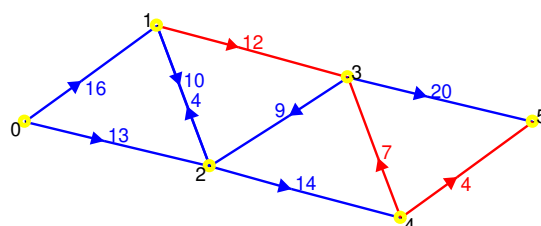
```
> draw_graph(G,spring)
```



```
> cut:=minimum_cut(G,0,5)
```

```
[[1,3],[4,3],[4,5]]
```

```
> draw_graph(highlight_edges(G,cut),spring)
```



By the [max-flow min-cut theorem](#), the sum of edge weights in minimum cut is equal to the value of maximum flow.

```
> w:=0;; for ed in cut do w:=w+get_edge_weight(G,ed); od;; w
```

“Done”, “Done”, 23

```
> maxflow(G,0,5)
```

23

## 4.8 Distance in graphs

### 4.8.1 Vertex distance

`vertex_distance(G,v,w|L)`

The command `vertex_distance` is used for computing the length of the shortest path(s) from the source vertex to some other vertex/vertices of a graph. It takes three arguments, a graph  $G(V, E)$ , a vertex  $v \in V$  called the **source** and a vertex  $w \in V$  called the **target** or a list  $L \subset V \setminus \{v\}$  of target vertices. The command returns the distance between  $v$  and  $w$  as the number of edges in a shortest path from  $v$  to  $w$ , or the list of distances if a list of target vertices is given.

The strategy is to use [breadth-first search](#) [33, p. 35] starting from the source vertex. Therefore, the algorithm runs in  $O(|V| + |E|)$  time.

```
> G:=graph("petersen")
```

an undirected unweighted graph with 10 vertices and 15 edges

```
> vertex_distance(G,1,3)
```

2

```
> vertex_distance(G,1,[3,6,9])
```

[2, 1, 2]

### 4.8.2 All-pairs vertex distance

`allpairs_distance(G)`

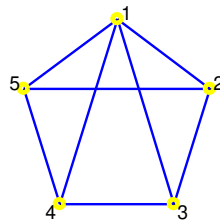
The command `allpairs_distance` is used for computing the matrix of distances between all pairs of vertices in a (weighted) graph. It takes a graph  $G(V, E)$  as its only argument and returns a square matrix  $D = [d_{ij}]$  with  $n = |V|$  rows and columns such that  $d_{ij} = \text{distance}(v_i, v_j)$  for all  $i, j = 1, 2, \dots, n$ , where  $v_1, v_2, \dots, v_n$  are the elements of  $V$ . If  $v_i v_j \notin E$ , then  $d_{ij} = +\infty$ . The strategy is to apply the algorithm of FLOYD and WARSHALL [28], which runs in  $O(|V|^3)$  time.

Note that, if  $G$  is weighted, it must not contain negative cycles. A cycle is **negative** if the sum of weights of its edges is negative.

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

an undirected unweighted graph with 5 vertices and 8 edges

```
> draw_graph(G)
```



```
> allpairs_distance(G)
```

$$\begin{pmatrix} 0 & 1 & 1 & 1 & 1 \\ 1 & 0 & 1 & 2 & 1 \\ 1 & 1 & 0 & 1 & 2 \\ 1 & 2 & 1 & 0 & 1 \\ 1 & 1 & 2 & 1 & 0 \end{pmatrix}$$

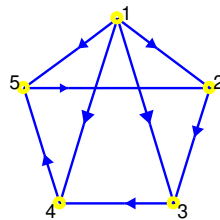
```
> H:=digraph(%{[1,2],[1,3],[1,4],[1,5],[2,3],[3,4],[4,5],[5,2]})
```

a directed unweighted graph with 5 vertices and 8 arcs

```
> allpairs_distance(H)
```

$$\begin{pmatrix} 0 & 1 & 1 & 1 & 1 \\ +\infty & 0 & 1 & 2 & 3 \\ +\infty & 3 & 0 & 1 & 2 \\ +\infty & 2 & 3 & 0 & 1 \\ +\infty & 1 & 2 & 3 & 0 \end{pmatrix}$$

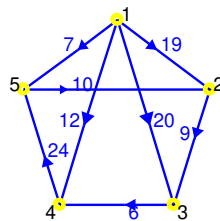
```
> draw_graph(H)
```



```
> H:=assign_edge_weights(H,5,25)
```

a directed weighted graph with 5 vertices and 8 arcs

```
> draw_graph(H)
```



```
> allpairs_distance(H)
```

$$\begin{pmatrix} 0 & 17 & 20 & 12 & 7 \\ +\infty & 0 & 9 & 15 & 39 \\ +\infty & 40 & 0 & 6 & 30 \\ +\infty & 34 & 43 & 0 & 24 \\ +\infty & 10 & 19 & 25 & 0 \end{pmatrix}$$

### 4.8.3 Diameter

`graph_diameter(G)`

The command `graph_diameter` is used for determining the maximum distance among all pairs of vertices in a graph. It takes a graph  $G(V, E)$  as its only argument and returns the maximum distance between two nodes in  $V$ , i.e. the cost of a maximum-size shortest path in  $G$  if the latter is connected and  $+\infty$  otherwise.

If  $G$  is weighted, then `graph_diameter` calls `allpairs_distance` and picks the largest element in the output matrix. Thus the complexity of the algorithm is  $O(|V|^3)$  in this case. For unweighted graphs it is sufficient to run a breadth-first search from each vertex, which requires  $O(|V||E|)$  time.

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

2

```
> graph_diameter(cycle_graph(19))
```

9

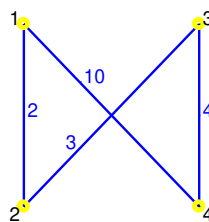
```
> graph_diameter(graph_complement(complete_graph(3,3)))
```

$+\infty$

```
> G:=graph(%{[[1,2],2],[[2,3],3],[[3,4],4],[[4,1],10]})
```

an undirected weighted graph with 4 vertices and 4 edges

```
> draw_graph(G)
```



```
> graph_diameter(G)
```

9

```
> dijkstra(G,1,4)
```

[[1, 2, 3, 4], 9]

### 4.8.4 Girth

`girth(G)`

`odd_girth(G)`



The commands `girth` and `odd_girth` are used for computing the (odd) girth of an undirected unweighted graph. Both commands take a graph  $G(V, E)$  as their only argument and return the girth and odd girth of  $G$ , respectively. The (odd) girth of  $G$  is defined to be the length of the shortest (odd) cycle in  $G$ . If there is no (odd) cycle in  $G$ , the command returns  $+\infty$ .

The strategy is to apply breadth-first search from each vertex of the input graph. The runtime is therefore  $O(|V||E|)$ .

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

5

```
> G:=hypercube_graph(3)
```

an undirected unweighted graph with 8 vertices and 12 edges

```
> G:=subdivide_edges(G,["000","001"])
```

an undirected unweighted graph with 9 vertices and 13 edges

```
> girth(G)
```

4

```
> odd_girth(G)
```

5

```
> girth(complete_binary_tree(2))
```

$+\infty$

## 4.9 Acyclic graphs

### 4.9.1 Acyclic graphs

`is_acyclic(G)`

The command `is_acyclic` is used for determining whether there are no directed cycles (closed paths) in a digraph. A directed graph with no directed cycle is said to be **acyclic**. `is_acyclic` takes a digraph  $G(V, E)$  as its only argument and returns `true` if  $G$  is acyclic and `false` otherwise.

The algorithm attempts to find topological order for its vertices. If that succeeds, the graph is acyclic, otherwise not. The running time is  $O(|V| + |E|)$ .

```
> is_acyclic(digraph(trail(1,2,3,4,5)))
```

true

```
> is_acyclic(digraph(trail(1,2,3,4,5,2)))
```

false

### 4.9.2 Topological sorting

`topologic_sort(G)`

`topological_sort(G)` alias

The command `topologic_sort` (alias `topological_sort`) is used for finding a linear ordering of vertices of an acyclic digraph which is consistent with the arcs of the digraph. This procedure is called *topological sorting*. `topologic_sort` takes a graph  $G(V, E)$  as its only argument and returns the list of vertices of  $G$  in a particular order: a vertex  $u$  precedes a vertex  $v$  if  $(u, v) \in E$ , i.e. if there is an arc from  $u$  to  $v$ .

Note that topological sorting is possible only if the input graph is acyclic. If this condition is not met, `topologic_sort` returns an error. Otherwise, it finds the required ordering by applying KAHN's algorithm [47], which runs in  $O(|V| + |E|)$  time.

```
> purge(a,b,c,d):: G:=digraph(%{[c,a],[c,b],[c,d],[a,d],[b,d],[a,b]})
```

“Done”, a directed unweighted graph with 4 vertices and 6 arcs

```
> is_acyclic(G)
```

true

```
> topologic_sort(G)
```

$[c, a, b, d]$

### 4.9.3 st ordering

```
st_ordering(G,s,t,<p>)
```

```
st_ordering(G,s,t,D,<p>)
```

The command `st_ordering` is used for finding *st-orderings* in undirected biconnected graphs. It takes three to five arguments. The first three arguments are mandatory: an undirected biconnected<sup>4.3</sup> graph  $G(V, E)$ , a vertex  $s \in V$  called the source, a vertex  $t \in V$  called the sink such that  $st \in E$ . Optionally, one can pass an unassigned identifier  $D$  and/or a real value  $p \in [0, 1]$ . The command returns the permutation of the vertex set  $V$  which corresponds to st-numbering of the vertices.

Given a st-numbering, an orientation of each  $e = uv \in E$  can be imposed by comparing the ordinals  $n$  and  $m$  assigned its endpoints  $u$  and  $v$ , respectively; if  $n < m$ , then  $u$  is the head and  $v$  is the tail of the corresponding arc, and vice versa otherwise. If an identifier  $D$  is given, a copy of  $G$ , which is made directed according to these orientations, is stored to  $D$ . The oriented variant of  $G$  is an acyclic graph (or DAG for short).

If the argument  $p$  is not specified, the strategy is to apply TARJAN's algorithm [76] which runs in  $O(|V| + |E|)$  time. When  $p \in [0, 1]$  is given, a parametrized st-ordering is computed, in which the length of the longest path from  $s$  to  $t$  in the respective DAG roughly corresponds to  $p|V|$ . Thus by varying  $p$  one controls the length of the longest directed path from  $s$  to  $t$ . The parametrized branch of the algorithm is implemented according to PAPAMANTHOU and TOLLIS [63] and runs in  $O(|V||E|)$  time.

```
> purge(a,b,c,d):: G:=graph(%{[a,b],[a,c],[a,d],[b,c],[b,d],[c,d]})
```

“Done”, an undirected unweighted graph with 4 vertices and 6 edges

```
> vertices(G)
```

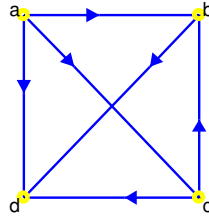
$[a, b, c, d]$

```
> st_ordering(G,a,d,D)
```

$[0, 2, 1, 3]$

```
> draw_graph(D)
```

<sup>4.3</sup> For a biconnected input graph, an st-ordering can be computed for any pair  $s, t \in V$  such that  $st \in E$  [76].



The following program demonstrates the usage of the parametrized `st-ordering` algorithm for finding a path between vertices  $u$  and  $v$  in an undirected, biconnected graph  $G(V, E)$ , the length of which depends on the parameter  $p \in [0, 1]$ .

```
FindPath:=proc(G,u,v,p)
  local tmp,D,W;
  tmp:=!has_edge(G,[u,v]);
  if tmp then G:=add_edge(G,[u,v]); fi;
  purge(D);
  st_ordering(G,u,v,D,p);
  if tmp then D:=delete_arc(D,[u,v]); fi;
  W:=is_weighted(G) ? weight_matrix(G) : adjacency_matrix(G);
  D:=make_weighted(D,-W);
  return bellman_ford(D,u,v)[0];
end;
```

The procedure `FindPath` uses [Bellman-Ford algorithm](#) to find a longest path from the vertex  $u \in V$  to the vertex  $v \in V$  in the DAG  $D$  induced by a parametrized `st-ordering` of  $G$  with parameter  $p$ . To trick Bellman-Ford into finding a longest path instead of the shortest one (which it was originally designed for), the edges of  $D$  are weighted with negative weights. Since  $D$  is acyclic, it contains no negative cycles, so the Bellman-Ford algorithm terminates successfully.

For  $p = 0$  one obtains a relatively short path, but usually not a minimal one. For  $p = 1$  one obtains near-Hamiltonian paths. For  $p \in (0, 1)$  one obtains a path of length  $l$  which obeys the relation

$$l \approx l_0 + p(|V| - l_0),$$

where  $l_0$  is the average path length for  $p = 0$ .

After compiling the above program in XCAS (by copying it into a programming cell which we create by pressing `Alt+P`), we demonstrate it in the following examples.

```
> G:=graph("soccerball")
```

an undirected unweighted graph with 60 vertices and 90 edges

```
> length(FindPath(G,3,33,0))
```

12

```
> length(FindPath(G,3,33,0.5))
```

39

```
> length(FindPath(G,3,33,1))
```

59

#### 4.9.4 Graph condensation

`condensation(G)`

The command `condensation` is used for constructing the [condensation graph](#) of a given digraph. It takes a digraph  $G(V, E)$  as its only argument and returns the acyclic digraph  $G'(V', E')$  obtained by contracting all strongly connected components of  $G$  to single vertices. These vertices form the set  $V'$ . Two vertices  $u, v \in V'$  are connected in  $G'$  if and only if there is an arc in  $G$  with tail in the component of  $G$  corresponding to  $u$  and head in the component of  $G$  corresponding to  $v$ . The order of vertices in  $V'$  is the same as the order of components as returned by the command `strongly_connected_components`.

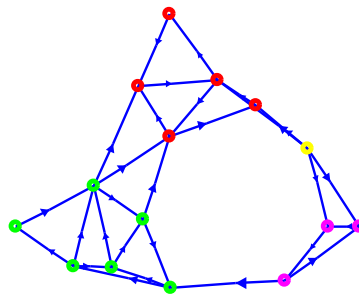
```
> E:=tran([[1,2,3,3,4,4,4,4,5,5,6,6,6,7,8,8,9,9,10,10,10,11,11,12,13,13,14,15],
[3,1,2,5,1,2,12,13,6,8,7,8,10,10,9,10,5,11,9,11,14,12,14,13,11,15,13,14]]);
G:=digraph(set[op(E)])
```

“Done”, a directed unweighted graph with 15 vertices and 28 arcs

```
> comp:=strongly_connected_components(G)
```

```
[[11, 12, 13, 14, 15], [5, 6, 7, 8, 9, 10], [1, 2, 3], [4]]
```

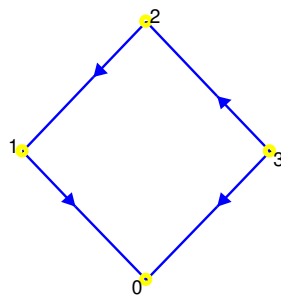
```
> c:=[red,green,magenta];;
for k from 0 to 2 do G:=highlight_vertex(G,comp[k],c[k]); od;;
draw_graph(G,spring,labels=false)
```



```
> C:=condensation(G)
```

a directed unweighted graph with 4 vertices and 4 arcs

```
> draw_graph(C,spring)
```



## 4.10 Matching in graphs

### 4.10.1 Maximum matching

```
maximum_matching(G)
```

The command `maximum_matching` is used for finding maximum [matchings](#) [34, p. 43] in undirected unweighted graphs. It takes an undirected graph  $G(V, E)$  as its only argument and returns a list of edges  $e_1, e_2, \dots, e_m \in E$  such that  $e_i$  and  $e_j$  are not adjacent (i.e. have no common endpoints) for all  $1 \leq i < j \leq m$  and that  $m$  is maximal. The return value can be interpreted as the list of matched pairs of vertices in  $G$ .

The strategy is to apply the [blossom algorithm](#) of EDMONDS [23], which runs in  $O(|V|^2 |E|)$  time, on connected components of  $G$  (one at a time). The implementation combines an efficient initial heuristic with implicit blossom-shrinking.

```
> maximum_matching(graph("octahedron"))
```

```
[[0, 4], [1, 3], [2, 5]]
```

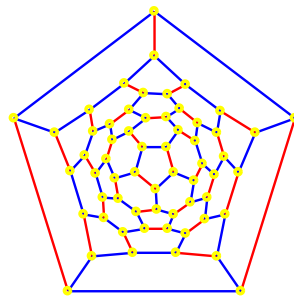
```
> G:=graph("soccerball")
```

an undirected unweighted graph with 60 vertices and 90 edges

```
> M:=maximum_matching(G); length(M)
```

```
"Done", 30
```

```
> draw_graph(highlight_edges(G,M), labels=false)
```



```
> G:=random_graph(10000,0.02)
```

an undirected unweighted graph with 10000 vertices and 998282 edges

```
> size(maximum_matching(G))
```

```
5000
```

```
1.592 sec
```

### 4.10.2 Maximum matching in bipartite graphs

```
bipartite_matching(G)
```

```
bipartite_matching(G,minimize|maximize,<epsilon=<real>>)
```

The command `bipartite_matching` is used for finding maximum (weighted) matchings in undirected bipartite graphs. It takes an undirected bipartite graph  $G(V, E)$  as its mandatory argument and returns the maximum matching in  $G$  as a list of edges. The strategy is to apply the algorithm of HOPCROFT and KARP [44] which runs in  $O(\sqrt{|V|} |E|)$  time. If  $G$  is weighted, then the edge weights are ignored.

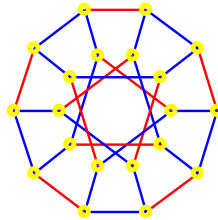
The optional second argument can be either `minimize` or `maximize`. If one is given, then  $G$  must be a weighted graph. In that case, `bipartite_matching` finds a minimum/maximum weighted matching (i.e. solves an assignment problem) using the out-of-kilter algorithm implementation in GLPK. If the latter is not available, then the task is converted to a transportation problem and solved by the `tpsolve` command. Note that negative edge weights are allowed. The return value is a sequence containing the weight of the matching followed by the list of edges in the matching.

The out-of-kilter algorithm requires all edge weights in  $G$  to be integer-valued. If that is not the case, `bipartite_matching` divides the weights by the value `epsilon` set by the optional third argument (by default  $10^{-5}$ ) and rounds them subsequently.

```
> G:=graph("desargues")
```

an undirected unweighted graph with 20 vertices and 30 edges

```
> draw_graph(highlight_edges(G,bipartite_matching(G)),labels=false)
```



```
> purge(A,B,C,D,E,F)::
```

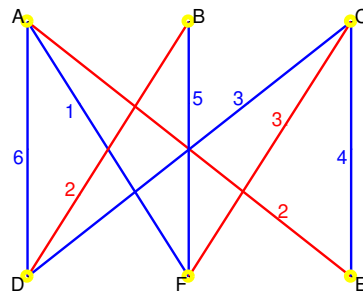
```
> G:=graph(%{[[A,D],6],[[A,E],2],[[A,F],1],[[B,D],2],[[B,F],5],[[C,D],3],[[C,E],4],[[C,F],3]%%})
```

an undirected weighted graph with 6 vertices and 8 edges

```
> w_min,ed_min:=bipartite_matching(G,minimize)
```

7, [[A, E], [B, D], [C, F]]

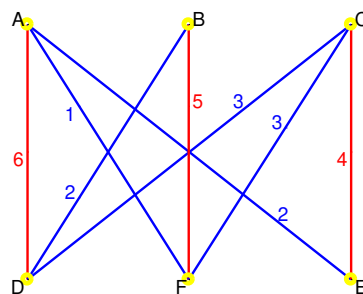
```
> draw_graph(highlight_edges(G,ed_min))
```



```
> w_max,ed_max:=bipartite_matching(G,maximize)
```

15, [[A, D], [B, F], [C, E]]

```
> draw_graph(highlight_edges(G,ed_max))
```



```
> R:=random_bipartite_graph(5000,20000)
```

an undirected unweighted graph with 5000 vertices and 20000 edges

```
> size(bipartite_matching(R))
```

1417

259 msec

```
> w,ed:=bipartite_matching(assign_edge_weights(R,1..100),maximize):;
```

16.508 sec

```
> size(ed)
```

1417

## 4.11 Vertex covers

### 4.11.1 Finding a vertex cover of the specified size

`find_vertex_cover(G, {k})`

The command `find_vertex_cover` is used for obtaining a [vertex cover](#) (optionally of the given size) of an undirected graph. It takes an undirected graph  $G(V, E)$  as its first argument and returns a vertex cover of  $G$ , i.e. a set of vertices  $C$  such that each edge  $e \in E$  has an endpoint in  $C$ . If the optional second argument  $k \geq 0$  is given, then size of the returned cover must be equal to  $k$ . If there exists no such cover, then the return value is `false`.

The strategy for  $k \geq 0$  is to compute an approximation of minimal vertex cover in  $G$  using the algorithm described in Section 4.11.2. If the obtained cover is of size  $m \leq k$ , then  $k - m$  vertices among the remaining ones are added to the cover at random. Otherwise, if  $m > k$ , then a cover of size  $k$  is obtained by solving the ILP formulation of the problem.

If  $k$  is not specified, `find_vertex_cover` approximates minimum vertex cover by using ALOM's algorithm [64] which runs in  $O(|V|^2)$  time and tries to minimize the number of vertices in the cover. Cover vertices are gathered one at a time, each time choosing a vertex with the maximum incident edges. Ties are broken by randomly choosing a candidate vertex with the smallest number of edges connecting it to other candidates. After a vertex is chosen, it is added to the cover and all edges incident to it are deleted. This procedure is repeated until there are no more edges in the graph.

```
> G:=random_graph(1000,0.1)
```

an undirected unweighted graph with 1000 vertices and 49981 edges

```
> length(find_vertex_cover(G))
```

956

```
> H:=random_graph(100,0.1)
```

an undirected unweighted graph with 100 vertices and 476 edges

```
> size(find_vertex_cover(H))
```

75

```
> size(minimum_vertex_cover(H))
```

68

### 4.11.2 Minimum vertex cover

```
minimum_vertex_cover(G, <approx>)
vertex_cover_number(G)
```

The command `minimum_vertex_cover` is used for finding minimum vertex covers of undirected graphs. The command `vertex_cover_number` is convenient when only the cardinality of a minimum cover is sought. Both commands take an undirected graph  $G(V, E)$  as their mandatory argument and return a minimum vertex cover (MVC)  $C \subseteq V$  of  $G$  resp. the cardinality  $|C|$ . The routine for computing MVC in GIAC operates as follows. First,  $G$  is splitted into connected components. Then MVC is found for each component separately. The union of the obtained covers is a MVC for  $G$ . There are three different kinds of components recognized by the algorithm.

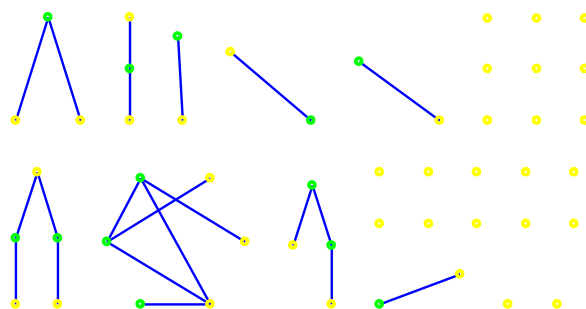
1. If component  $C(V_C, E_C)$  is a tree, cyclic, or clique graph, then its MVC is straightforward to construct. This requires  $O(|V_C|)$  time.
2. If  $C$  is bipartite, then its MVC can be obtained by applying [König's theorem](#) which obtains MVC from maximum matching  $M$  (`vertex_cover_number` simply computes the size of  $M$ ). This requires  $O(\sqrt{|V_C|} |E_C|)$  time.
3. If  $C$  is neither a tree, cyclic, clique, or bipartite graph, then solving the integer linear programming (ILP) formulation of the MVC problem is attempted. The inclusion of a vertex  $v \in V$  is represented by a binary variable  $x_v \in \{0, 1\}$ . The objective to be minimized is  $\sum_{v \in V} x_v$  and the constraints are  $x_v + x_w \geq 1$  for each  $vw \in E$ . The branching and reduction techniques by AKIBA and IWATA [3] are used in the process. Note that MVC problem is NP-hard, which means that exponential time is required for certain choices of  $G$ .

If the optional second argument `approx` is provided, then the solution in the case 3 is approximated as follows. First, an approximately maximum independent set  $M$  in the component  $C$  induced by  $V_C \subseteq V$  is computed by applying the greedy algorithm described in Section 4.12.5. The complement  $V_C \setminus M$  is then returned as an approximate MVC of  $C$ . This strategy usually gives very good (near-optimal) results in a short amount of time. It is also used by the exact solver for obtaining an initial feasible solution.

```
> G:=random_graph(50,0.02)
```

an undirected unweighted graph with 50 vertices and 21 edges

```
> draw_graph(highlight_vertex(G,minimum_vertex_cover(G)),labels=false)
```



```
> vertex_cover_number(G)
```

13

```
> P:=petersen_graph(10,2)
```

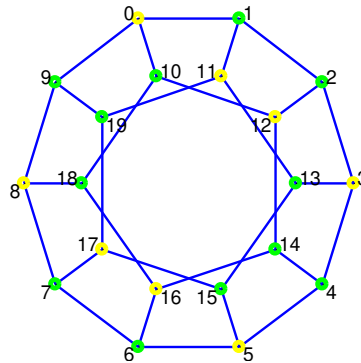
an undirected unweighted graph with 20 vertices and 30 edges

```
> C:=minimum_vertex_cover(P)
```



[1, 2, 4, 6, 7, 9, 10, 13, 14, 15, 18, 19]

```
> draw_graph(highlight_vertex(P,C))
```



```
> R:=random_graph(100,0.15)
```

an undirected unweighted graph with 100 vertices and 729 edges

```
> size(minimum_vertex_cover(R,approx))
```

76

```
> vertex_cover_number(R)
```

75

6.437 sec

## 4.12 Cliques and independent sets

### 4.12.1 Clique graphs

`is_clique(G)`

Given an undirected graph  $G(V, E)$ , a subset  $S \subset V$  is called a **clique** in  $G$  if any two distinct vertices from  $S$  are adjacent in  $G$ , i.e. if the subgraph of  $G$  induced by the set  $S$  is complete. To check whether an undirected graph is a clique, one can use the `is_clique` command. It takes an undirected graph  $G(V, E)$  as its only argument and returns `true` if every pair of distinct vertices is connected by a unique edge in  $E$ . Otherwise, it returns `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

### 4.12.2 Finding maximal cliques

```
find_cliques(G,⟨C⟩)
find_cliques(G,k,⟨C⟩)
find_cliques(G,m..n,⟨C⟩)
```

A clique in an undirected graph  $G(V, E)$  is **maximal** if it cannot be extended by adding more vertices from  $V$  to it. To count all maximal cliques in a graph (and optionally list them) one can use the `find_cliques` command. It takes an undirected graph  $G(V, E)$  as the mandatory first argument. If no other arguments are given, the command returns a list of pairs, each pair consisting of two integers: clique cardinality  $k$  and the number  $n_k > 0$  of  $k$ -cliques in  $G$ , respectively. (Therefore, the sum of second members of all returned pairs is equal to the total count of all maximal cliques in  $G$ .) If two arguments are passed to `find_cliques`, the second argument must be a positive integer  $k$  or an interval with integer bounds  $m .. n$ . In the first case the number of  $k$ -cliques is returned; in the second case, only cliques with cardinality between  $m$  and  $n$  (both inclusive) are counted.

If  $C$  is specified as the last argument, it must be an unassigned identifier. Maximal cliques are in that case stored to  $C$  as a list of lists of cliques of equal size. This option is therefore used for listing all maximal cliques.

The strategy used to find all maximal cliques is a variant of the algorithm of BRON and KERBOSCH developed by TOMITA et al. [78]. Its worst-case running time is  $O(3^{|V|/3})$ . However, the algorithm is usually very fast, typically taking only a moment for graphs with few hundred vertices or less.

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

an undirected unweighted graph with 50 vertices and 590 edges

```
> find_cliques(G)
```

$$\begin{pmatrix} 3 & 5 \\ 4 & 214 \\ 5 & 442 \\ 6 & 196 \\ 7 & 10 \end{pmatrix}$$

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

an undirected unweighted graph with 100 vertices and 2507 edges

```
> find_cliques(G,5)
```

3529

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

an undirected unweighted graph with 500 vertices and 31163 edges

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

$$\begin{pmatrix} 5 & 149442 \\ 6 & 17105 \\ 7 & 349 \end{pmatrix}$$

1.457 sec

```
> G:=graph("octahedron")
```

an undirected unweighted graph with 6 vertices and 12 edges

```
> purge(C); find_cliques(G,C)
```

```
“Done”, ( 3 8 )
```

```
> C
```

```
[[0, 2, 4], [0, 2, 5], [0, 3, 4], [0, 3, 5], [1, 2, 4], [1, 2, 5], [1, 3, 4], [1, 3, 5]]
```

### 4.12.3 Maximum clique

```
maximum_clique(G)
```

```
clique_number(G)
```

Any largest maximal clique in an undirected graph is called **maximum clique**. The command `maximum_clique` can be used to find one in a graph. If only the size of a maximum clique is desired, one can use the command `clique_number`.

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

The strategy used to find maximum clique is an improved variant of the classical algorithm of CARRAGHAN and PARDALOS developed by ÖSTERGÅRD [60].

`clique_number` has the same calling syntax, but returns only the size of a maximum clique in  $G$ .

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

```
an undirected unweighted graph with 3125 vertices and 7810 edges
```

```
> maximum_clique(G)
```

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

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

```
an undirected unweighted graph with 300 vertices and 13603 edges
```

```
> maximum_clique(G)
```

```
[53, 93, 103, 179, 183, 224, 277, 289]
```

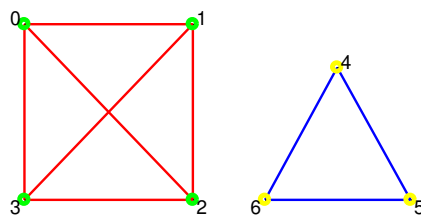
```
> G:=graph_complement(complete_graph(4,3))
```

```
an undirected unweighted graph with 7 vertices and 9 edges
```

```
> cliq:=maximum_clique(G)
```

```
[0, 1, 2, 3]
```

```
> draw_graph(highlight_subgraph(G,induced_subgraph(G,cliq)))
```



`clique_number` takes an undirected graph  $G$  as its only argument and returns the number of vertices forming a maximum clique in  $G$ .

```
> clique_number(G)
```

4

#### 4.12.4 Maximum independent set

```
maximum_independent_set(G)
```

```
independence_number(G)
```

The command `maximum_independent_set` is used for finding maximum *independent sets* in undirected graphs. For obtaining just the size of a maximum independent set use the command `independence_number`.

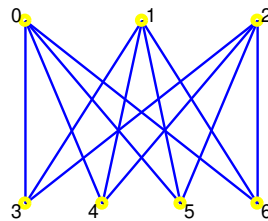
`maximum_independent_set` takes an undirected graph  $G$  as its only argument and finds a maximum clique in the complement of  $G$  (see Section 4.12.3), which corresponds to a maximum independent set in  $G$ .

`independence_number` has the same calling syntax, but returns only the size of a maximum independent set in  $G$ .

```
> G:=complete_graph(3,4)
```

an undirected unweighted graph with 7 vertices and 12 edges

```
> draw_graph(G)
```



```
> maximum_independent_set(G)
```

[3, 4, 5, 6]

```
> independence_number(G)
```

4

```
> C:=graph_complement(G)
```

an undirected unweighted graph with 7 vertices and 9 edges

```
> maximum_clique(C)
```

[3, 4, 5, 6]

#### 4.12.5 Greedy clique finding

```
greedy_clique(G, <n>)
```

```
greedy_independent_set(G, <n>)
```

The commands `greedy_clique` and `greedy_independent_set` are used for finding large cliques and independent sets in undirected graphs.

`greedy_clique` takes an undirected graph  $G(V, E)$  as its mandatory first argument and an integer  $n \geq 2$  as the optional second argument (by default,  $n = 5$ ). It attempts to find a large clique in  $G$ , returning the list of corresponding vertex labels.

The strategy is to apply a greedy randomized adaptive search procedure (GRASP) tailored for the local maximum clique problem as described by ABELLO and PARDALOS in [1, procedure `grasp`, pp. 4–5] with `maxitr=n` (the number of iterations).

`greedy_independent_set` attempts to find a large independent set of the graph  $G$ , returning the list of corresponding vertex labels. The strategy is to call `greedy_clique` on the complement of  $G$ .

```
> G1:=random_graph(1000,0.95)
```

an undirected unweighted graph with 1000 vertices and 474417 edges

```
> c1:=greedy_clique(G1)
```

```
[1, 26, 31, 42, 46, 53, 57, 59, 66, 77, 96, 141, 154, 159, 161, 174, 175, 179, 180, 201, 212, 213, 223, 240,
247, 249, 255, 277, 280, 282, 285, 303, 304, 312, 321, 329, 374, 382, 400, 415, 425, 427, 442, 452, 458,
478, 490, 492, 499, 504, 519, 532, 539, 546, 563, 564, 566, 568, 577, 603, 638, 648, 657, 658, 665, 678,
682, 683, 699, 701, 713, 726, 730, 746, 750, 765, 773, 790, 791, 794, 801, 810, 819, 845, 854, 856, 858,
865, 869, 874, 899, 923, 925, 941, 957, 958, 973, 976, 981, 986]
```

```
> is_clique(induced_subgraph(G1,c1))
```

true

```
> length(c1)
```

100

It can be shown that the expected number of cliques of size  $k$  in  $G_1$  is equal to  $\binom{1000}{k} 0.95^{\binom{k}{2}}$ . This number gets below 1 for about  $k = 120$ , which indicates that a maximum clique should be of size around 120.

In the following example, the same is tried with a large sparse graph, now running 50 iterations instead of the default 5.

```
> G2:=random_graph(3000,0.01)
```

an undirected unweighted graph with 3000 vertices and 44882 edges

```
> c2:=greedy_clique(G2,50)
```

```
[241, 350, 1216, 2116]
```

```
> is_clique(induced_subgraph(G2,c2))
```

true

By the same argument as before, but now with the formula  $\binom{3000}{k} 0.01^{\binom{k}{2}}$ , it is suggested that the maximum clique in  $G_2$  should be of size about 4.

In the next example a random regular graph is used.

```
> G3:=random_regular_graph(100,30)
```

an undirected unweighted graph with 100 vertices and 1500 edges

```
> greedy_clique(G3)
```

[7, 29, 38, 46, 68]

Finally, we also find an independent set using 8 iterations.

```
> greedy_independent_set(G3,8)
```

[2, 5, 7, 8, 12, 13, 56, 60, 74, 75, 76, 94]

#### 4.12.6 Minimum clique cover

```
clique_cover(G,⟨b⟩)
```

A **minimum clique cover** for an undirected graph  $G$  is any minimal set  $S = \{C_1, C_2, \dots, C_k\}$  of cliques in  $G$  such that for every vertex  $v$  in  $G$  there exists  $i \leq k$  such that  $v \in C_i$ . Such a cover can be obtained by calling the `clique_cover` command. It takes an undirected graph  $G(V, E)$  as its mandatory argument and returns the smallest possible cover. Optionally, a positive integer  $b$  may be passed as the second argument. In that case the requirement  $k \leq b$  is set. If no such cover is found, then an empty list is returned.

The strategy is to find a minimal vertex coloring in the complement  $G^c$  of  $G$ . Each set of equally colored vertices in  $G^c$  corresponds to a clique in  $G$ . Therefore, the color classes of  $G^c$  correspond to the elements  $C_1, \dots, C_k$  of a minimal clique cover in  $G$ .

There is a special case in which  $G$  is triangle-free (i.e. contains no 3-cliques), which is computed separately in the algorithm. In that case,  $G$  contains only 1- and 2-cliques. Therefore, every clique cover in  $G$  consists of a set  $M \subset E$  of matched edges together with the singleton cliques (i.e. the isolated vertices in  $V$  which remain unmatched). The total number of cliques in the cover is equal to  $|V| - |M|$ , hence to find a minimal cover one just needs to find a maximum matching in  $G$ , which can be done in polynomial time.

```
> G:=random_graph(30,0.2)
```

an undirected unweighted graph with 30 vertices and 98 edges

```
> clique_cover(G)
```

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

```
> clique_cover(graph("octahedron"))
```

[[2, 4, 5], [1, 3, 6]]

The vertices of Petersen graph can be covered with five, but not with three cliques.

```
> clique_cover(graph("petersen"),3)
```

[]

```
> clique_cover(graph("petersen"),5)
```

[[7, 9], [6, 8], [0, 5], [3, 4], [1, 2]]

#### 4.12.7 Clique cover number

```
clique_cover_number(G)
```

The command `clique_cover_number` is used for computing the **clique cover number** of a graph. It takes an undirected graph  $G(V, E)$  as its only argument and returns the minimum number of cliques in  $G$  needed to cover the vertex set  $V$ . (More precisely, it calls the `clique_cover` command and returns the length of the output list.) This number, denoted by  $\theta(G)$ , is equal to the chromatic number  $\chi(G^c)$  of the complement graph  $G^c$  of  $G$ .

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

5

```
> clique_cover_number(graph("soccerball"))
```

30

### 4.12.8 Split graphs

`is_split_graph(G, <part>)`

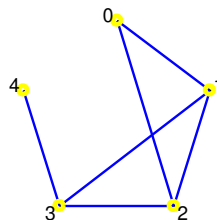
The command `is_split_graph` is used for detecting **split graphs** and obtaining decompositions of such graphs. It takes single mandatory argument, an undirected graph  $G(V, E)$ , and returns **true** if and only if  $G$  is a split graph, which means that  $V$  can be partitioned into a clique  $C \subset V$  and an independent set  $D = V \setminus C$ . If the keyword `part` is given and  $G$  is a split graph, the list containing  $C$  and  $D$  (in that order) is also returned.

The strategy is to apply the criterion of HAMMER and SIMEONE [39] which uses only the degree sequence of  $G$ . The algorithm operates in  $O(|V| \log |V|)$  time.

```
> K:=graph(5,%{[0,1],[0,2],[1,2],[1,3],[2,3],[3,4]})
```

an undirected unweighted graph with 5 vertices and 6 edges

```
> draw_graph(K)
```



```
> is_split_graph(K)
```

true

```
> is_split_graph(K,part)
```

true, [[3, 2, 1], [0, 4]]

### 4.12.9 Simplicial vertices

`simplicial_vertices(G)`

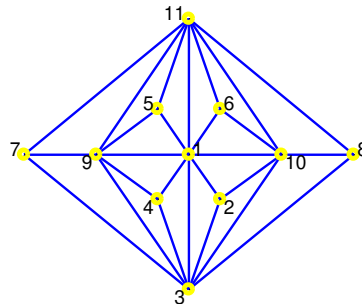
A vertex in an undirected graph is called **simplicial** if its neighborhood is a clique. The command `simplicial_vertices` is used for finding such vertices in the given graph. It takes an undirected graph  $G(V, E)$  as its only argument and returns the list of simplicial vertices in  $V$ , i.e. the vertices for which the corresponding neighborhood-induced subgraphs are complete.

The strategy is to use the algorithm of KLOKS et al. [49], which in the present implementation has the worst-case running time  $O(|E|^{3/2})$ .

```
> G:=graph("goldner-harary")
```

an undirected unweighted graph with 11 vertices and 26 edges

```
> draw_graph(G)
```



```
> simplicial_vertices(G)
```

[2, 4, 5, 6]

```
> H:=sierpinski_graph(3,6)
```

an undirected unweighted graph with 216 vertices and 645 edges

```
> simplicial_vertices(H)
```

[0, 43, 86, 129, 172, 215]

```
> is_clique(induced_subgraph(H,neighbors(H,43)))
```

true

## 4.13 Network analysis

### 4.13.1 Counting triangles

```
number_of_triangles(G,⟨L⟩)
```

The command `number_of_triangles` is used for counting [triangles](#) in graphs. It takes a graph  $G$  as its first, mandatory argument and returns the number  $n$  of 3-cliques in  $G$  if  $G$  is undirected resp. the number  $m$  of directed cycles of length 3 if  $G$  is directed. If an unassigned identifier  $L$  is given as the second argument, the triangles are also listed and stored to  $L$ . Note that triangle listing is supported only for undirected graphs.

For undirected graphs the algorithm of SCHANK and WAGNER [67, Algorithm *forward*], improved by LATAPY [52], is used, which runs in  $O(|E|^{3/2})$  time. For digraphs, the strategy is to compute the trace of  $A^3$  where  $A$  is the adjacency matrix of  $G$  encoded in a sparse form. This algorithm requires  $O(|V||E|)$  time.

```
> number_of_triangles(graph("tetrahedron"))
```

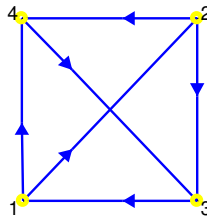
4

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

a directed unweighted graph with 4 vertices and 6 arcs



```
> draw_graph(G, spring)
```



```
> number_of_triangles(G)
```

2

```
> G:=sierpinski_graph(7,3,triangle)
```

an undirected unweighted graph with 1095 vertices and 2187 edges

```
> number_of_triangles(G)
```

972

Petersen graph is triangle-free, i.e. contains no 3-cliques.

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

0

Counting triangles in undirected graphs is very fast, as illustrated by the following example.

```
> G:=random_graph(10^5,10^6)
```

an undirected unweighted graph with 100000 vertices and 1000000 edges

```
> number_of_triangles(G)
```

25306

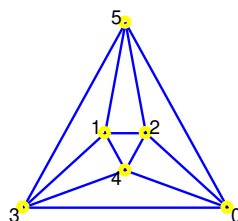
1.155 sec

To list all triangles in a graph, pass an unassigned identifier as the second argument. The triangles will be stored to it as a list of triples of vertices.

```
> G:=graph("octahedron")
```

an undirected unweighted graph with 6 vertices and 12 edges

```
> draw_graph(G)
```



```
> purge(L); number_of_triangles(G,L)
```

"Done", 8

```
> L
```

```
[[1, 3, 5], [1, 3, 4], [0, 3, 5], [0, 3, 4], [1, 2, 5], [1, 2, 4], [0, 2, 5], [0, 2, 4]]
```

### 4.13.2 Clustering coefficient

```
clustering_coefficient(G, <opt>)  
clustering_coefficient(G, v)  
clustering_coefficient(G, v1, v2, ..., vk)  
clustering_coefficient(G, [v1, v2, ..., vk])
```

The command `clustering_coefficient` is used for computing the [average clustering coefficient](#) (or simply: clustering coefficient) of an undirected graph as well as the [local clustering coefficient](#) of a particular vertex in that graph. It takes one or two arguments, an undirected graph  $G(V, E)$  and optionally a vertex  $v \in V$  or a list/sequence of vertices  $v_1, v_2, \dots, v_k \in V$ . If  $G$  is the only argument, the clustering coefficient  $c(G)$  [12, p. 5] is returned. Otherwise, the local clustering coefficient  $c_G(v)$  [12, p. 4] of  $v$  resp. a list of local clustering coefficients of  $v_1, v_2, \dots, v_k$  is returned. The second argument may also be one of the following options.

- **exact** — the clustering coefficient  $c(G)$  is returned as a rational number (by default it is a floating point number). Note that local clustering coefficient is always returned in exact form
- **approx** — an approximation of the clustering coefficient  $c(G)$ , lying within  $0.5 \times 10^{-2}$  of the exact value with probability  $p = 1 - 10^{-5}$ , is returned

In any case, the return value is—by definition—a rational number in the range  $[0, 1]$ .

The clustering coefficient of  $G$  is defined as the mean of  $c_G(v)$ ,  $v \in V$ :

$$c(G) = \frac{1}{|V|} \sum_{v \in V} c_G(v).$$

$c(G)$  can be interpreted as the probability that, for a randomly selected pair of incident edges  $(u, v)$  and  $(v, w)$  in  $G$ , the vertices  $u$  and  $w$  are connected. The number  $c_G(v)$  is interpreted analogously but for a fixed  $v \in V$ . It represents the probability that two neighbors of  $v$  are connected to each other.

For example, assume that  $G$  represents a social network in which  $uv \in E$  indicates that  $u$  and  $v$  are friends (which is a symmetric relation). In this context,  $c(v)$  represents the probability that two friends of  $v$  are also friends of each other.

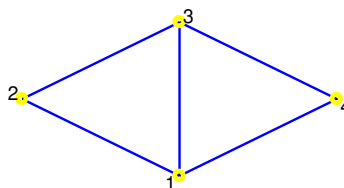
The time complexity of computing  $c(G)$  is  $O(|E|^{3/2})$ , whereas the algorithm of SCHANK and WAGNER [68, Algorithm 1, p. 269] for approximating  $c(G)$  runs in  $O(\log |V|)$  time.

Note that the command `random_graph` is able to generate—using a preferential attachment rule—realistic random networks with adjustable clustering coefficient, which are suitable for testing purposes.

```
> G:=graph("diamond")
```

an undirected unweighted graph with 4 vertices and 5 edges

```
> draw_graph(G, spring)
```



The command lines below compute  $c(G)$ ,  $c_G(1)$  and  $c_G(2)$ .

```
> clustering_coefficient(G, exact)
```

$$\frac{5}{6}$$

```
> clustering_coefficient(G,1)
```

$$\frac{2}{3}$$

```
> clustering_coefficient(G,2)
```

$$1$$

The next example demonstrates the performance of `clustering_coefficient` on a large graph.

```
> G:=random_graph(25000,10,100)
```

an undirected unweighted graph with 25000 vertices and 988571 edges

```
> clustering_coefficient(G)
```

0.637641843214

1.469 sec

```
> clustering_coefficient(G,approx)
```

0.637380772718

491 msec

The probability that two neighbors of a vertex in  $G$  are connected is therefore about 64%.

### 4.13.3 Network transitivity

`network_transitivity(G)`

The command `network_transitivity` is used for computing the **transitivity** (also called **triangle density** or the **global clustering coefficient**) of a network. It takes a graph  $G$  as its only argument and returns the transitivity  $T(G)$  of  $G$  [12, p. 5] as a rational number in the range  $[0, 1]$ :

$$T(G) = \frac{3 N_{\text{triangles}}}{N_{\text{triplets}}}.$$

$T(G)$  is a measure of transitivity of a non-symmetric relation between the vertices of a network. If  $G$  is a digraph, a **triplet** in  $G$  is any directed path  $(v, w, z)$  where  $v, w, z \in V$ . For example, in a Twitter-like social network this could mean that  $v$  following  $w$  and  $w$  following  $z$ . The triplet  $(v, w, z)$  is **closed** if  $(v, z) \in E$ , i.e. if  $v$  also follows  $z$  [82, p. 243]. A closed triplet is called a **triangle**. If  $G$  is undirected,  $N_{\text{triangles}}$  is the number of 3-cliques and  $N_{\text{triplets}}$  is the number of two-edge paths in  $V$ .

The complexity of computing  $T(G)$  is  $O(\Delta_G |E|)$  for digraphs, where  $\Delta_G$  is the maximum vertex degree in  $G$ , resp.  $O(|E|^{3/2})$  for undirected graphs.

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

an undirected unweighted graph with 4 vertices and 5 edges

```
> network_transitivity(G)
```

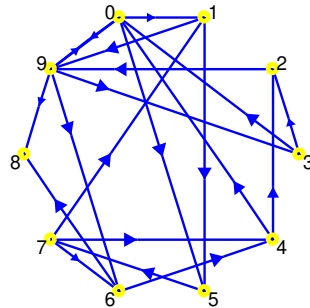
$$\frac{3}{4}$$

Observe that the above result is different than  $c(G)$  obtained in Section 4.13.2. Hence  $c(G) \neq T(G)$  in general [12, p. 5].

```
> G:=random_digraph(10,20)
```

a directed unweighted graph with 10 vertices and 20 arcs

```
> draw_graph(G)
```



In the above digraph, the triplet (7,6,8) is open while the triplet (7,6,4) is closed. Triangles (1,5,7) and (3,2,9) are not closed by definition.

```
> network_transitivity(G)
```

$$\frac{1}{8}$$

The transitivity algorithms are suitable for large networks, as demonstrated in the examples below.

```
> G:=random_digraph(1000,500000)
```

a directed unweighted graph with 1000 vertices and 500000 arcs

```
> nt:=network_transitivity(G);;
```

2.137 sec

```
> evalf(nt)
```

0.500525000328

```
> H:=random_graph(30000,10,50)
```

an undirected unweighted graph with 30000 vertices and 1015074 edges

```
> evalf(network_transitivity(H))
```

0.135416551785

1.418 sec

#### 4.13.4 Centrality measures

```
betweenness centrality(G,⟨v⟩)
closeness centrality(G,⟨v⟩)
communicability_betweenness centrality(G,⟨v⟩)
degree centrality(G,⟨v⟩)
harmonic centrality(G,⟨v⟩)
information centrality(G,⟨v⟩,⟨approx⟩)
katz centrality(G,alpha,⟨v⟩)
```

GIAC provides several commands for measuring vertex **centrality** in networks. These commands compute the indicated centrality measure for the vertex  $v \in V$  in a graph  $G(V, E)$  with  $|V| > 1$ . If  $v$  is omitted, the list of values for every vertex in  $V$  is returned, in order as provided by `vertices(G)`.

**Degree centrality** of vertex  $v$  is computed using the formula

$$C_D(v) = \frac{\deg(v)}{|V| - 1}.$$

**Closeness centrality** of vertex  $v$  is computed using the formula

$$C(v) = \frac{|V| - 1}{\sum_{u \in V} d(u, v)},$$

where  $d(u, v)$  is the distance from  $u$  to  $v$  [7].

**Harmonic centrality** of vertex  $v$  is computed using the formula [54]

$$H(v) = \sum_{u \in V} \frac{1}{d(u, v)}.$$

The worst case complexity in both cases is  $O(|V|^3)$  when closeness/harmonic centrality is computed for all vertices in a weighted graph  $G$ . For unweighted graphs, the complexity drops to  $O(|V|^2 + |V||E|)$ .

**Betweenness centrality** of vertex  $v$  is computed using the formula

$$C_B(v) = \sum_{s \neq v \neq t \in V} \frac{\sigma_{st}(v)}{\sigma_{st}},$$

where  $\sigma_{st}$  is total number of shortest paths from  $s$  to  $t$  and  $\sigma_{st}(v)$  is the number of those paths which pass through  $v$  [30]. The strategy is to use the algorithm by BRANDES [13] which operates in  $O(|V||E|)$  time and  $O(|V| + |E|)$  space. Edge weights are ignored.

**Communicability betweenness centrality** of vertex  $v$  is computed using the formula

$$C_{CB}(v) = \frac{1}{(n-1)(n-2)} \sum_{s \neq v} \sum_{t \neq s, v} \left( 1 - \frac{(e^{A_v})_{st}}{(e^A)_{st}} \right),$$

where  $A$  is the adjacency matrix of  $G$  and  $A_v$  is the same matrix with the row corresponding to  $v$  filled with zeros [26]. It is always  $C_{CB}(v) \in [0, 1]$  and this value is interpreted as the weighted proportion of walks which pass through  $v$ , but do not start nor end in  $v$ . Matrix exponentials are computed in floating-point arithmetic for efficiency; hence the output is always inexact. Note that  $G$  must be (strongly) connected for  $C_{CB}(v)$  to be defined for all  $v \in V$ . If this condition is not met, `communicability_betweenness_centrality` returns an error.

**Information centrality** of vertex  $v$  is computed using the formula [71]

$$C_I(v) = \frac{|V|}{\sum_{u \in V} (B_{uu} + B_{vv} - 2B_{uv})},$$

where  $B = (L + J)^{-1}$ ,  $L$  is the Laplacian matrix of  $G$  and  $J$  is the  $|V| \times |V|$  matrix in which every entry is 1 [69]. The graph  $G$  must be undirected and connected (the matrix  $B$  does not exist if  $G$  is disconnected). If the optional argument `approx` is given, the result is computed using the floating-point arithmetic, which is faster. Note that information centrality takes edge weights into account. If  $G$  is weighted, then the corresponding weight function must be nonnegative.

**Katz centrality** of vertex  $v$  is computed using the formula

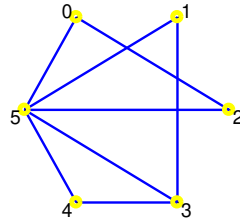
$$C_K(v) = \sum_{w \in V} (I - \alpha A^T)^{-1}_{v,w}$$

where  $A$  is the adjacency matrix of  $G$ ,  $\alpha < \frac{1}{|\lambda|}$  is attenuation (given as the second argument), and  $\lambda$  is eigenvalue of  $A$  with the largest magnitude [48]. Note that if the above condition on  $\alpha$  is not met, the result is meaningless. If  $\alpha$  is a floating-point value, the computation is done using the floating-point arithmetic, otherwise it is exact.

```
> G:=graph(6,%{[0,2],[0,5],[1,3],[1,5],[2,5],[3,4],[3,5],[4,5]})
```

an undirected unweighted graph with 6 vertices and 8 edges

```
> draw_graph(G,circle)
```



```
> degree centrality(G)
```

$$\left[ \frac{2}{5}, \frac{2}{5}, \frac{2}{5}, \frac{3}{5}, \frac{2}{5}, 1 \right]$$

```
> closeness centrality(G)
```

$$\left[ \frac{5}{8}, \frac{5}{8}, \frac{5}{8}, \frac{5}{7}, \frac{5}{8}, 1 \right]$$

```
> harmonic centrality(G)
```

$$\left[ \frac{7}{2}, \frac{7}{2}, \frac{7}{2}, 4, \frac{7}{2}, 5 \right]$$

```
> betweenness centrality(G)
```

$$\left[ 0, 0, 0, \frac{1}{2}, 0, \frac{13}{2} \right]$$

```
> information centrality(G)
```

$$\left[ \frac{72}{61}, \frac{36}{29}, \frac{72}{61}, \frac{72}{49}, \frac{36}{29}, \frac{72}{37} \right]$$

```
> katz centrality(G,0.1)
```

```
[1.29598461169, 1.30920894446, 1.29598461169, 1.42822793941, 1.30920894446, 1.66386150517]
```

```
> communicability_betweenness centrality(G)
```

```
[0.188215207081, 0.199985710756, 0.188215207081, 0.363437500766, 0.199985710756, 0.8472283\
14216]
```

The above results show that, according to each of the implemented centrality measures, the vertex with label 5 is more important than other vertices.

## 4.14 Graph coloring

To color vertices or edges of a graph  $G(V, E)$  means to assign to each vertex  $v \in V$  or edge  $e \in E$  a positive integer. Each integer represents a distinct color. The key property of [graph coloring](#) is that the colors of a pair of adjacent vertices, or incident edges, must be mutually different. Two different colorings of  $G$  may use different number of colors.

value	1	2	3	4	5	6	7
color	red	green	yellow	blue	magenta	cyan	black

Table 4.1. Vertex/edge colors in XCAS.

### 4.14.1 Greedy vertex coloring

`greedy_color(G,⟨p⟩)`

The command `greedy_color` is used for coloring vertices of a graph in a greedy fashion. It takes one mandatory argument, a graph  $G(V, E)$ . Optionally, a permutation  $p$  of order  $|V|$  may be passed as the second argument. Vertices are colored one by one in the order specified by  $p$  (or in the default order if  $p$  is not given) such that each vertex gets the smallest available color. The list of vertex colors is returned in the order of `vertices(G)`.

Generally, different choices of permutation  $p$  produce different colorings. The total number of different colors may not be the same each time. The complexity of the algorithm is  $O(|V| + |E|)$ .

```
> G:=graph("petersen")
```

an undirected unweighted graph with 10 vertices and 15 edges

```
> greedy_color(G)
```

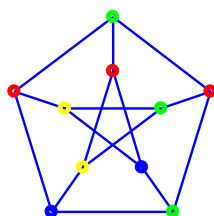
```
[1, 2, 1, 1, 2, 3, 2, 1, 3, 3, 2]
```

```
> L:=greedy_color(G,randperm(10))
```

```
[2, 1, 2, 4, 1, 1, 2, 4, 3, 3]
```

Observe that a different number of colors is obtained by executing the last command line. To display the colored graph, input:

```
> draw_graph(highlight_vertex(G,vertices(G),L),labels=false)
```



The first six positive integers are always mapped to the standard XCAS colors, as indicated in Table 4.1. Note that the color 0 (black) and color 7 (white) are swapped; a vertex with color 0 is white (uncolored) and vertex with color 7 is black. Also note that XCAS maps numbers greater than 7 to colors too, but the number of available colors is limited.

### 4.14.2 Minimal vertex coloring

`minimal_vertex_coloring(G,⟨sto⟩)`

A vertex coloring of  $G$  is **minimal** (or **optimal**) if the total number of used colors is minimal. To obtain such a coloring use the command `minimal_vertex_coloring`. It takes one mandatory argument, an undirected graph  $G(V, E)$  where  $V = \{v_1, v_2, \dots, v_n\}$ . Optionally, the keyword `sto` may be passed as the second argument. The command returns the vertex colors  $c_1, c_2, \dots, c_n$  in order of `vertices(G)` or, if the second argument is given, stores the colors as vertex attributes and returns the modified copy of  $G$ .

The minimal vertex coloring problem (MVCP) is converted to the equivalent integer linear programming problem and solved by using the branch-and-bound method with specific branching and backtracking techniques [20], for which the GLPK library is required. Simplicial vertices are removed prior to the conversion, to be handled afterwards. The lower resp. the upper bound for the number  $n$  of colors is obtained by finding a maximal clique ( $n$  cannot be smaller than its cardinality) resp. by applying the heuristic proposed by BRÉLAZ in [14] (which will use at least  $n$  colors). Note that the algorithm performs some randomization when applying heuristics, hence coloring a graph generally does not take the same amount of computation time in each instance. Since the vertex coloring problem is NP hard, the algorithm may take exponential time on some graphs.

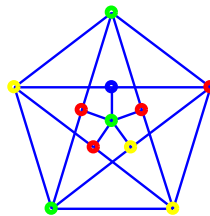
```
> G:=graph("groetzsch")
```

an undirected unweighted graph with 11 vertices and 20 edges

```
> coloring:=minimal_vertex_coloring(G)
```

```
[2, 1, 3, 2, 3, 4, 1, 3, 1, 1, 2]
```

```
> draw_graph(highlight_vertex(G,vertices(G),coloring),labels=false)
```



#### 4.14.3 Chromatic number

```
chromatic_number(G,<c>)
```

```
chromatic_number(G,approx|interval)
```

The command `chromatic_number` is used for exact computation or approximation of the **chromatic number** of a graph. It takes one mandatory argument, an undirected graph  $G(V, E)$ , and optionally a second argument. To obtain only upper and lower bound for the chromatic number (which is much faster than computing exactly) the option `approx` or `interval` should be passed as the second argument. Alternatively, an unassigned identifier `c` is passed as the second argument; in that case the corresponding coloring will be stored to it in form of a list of colors of the individual vertices, ordered as in `vertices(G)`.

The command returns the chromatic number  $\chi_G$  of the graph  $G$  in the case of exact computation. If the option `approx` or `interval` is given, an interval `lb..ub` is returned, where `lb` is the best lower bound and `ub` the best upper bound for  $\chi_G$  found by the algorithm.

The strategy is call `minimal_vertex_coloring` in the case of exact computation. When approximating the chromatic number, the algorithm will establish the lower bound by finding a maximum clique. The timeout for this operation is set to 5 seconds as it can be time consuming. If no maximum clique is not found after that time, the largest clique found is used. Then, an upper bound is established by by using the heuristic proposed by BRÉLAZ in [14]. Obtaining the bounds for  $\chi_G$  is usually very fast; however, their difference grows with  $|V|$ .

```
> chromatic_number(graph("groetzsch"),cols)
```

```
4
```

```
> cols
```

```
[4, 3, 2, 1, 1, 2, 1, 1, 3, 1, 2]
```



```
> G:=random_graph(30,0.75)
```

an undirected unweighted graph with 30 vertices and 325 edges

```
> chromatic_number(G)
```

11

```
> G:=random_graph(300,0.05)
```

an undirected unweighted graph with 300 vertices and 2188 edges

```
> chromatic_number(G,approx)
```

4...7

#### 4.14.4 Mycielski graphs

`mycielski(G)`

The command `mycielski` is used for constructing [Mycielski graphs](#). It takes an undirected graph  $G(V, E)$  as its only argument and returns the corresponding Mycielski graph  $M$  (also called the **Mycielskian** of  $G$ ) with  $2|V| + 1$  vertices and  $3|E| + |V|$  edges. If  $G$  is triangle-free then  $M$  is also triangle-free and  $\chi_M = \chi_G + 1$ .

```
> P:=graph("petersen")
```

an undirected unweighted graph with 10 vertices and 15 edges

```
> M:=mycielski(P)
```

an undirected unweighted graph with 21 vertices and 55 edges

```
> apply(number_of_triangles,[P,M])
```

[0, 0]

```
> chromatic_number(P)
```

3

```
> chromatic_number(M)
```

4

`mycielski` can be applied iteratively, producing arbitrarily large graphs from the most simple ones. For example, Grötzsch graph is obtained as the Mycielskian of a cycle graph on 5 vertices, which is the Mycielskian of a path graph on two vertices.

```
> G1:=path_graph(2)
```

an undirected unweighted graph with 2 vertices and 1 edge

```
> G2:=mycielski(G1)
```

an undirected unweighted graph with 5 vertices and 5 edges

```
> is_isomorphic(G2,cycle_graph(5))
```

true

```
> G3:=mycielski(G2)
```

an undirected unweighted graph with 11 vertices and 20 edges

```
> is_isomorphic(G3,graph("groetzsch"))
```

true

All three graphs are triangle-free. Since it is obviously  $\chi_{G_1} = 2$ , it follows  $\chi_{G_2} = 3$  and  $\chi_{G_3} = 4$ .

```
> apply(chromatic_number,[G1,G2,G3])
```

[2, 3, 4]

#### 4.14.5 $k$ -coloring

`is_vertex_colorable(G,k,<c>)`

The command `is_vertex_colorable` is used for determining whether the vertices of a graph can be colored with at most  $k$  colors. It takes two or three arguments: a graph  $G(V, E)$ , a positive integer  $k$  and optionally an unassigned identifier  $c$ . The command returns **true** if  $G$  can be colored using at most  $k$  colors and **false** otherwise. If the third argument is given, a coloring using at most  $k$  colors is stored to  $c$  as a list of vertex colors, in the order of `vertices(G)`.

The strategy is to first apply a simple greedy coloring procedure which runs in linear time. If the number of required colors is greater than  $k$ , the heuristic proposed by BRÉLAZ in [14] is used, which runs in quadratic time. If the number of required colors is still larger than  $k$ , the algorithm attempts to find the chromatic number  $\chi_G$  using  $k$  as the upper bound in the process.

```
> G:=graph("groetzsch")
```

an undirected unweighted graph with 11 vertices and 20 edges

```
> is_vertex_colorable(G,3)
```

false

```
> is_vertex_colorable(G,4)
```

true

```
> G:=graph("brouwer-haemers")
```

an undirected unweighted graph with 81 vertices and 810 edges

```
> chromatic_number(G,approx)
```

3...8

```
> is_vertex_colorable(G,4)
```

false

#### 4.14.6 Minimal edge coloring

`minimal_edge_coloring(G,<sto>)`

`minimal_edge_coloring(G,sto)`

The command `minimal_edge_coloring` is used for finding a minimal coloring of edges in a graph, satisfying the following two conditions: any two mutually incident edges are colored differently and the total number  $n$  of colors is minimal. The theorem of VIZING [21, p. 103] implies that every simple undirected graph falls into one of two categories: 1 if  $n = \Delta$  or 2 if  $n = \Delta + 1$ , where  $\Delta$  is the maximum degree of the graph.

`minimal_edge_coloring` takes one or two arguments, a graph  $G(V, E)$  and optionally the keyword `sto`. If the latter is given, a minimal coloring is stored to the input graph (each edge  $e \in E$  gets a color  $c_e$  stored as an attribute) and a modified copy of  $G$  is returned. Otherwise, the command returns a sequence of two objects: integer 1 or 2, indicating the category, and the list of edge colors  $c_{e_1}, c_{e_2}, \dots, c_{e_m}$  according the order of edges  $e_1, e_2, \dots, e_m \in E$  as returned by `edges`.

The strategy is to find a minimal vertex coloring of the line graph of  $G$  by using the algorithm described in Section 4.14.2.

```
> G:=graph("petersen")
```

an undirected unweighted graph with 10 vertices and 15 edges

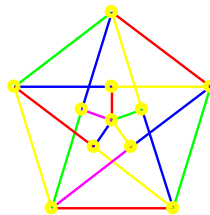
```
> minimal_edge_coloring(G)
```

```
2, [1, 2, 3, 3, 2, 1, 4, 3, 2, 1, 1, 4, 1, 3, 2]
```

```
> H:=minimal_edge_coloring(graph("groetzsch"),sto)
```

an undirected unweighted graph with 11 vertices and 20 edges

```
> draw_graph(H,labels=false)
```



```
> G:=random_graph(50,0.15)
```

an undirected unweighted graph with 50 vertices and 157 edges

```
> minimal_edge_coloring(G);;
```

15.504 sec

#### 4.14.7 Chromatic index

```
chromatic_index(G,<c>)
```

The command `chromatic_index` is used for computing the chromatic index of an undirected graph. It takes one or two arguments, an undirected graph  $G(E, V)$  and optionally an unassigned identifier  $c$ . The command returns the minimal number  $\chi'(G)$  of colors needed to color each edge in  $G$  such that two incident edges never share the same color. If the second argument is given, it specifies the destination for storing the coloring in form of a list of colors according to the order of edges in  $E$  as returned by the command `edges`.

The example below demonstrates how to color the edges of a graph with colors obtained by passing unassigned identifier  $c$  to `chromatic_index` as the second argument.

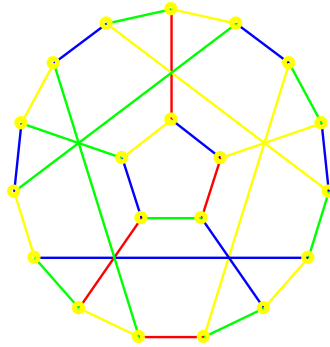
```
> J5:=flower_snark(5)
```

an undirected unweighted graph with 20 vertices and 30 edges

```
> purge(c); chromatic_index(J5,c)
```

“Done”, 4

```
> draw_graph(highlight_edges(J5,edges(J5),c),labels=false)
```



# Chapter 5

## Traversing graphs

### 5.1 Walks and tours

#### 5.1.1 Eulerian graphs

`is_eulerian(G,⟨T⟩)`

The command `is_eulerian` is used for determining whether a graph contains an **Eulerian trail**, i.e. a trail which passes through each of its edges exactly once [34, p. 395]. A graph is **Eulerian** if it has such a trail. An Eulerian trail may be closed, in which case it is an **Eulerian circuit**.

`is_eulerian` takes one or two arguments, a (di)graph  $G(V, E)$  and optionally an unassigned identifier `T`, and returns `true` if  $G$  is Eulerian and `false` otherwise. If the second argument is given and  $G$  is undirected, an Eulerian trail is computed and stored to `T`.

The strategy for finding an Eulerian trail is to apply HIERHOLZER's algorithm [41]. It works by covering one cycle at a time in the input graph. The required time is  $O(|E|)$ .

```
> is_eulerian(complete_graph(4))
```

false

```
> is_eulerian(complete_graph([1,2,3,4,5]),T); T
```

true, [1, 2, 3, 4, 1, 5, 2, 4, 5, 3, 1]

```
> is_eulerian(graph("tetrahedron"))
```

false

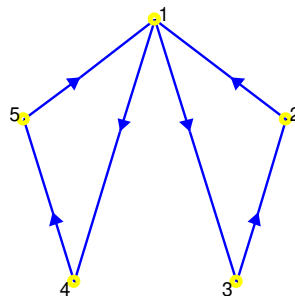
```
> is_eulerian(graph("octahedron"))
```

true

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

a directed unweighted graph with 5 vertices and 6 arcs

```
> draw_graph(G)
```



```
> is_eulerian(G)
```

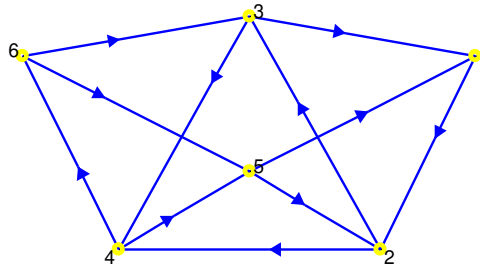
Input digraph has an Eulerian circuit

true

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

a directed unweighted graph with 6 vertices and 11 arcs

```
> draw_graph(H, spring)
```



```
> is_eulerian(H)
```

Input digraph has an Eulerian trail starting at 6 and ending at 1

true

### 5.1.2 Hamiltonian graphs

`is_hamiltonian(G, <hc>)`

The command `is_hamiltonian` is used for determining whether a graph is Hamiltonian. The command can also construct a [Hamiltonian cycle](#) in the input graph if the latter is Hamiltonian. It takes one or two arguments, a (di)graph  $G(V, E)$  and optionally an unassigned identifier `hc`. The command returns `true` if  $G$  is Hamiltonian and `false` otherwise. If the second argument is given, a Hamiltonian cycle is stored to `hc`.

The strategy is to apply a simple backtracking algorithm for finding a Hamiltonian cycle. However, some known characterizations of (non)hamiltonicity are applied first, as follows.

- If  $G$  is directed then the following criteria are applied. If  $G$  is not strongly connected, then it is not Hamiltonian. Otherwise, the criterion of GHOUILA and HOURI [53] is applied: if  $\deg(v) \geq |V|$  for all  $v \in V$ , then  $G$  is Hamiltonian. Otherwise, the criterion of MEYNIEL [53] is applied: if  $\deg(v) + \deg(w) \geq 2|V| - 1$  for any pair of non-adjacent vertices  $v, w \in V$ , then  $G$  is Hamiltonian.

- If  $G$  is undirected then the criteria listed by DELEON [19] are applied, in the following order.

**Connectivity criterion** — If  $G$  is not biconnected, then it is not Hamiltonian.

**DIRAC criterion** — If  $\delta(G) \geq \frac{|V|}{2}$ , where  $\delta(G) = \min \{\deg(v) : v \in V\}$ , then  $G$  is Hamiltonian.

**Bipartite-graph criterion** — If  $G$  is bipartite with vertex partition  $V = V_1 \cup V_2$  and  $|V_1| \neq |V_2|$ , then  $G$  is not Hamiltonian.

**ORE criterion** — If  $\deg(u) + \deg(v) \geq |V|$  holds for every pair  $u, v$  of non-adjacent vertices from  $V$ , then  $G$  is Hamiltonian.

**BONDY–CHVÁTAL theorem** — If the closure  $\text{cl}(G)$  of  $G$  (obtained by finding a pair  $u, v$  of non-adjacent vertices from  $V$  such that  $\deg(u) + \deg(v) \geq |V|$ , adding a new edge  $uv$  to  $E$  and repeating the process until exhaustion) is Hamiltonian, then  $G$  is Hamiltonian. Note that in this case the previously tried criteria are applied to  $\text{cl}(G)$ ; vertex degrees in  $\text{cl}(G)$  are generally higher than those in  $G$  and hence the probability of success is greater.

**NASH–WILLIAMS criterion (for large edge-density)** — If  $\delta(G) \geq \max\left\{\frac{|V|+2}{3}, \beta\right\}$ , where  $\beta$  is the independence number of  $G$ , then  $G$  is Hamiltonian.

The backtracking algorithm is space-efficient but may take a long time on larger graphs.

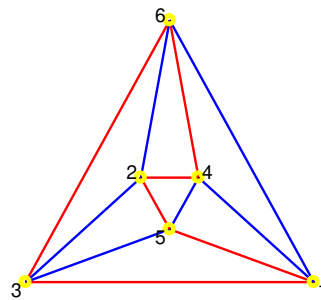
```
> is_hamiltonian(graph("soccerball"))
```

true

```
> is_hamiltonian(graph("octahedron"),hc)
```

true

```
> draw_graph(highlight_trail(graph("octahedron"),hc))
```



```
> is_hamiltonian(graph("herschel"))
```

false

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

false

```
> is_hamiltonian(hypercube_graph(6))
```

true

8.455 sec

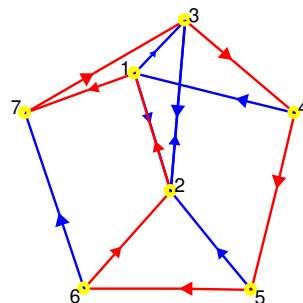
```
> G:=digraph(%{[1,2],[1,3],[1,7],[2,1],[2,3],[3,2],[3,4],[4,1],[4,5],[5,2],[5,6],[6,2],[6,7],[7,3]})
```

a directed unweighted graph with 7 vertices and 14 arcs

```
> purge(hc):: is_hamiltonian(G,hc)
```

“Done”, true

```
> draw_graph(highlight_trail(G,hc),spring)
```



## 5.2 Optimal routing

### 5.2.1 Shortest unweighted paths

```
shortest_path(G,s,t|T)
```

The command `shortest_path` is used for finding shortest paths in unweighted graphs. It takes three arguments: an undirected unweighted 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  $O(|V| + |E|)$ .

```
> G:=graph("dodecahedron")
```

an undirected unweighted graph with 20 vertices and 30 edges

```
> shortest_path(G,1,16)
```

```
[1, 0, 10, 18, 16]
```

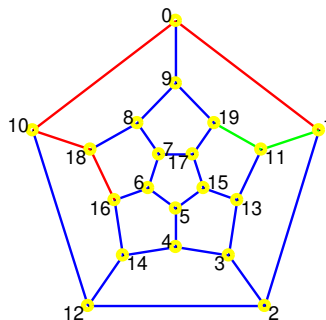
```
> paths:=shortest_path(G,1,[16,19])
```

```
[[1, 0, 10, 18, 16], [1, 11, 19]]
```

```
> H:=highlight_trail(G,paths,[red,green])
```

an undirected unweighted graph with 20 vertices and 30 edges

```
> draw_graph(H)
```



### 5.2.2 Cheapest weighted paths

```
dijkstra(G,s,<t|T>)
```

```
bellman_ford(G,s,<t|T>)
```

The commands `dijkstra` and `bellman_ford` are used for finding cheapest paths in weighted (directed) graphs. Both commands take two or three arguments: a weighted (di)graph  $G(V, E)$ , a vertex  $s \in V$  and optionally a vertex  $t \in V$  or a list  $T$  of vertices in  $V$ . It returns the cheapest path from  $s$  to  $t$  or, if more target vertices are given, the sequence of such paths to each target vertex  $t \in T$ . If no target vertex is specified, all vertices in  $V \setminus \{s\}$  are assumed to be targets. If `dijkstra` is used, the weights of edges in  $E$  must all be nonnegative. `bellman_ford` takes negative weights, but does not work if the input graph contains negative cycles (in which the weights of the corresponding edges sum up to a negative value).



A cheapest path from  $s$  to  $t$  is represented with a list  $[[v_1, v_2, \dots, v_k], c]$  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.

`dijkstra` computes the cheapest path using DIJKSTRA's [algorithm](#) which runs in  $O(|V|^2)$  time [22]. `bellman_ford` applies a similar [algorithm](#) of BELLMAN and FORD (see [9] and [29]), which runs in  $O(|V||E|)$  time but imposes fewer requirements upon its input.

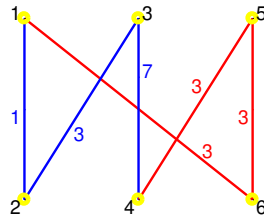
```
> G:=graph(%{[[1,2],1],[[1,6],3],[[2,3],3],[[3,4],7],[[4,5],3],[[5,6],3]})
```

an undirected weighted graph with 6 vertices and 6 edges

```
> res:=dijkstra(G,1,4)
```

```
[[1,6,5,4],9]
```

```
> draw_graph(highlight_trail(G,res[0]))
```



```
> dijkstra(G,1)
```

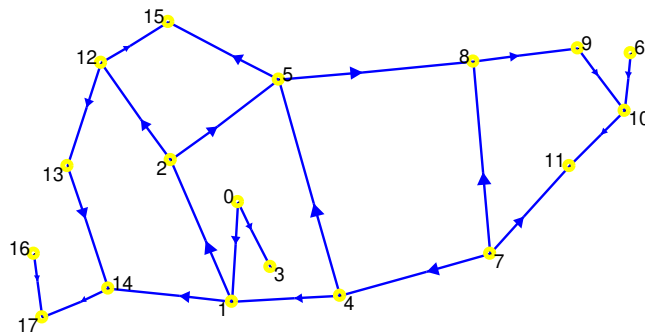
```
[[1],0],[[1,2],1],[[1,6],3],[[1,2,3],4],[[1,6,5,4],9],[[1,6,5],6]
```

In the following example, a longest path in an unweighted acyclic graph is found using Bellman-Ford algorithm and negative unit weights.

```
> G:=random_network(3,2,acyclic=true)
```

a directed unweighted graph with 18 vertices and 22 arcs

```
> draw_graph(G,planar)
```



```
> W:=make_weighted(G,-adjacency_matrix(G))
```

a directed weighted graph with 18 vertices and 22 arcs

```
> L:=[]::; for v in vertices(W) do L.append(bellman_ford(W,v)); od::
```

```
"Done","Done"
```

```
> lp:=[]; for p in L do if length(lp) < length(p[0]) then lp:=p[0]; fi; od;
```

“Done”, “Done”

```
> lp
```

[7, 4, 1, 2, 5, 8, 9, 10, 11]

### 5.2.3 $k$ -shortest paths

The command `kspaths` is used for obtaining  $k$ -shortest paths from the given source to the given destination in a (weighted) graph.

Syntax: `kspaths(G,s,t,k)`

`kspaths` takes four arguments, a (weighted) (di)graph  $G(V, E)$ , a source vertex  $s \in V$ , a sink vertex  $t \in V$  and a positive integer  $k$ . It returns a list containing a largest number not greater than  $k$  of shortest (cheapest) paths from  $s$  to  $t$ , sorted in ascending order with respect to their costs (weights). The cost of a path is equal to the sum of weights of its edges if  $G$  is weighted resp. to the number of edges if  $G$  is unweighted.

The strategy is to apply the algorithm of YEN [86] which uses DIJKSTRA’s algorithm [22] as a subroutine. The algorithm runs in  $O(k|V|^3)$  time.

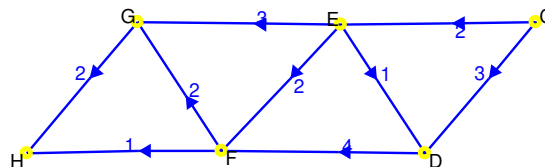
*Example.*

```
> purge(C,D,E,F,G,H);
```

```
> DG:=digraph(%{[[C,D],3],[[C,E],2],[[D,F],4],[[E,D],1],[[E,F],2],[[E,G],3],[[F,G],2],[[F,H],1],[[G,H],2]}%);
```

a directed weighted graph with 6 vertices and 9 arcs

```
> draw_graph(DG,spring)
```



```
> kspaths(DG,C,H,5)
```

[[C, E, F, H], [C, E, G, H], [C, E, D, F, H], [C, E, F, G, H], [C, D, F, H]]

### 5.2.4 Traveling salesman problem

`traveling_salesman(G, <opts>)`

`traveling_salesman(G,M, <opts>)`

The command `traveling_salesman` is used for solving traveling salesman problem (TSP)<sup>5.1</sup>. It takes the following arguments: a (di)graph  $G(V, E)$ , a weight matrix  $M$  (optional) and a sequence of options (optional). The supported options are `approx` and `vertex_distance` for undirected graphs and `is_included=arc|[arcs]` for directed graphs.

If the input graph  $G$  is unweighted and  $M$  is not specified, a Hamiltonian cycle (tour) is returned (the adjacency matrix of  $G$  is used for the edge weights). If  $G$  is weighted, two objects are returned: the optimal value for the traveling salesman problem and a Hamiltonian cycle which achieves the optimal value. If  $M$  is given and  $G$  is unweighted,  $M$  is used as the weight matrix for  $G$ .

<sup>5.1</sup>. For the details on traveling salesman problem and a historical overview see [18].

If the option `vertex_distance` is passed and  $M$  is not specified, then for each edge  $e \in E$  the Euclidean distance between its endpoints is used as the weight of  $e$ . Therefore it is required for each vertex in  $G$  to have a predefined position.

If the option `approx` is passed, a near-optimal tour is returned. In this case it is required that  $G$  is a complete undirected weighted graph. For larger graphs, this is significantly faster than finding optimal tour. Results thus obtained are usually only a few percent larger than the corresponding optimal values, despite the fact that the reported guarantee is generally much weaker (around 30%).

If the option `is_included=arc|[arcs]` is passed, then the algorithm finds a shortest Hamiltonian cycle in  $G$  which contains the specified arc(s).

When  $G$  is a digraph, an optional argument  $k$  may be passed, which must be a positive integer. If  $k > 1$  then the first  $k$  shortest Hamiltonian cycles are returned (the return value is a sequence containing the list of tour costs and the list of the corresponding Hamiltonian cycles).

The strategy for undirected graphs is to formulate TSP as an integer linear programming problem and to solve it by branch-and-cut method, using the GLPK library along with the routine written by its author ANDREW MAKHORIN (see the example program TSPSOL which is a part of GLPK) for generating subtour elimination constraints on the fly. The branching rule is implemented according to PADBERG and RINALDI [62]. In addition, the algorithm combines the method of CHRISTOFIDES [16], the method of farthest insertion and a variant of the powerful tour improvement heuristic developed by LIN and KERNIGHAN [40] to generate near-optimal feasible solutions during the branch-and-cut process.

For Euclidean TSP instances, i.e. in cases when  $G$  is a complete undirected graph with vertex distances as edge weights, the algorithm usually finishes in a few seconds for TSP with up to, say, 42 cities. For problems with 100 or more cities, the option `approx` is recommended since finding the optimal value takes a long time. Note that TSP is NP-hard, meaning that no polynomial time algorithm is known. Hence the algorithm may take exponential time to find the optimum in some instances.

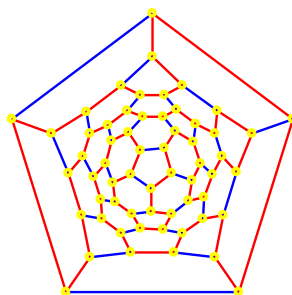
For directed graphs, an integer linear programming formulation of the problem, using enhanced subtour elimination constraints of MILLER, TUCKER and ZEMLIN [66], is solved by branch-and-cut method.

The following example demonstrates finding a Hamiltonian cycle in the truncated icosahedral (“soccer ball”) graph. The result is visualized by using `highlight_trail`.

```
> G:=graph("soccerball")
```

an undirected unweighted graph with 60 vertices and 90 edges

```
> draw_graph(highlight_trail(G,traveling_salesman(G)),labels=false)
```



A matrix may be passed alongside an undirected graph to specify the edge weights. The alternative is to pass a weighted graph as the single argument.

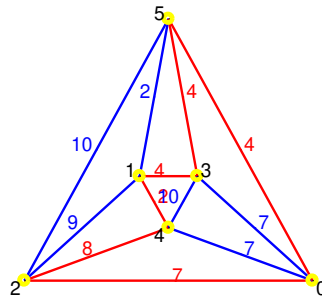
```
> G:=assign_edge_weights(graph("octahedron"),1,10)
```

an undirected weighted graph with 6 vertices and 12 edges

```
> c,t:=traveling_salesman(G)
```

29.0, [4, 1, 3, 5, 0, 2, 4]

```
> draw_graph(highlight_trail(G,t))
```

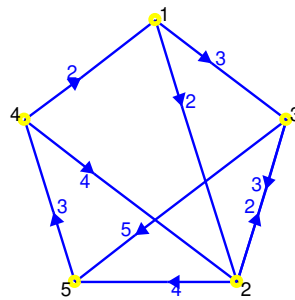


The following examples demonstrate finding shortest Hamiltonian cycle(s) in a weighted directed graph.

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

a directed weighted graph with 5 vertices and 9 arcs

```
> draw_graph(D,circle=[1,3,2,5,4])
```



```
> traveling_salesman(D)
```

14.0, [1, 2, 3, 5, 4, 1]

```
> traveling_salesman(D,is_included=[2,5])
```

15.0, [1, 3, 2, 5, 4, 1]

```
> traveling_salesman(D,2)
```

$[14.0, 15.0], \begin{pmatrix} 1 & 2 & 3 & 5 & 4 & 1 \\ 1 & 3 & 2 & 5 & 4 & 1 \end{pmatrix}$

In the next example, an instance of Euclidean TSP with 42 cities is solved to optimality. The vertex positions are pairs of integers randomly chosen on the grid  $[0, 1000] \times [0, 1000] \in \mathbb{Z}^2$ .

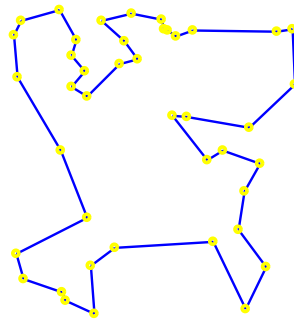
```
> G:=set_vertex_positions(complete_graph(42),[randvector(2,1000)$(k=1..42)])
```

an undirected unweighted graph with 42 vertices and 861 edges

```
> c,t:=traveling_salesman(G,vertex_distance):;
```

10.74 sec

```
> draw_graph(subgraph(G, trail2edges(t)), labels=false)
```



For large instances of Euclidean TSP the `approx` option may be used, as in the following example with 555 cities.

```
> H:=set_vertex_positions(complete_graph(555),[randvector(2,10000)$(k=1..555)])
```

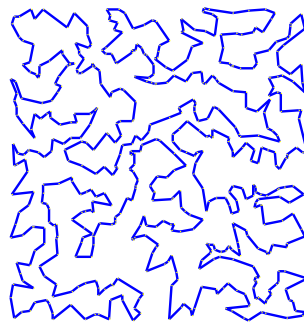
an undirected unweighted graph with 555 vertices and 153735 edges

```
> ac,t:=traveling_salesman(H,vertex_distance,approx):;
```

The tour cost is within 32% of the optimal value

33.36 sec

```
> draw_graph(subgraph(H, trail2edges(t)))
```



Near-optimal tours produced by the `approx` option are usually only slightly more expensive than the optimal ones. For example, a sub-optimal tour for the previous instance  $G$  with 42 cities is obtained by the following command.

```
> ac,st:=traveling_salesman(G,vertex_distance,approx):;
```

The tour cost is within 39% of the optimal value

Although it is guaranteed that the near-optimal cost `ac` is for at most 28% larger than `c` (the optimum), the actual relative difference is smaller than 3%, as computed below.

```
> 100*(ac-c)/c
```

2.7119936606

## 5.3 Spanning trees

### 5.3.1 Construction of spanning trees

```
spanning_tree(G)
spanning_tree(G,r)
```

The command `spanning_tree` is used for construction of [spanning trees](#) in graphs. It takes one or two arguments, an undirected graph  $G(V, E)$  and optionally a vertex  $r \in V$ . It returns the spanning tree  $T$  (rooted in  $r$ ) of  $G$ , obtained by depth-first traversal in  $O(|V| + |E|)$  time.

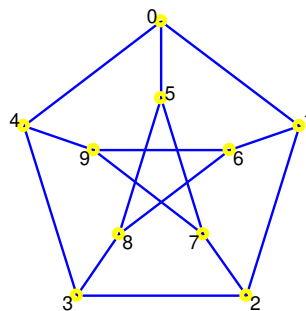
```
> P:=graph("petersen")
```

an undirected unweighted graph with 10 vertices and 15 edges

```
> T1:=spanning_tree(P)
```

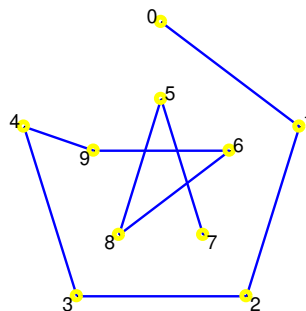
an undirected unweighted graph with 10 vertices and 9 edges

```
> draw_graph(P)
```



By extracting  $T_1$  from  $P$  as a subgraph, it inherits vertex positions from  $P$ .

```
> draw_graph(subgraph(P, edges(T1)))
```



```
> T2:=spanning_tree(P,4)
```

an undirected unweighted graph with 10 vertices and 9 edges

```
> edges(T1)
```

```
[[0, 1], [1, 2], [2, 3], [3, 4], [4, 9], [5, 7], [5, 8], [6, 8], [6, 9]]
```

```
> edges(T2)
```

```
[[0, 1], [0, 4], [1, 2], [2, 3], [3, 8], [5, 7], [5, 8], [6, 9], [7, 9]]
```

### 5.3.2 Minimal spanning tree

`minimal_spanning_tree(G)`

The command `minimal_spanning_tree` is used for obtaining [minimal spanning trees](#) in undirected graphs. It takes an undirected graph  $G(V, E)$  as its only argument and returns its minimal spanning tree as a graph. If  $G$  is not weighted, then unity weights are assumed for all edges.

The strategy is to apply KRUSKAL's algorithm which runs in  $O(|E|\log|V|)$  time.

```
> A:=[[0,1,0,4,0,0],[1,0,1,0,4,0],[0,1,0,3,0,1],[4,0,3,0,1,0],[0,4,0,1,0,4],[0,0,1,0,4,0]];
```

```
> G:=graph(A)
```

an undirected weighted graph with 6 vertices and 8 edges

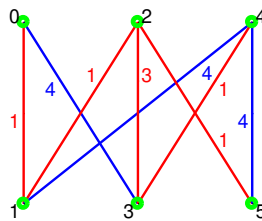
```
> T:=minimal_spanning_tree(G)
```

an undirected weighted graph with 6 vertices and 5 edges

```
> edges(T,weights)
```

```
[[[0, 1], 1], [[1, 2], 1], [[2, 3], 3], [[2, 5], 1], [[3, 4], 1]]
```

```
> draw_graph(highlight_subgraph(G,T))
```



### 5.3.3 Counting the spanning trees in a graph

`number_of_spanning_trees(G)`

The command `number_of_spanning_trees` is used for [counting spanning trees](#) in a graph. It takes an undirected graph  $G(V, E)$  as its only argument and returns the total number  $n$  of (labeled) spanning trees in  $G$ .

The strategy is to use [KIRCHHOFF's Theorem](#) [84, Theorem 2.2.12, p. 86]. The number of spanning trees is equal to the first principal minor of the [Laplacian matrix](#) of  $G$ .

```
> number_of_spanning_trees(graph("octahedron"))
```

384

```
> number_of_spanning_trees(graph("dodecahedron"))
```

5184000

```
> number_of_spanning_trees(hypercube_graph(4))
```

42467328

```
> number_of_spanning_trees(graph("soccerball"))
```

375291866372898816000

### 5.3.4 Vertex reachability

`is_reachable(G,u,v)`

`reachable(G,u)`

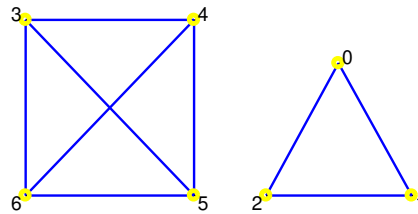
The commands `is_reachable` and `reachable` are used for obtaining information about reachability of vertices in a graph from the given vertex. Both commands takes a (di)graph  $G(V, E)$  as their first argument and a vertex  $u \in V$ . `is_reachable` additionally takes a vertex  $v \in V$  as its third argument and returns `true` if there is a path from  $u$  to  $v$  in  $G$ , else returns `false`. `reachable` returns the list of vertices in  $V$  which are reachable from  $u$  (including  $u$  itself).

The strategy is to perform breadth-first search from  $u$ . Hence both algorithms run in at most  $O(|V| + |E|)$  time.

```
> C34:=graph_complement(complete_graph(3,4))
```

an undirected unweighted graph with 7 vertices and 9 edges

```
> draw_graph(C34)
```



```
> is_reachable(C34,3,5); is_reachable(C34,3,2)
```

true, false

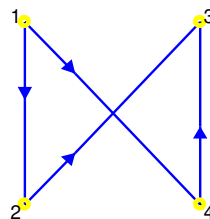
```
> reachable(C34,3)
```

[4, 5, 6, 3]

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

a directed unweighted graph with 4 vertices and 4 arcs

```
> draw_graph(G)
```



```
> is_reachable(G,1,3); is_reachable(G,2,4)
```

true, false

```
> reachable(G,1), reachable(G,2), reachable(G,3), reachable(G,4)
```

[2, 4, 3], [3], [], [3]



# Chapter 6

## Visualizing graphs

### 6.1 Drawing graphs

#### 6.1.1 Overview

`draw_graph(G, <opts>)`

The `draw_graph` command is used for visualizing graphs. It takes 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 optional argument is one of the following.

- `labels=true|false` — controls the visibility of vertex labels and edge weights (by default `true`, i.e. the labels and weights are displayed)
- `spring` — applies the multilevel force-directed algorithm
- `tree<=r|[r1,r2,...]>` — draws the tree or forest graph  $G$ , optionally specifying the root node for each tree (by default the first node is used)
- `bipartite` — draws the bipartite graph  $G$ , separating vertex partitions from one another
- `circle<=L>` or `convexhull<=L>` — draws the graph  $G$  by spreading the *hull vertices* from list  $L \subset V$  (assuming  $L = V$  by default) across the unit circle and putting all other vertices in origin and applying a force-directed vertex placement algorithm to generate the layout while keeping the hull vertices fixed
- `planar` or `plane` — draws the planar graph  $G$  using a force-directed algorithm
- `plot3d` — draws the graph  $G$  as if the `spring` option was enabled, but with vertex positions in 3D instead of 2D
- `[x,y,<z>]` — sets the anchor point of the layout, which corresponds to the bottom-left corner in 2D drawings
- `size=[width,height,<depth>]` — sets the size of the layout's bounding box
- `scale=<real>` — sets the scaling factor of the layout
- `title=<string>` — prints the title above the drawing (left-aligned)
- an unassigned identifier — sets the destination for storing the list of vertex positions (in order as returned by `vertices`)

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.

If no style option is specified, the algorithm first checks whether  $G$  is a tree or a bipartite graph, in which cases it is drawn accordingly. Otherwise, the graph is drawn as if the option `circle` was specified.

Tree, circle and bipartite drawings are obtained in linear time, while force-directed algorithms require  $O(|V|^2)$  time.

### 6.1.2 Spring method

When the option `spring` is specified, the input graph is drawn using the force-directed algorithm described in [45]. The idea, originally due to FRUCHTERMAN and REINGOLD [31], is to simulate physical forces in a spring-electrical model where the vertices and edges represent equally charged particles and springs connecting them, respectively.

In a spring-electrical model, each vertex is being repulsed by every other vertex with a force inversely proportional to the distance between them. At the same time, it is attracted to each of its neighbors with a force proportional to the square of the distance. Assuming that  $x_v$  is the vector representing the position of the vertex  $v \in V$ , the total force  $F_v$  applied to  $v$  is equal to

$$F_v = \sum_{w \in V \setminus \{v\}} -\frac{CK^2}{\|x_v - x_w\|^2} (x_v - x_w) + \sum_{w \in N(v)} \frac{\|x_v - x_w\|}{K} (x_v - x_w),$$

where  $N(v)$  is the set of neighbors of  $v$  and  $C, K$  are certain positive real constants (actually,  $K$  may be any positive number, it affects only the scaling of the entire layout). Applying the forces iteratively and updating vertex positions in each iteration (starting from a random layout) leads the system to the state of minimal energy. By applying a certain “cooling” scheme to the model which cuts down the force magnitude in each iteration, the layout “freezes” after a number of iterations large enough to achieve the minimal energy state.

The force-directed method is computationally expensive and for larger graphs the pleasing layout cannot be obtained most of the time since the algorithm, starting with a random initial layout, gets easily “stuck” in a local energy minimum. To avoid this, a multilevel scheme is applied. The input graph is iteratively coarsened, either by removing the vertices from a maximal independent vertex set or by contracting the edges of a maximal matching in each iteration. Each coarsening level is processed by the force-directed algorithm, starting from the deepest (coarsest) one and “lifting” the obtained layout to the first upper level, using it as the initial layout for that level. The lifting done using a prolongation matrix technique described in [46]. To support drawing large graphs (with, say, 1000 vertices or more), the matrices used in the lifting process are stored in sparse form. The multilevel scheme also speeds up the layout process significantly.

If the structure of the input graph is symmetric, a layout obtained by using a force-directed method typically reveals these symmetries, which is a unique property among graph drawing algorithms. To make the symmetries more prominent, the layout is rotated such that the axis, with respect to which the layout exhibits the largest *symmetry score*, becomes vertical. Because symmetry detection is computationally quite expensive (up to  $O(|V|^7)$  when using the symmetry measure of PURCHASE [83], for example), the algorithm accounts only the convex hull and the barycenter of the layout, which may not always be enough to produce the optimal result. Nevertheless, this approach is fast and works (most of the time) for highly symmetrical graphs.

For example, the following command lines produce a drawing of the tensor product of two graphs using the force-directed algorithm.

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

an undirected unweighted graph with 5 vertices and 5 edges

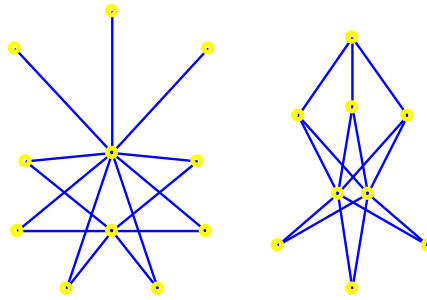
```
> G2:=star_graph(3)
```

an undirected unweighted graph with 4 vertices and 3 edges

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

an undirected unweighted graph with 20 vertices and 30 edges

```
> draw_graph(G,spring,labels=false)
```

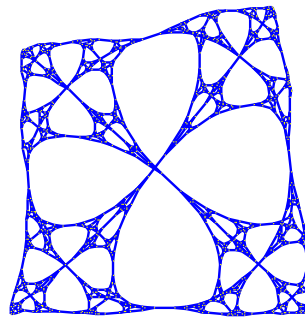


The following example demonstrates drawing a much larger graph.

```
> S:=sierpinski_graph(5,4)
```

an undirected unweighted graph with 1024 vertices and 2046 edges

```
> draw_graph(S, spring)
```

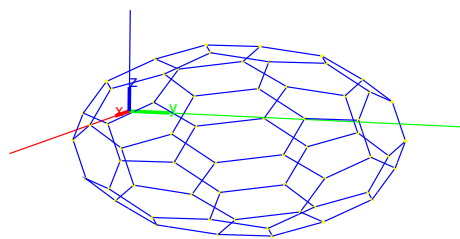


8.568 sec

Note that vertex labels are automatically suppressed because of the large number of vertices.

The spring method is also used for creating 3D graph layouts, which are obtained by passing the option `plot3d` to the `draw_graph` command.

```
> draw_graph(graph("soccerball"), plot3d, labels=false)
```



click k: kill 3d view

```
> G1:=graph("icosahedron"); G2:=graph("dodecahedron");
```

“Done”, “Done”

```
> G1:=highlight_edges(G1, edges(G1), red)
```

an undirected unweighted graph with 12 vertices and 30 edges

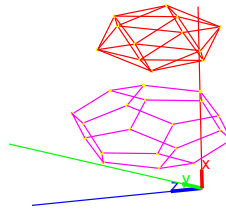
```
> G2:=highlight_edges(G2, edges(G2), magenta)
```

an undirected unweighted graph with 20 vertices and 30 edges

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

an undirected unweighted graph with 32 vertices and 60 edges

```
> draw_graph(G,plot3d,labels=false)
```



click k: kill 3d view

### 6.1.3 Drawing trees

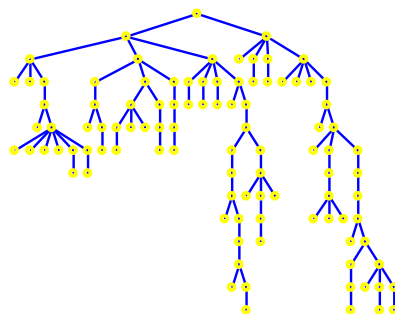
When the `tree[=r]` option is specified and the input graph  $G$  is a tree (and  $r \in V$ ), it is drawn using a fast but simple node positioning algorithm inspired by the algorithm of WALKER [81], using the vertex  $r$  as the root node. If  $r$  is not specified, the first node which admits the minimum height of the tree is used instead.

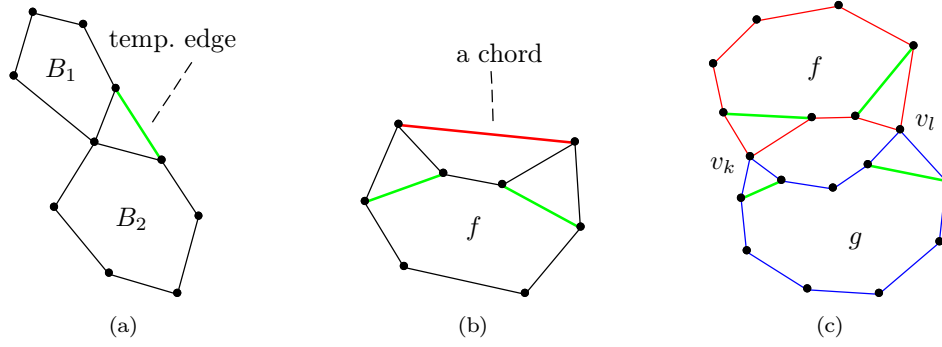
When drawing a rooted tree, one usually requires the following aesthetic properties [15].

- A1.** The layout displays the hierarchical structure of the tree, i.e. the  $y$ -coordinate of a node is given by its level.
- A2.** The edges do not cross each other.
- A3.** The drawing of a sub-tree does not depend on its position in the tree, i.e. isomorphic sub-trees are drawn identically up to translation.
- A4.** The order of the children of a node is displayed in the drawing.
- A5.** The algorithm works symmetrically, i.e. the drawing of the reflection of a tree is the reflected drawing of the original tree.

The algorithm implemented in GIAC generally satisfies all the above properties except **A3**. Instead, it tries to spread the inner sub-trees evenly across the available horizontal space. It works by organizing the structure of the input tree into levels by using depth-first search and laying out each level subsequently, starting from the deepest one and climbing up to the root node. In the end, another depth-first traversal is made, shifting the sub-trees horizontally to avoid intersections between their edges. The algorithm runs in  $O(|V|)$  time and uses the minimum of horizontal space to draw the tree with respect to the specified root node  $r$ .

```
> draw_graph(random_tree(100))
```





**Fig. 6.1.** (a) Joining blocks by adding a temporary edge, (b) A chorded face  $f$ , (c) Faces  $f$  and  $g$  having two vertices but no edges in common.

#### 6.1.4 Drawing planar graphs

The algorithm for drawing planar graphs implemented in GIAC applies augmentation techniques to extend the input graph  $G$  to a graph  $G'$ , which is homeomorphic to a triconnected graph, by adding temporary edges. The augmented graph  $G'$  is drawn using TUTTE's barycentric method (see [79] and [34, p. 293]) which puts each vertex in the barycenter of its neighbors. It is guaranteed that a (non-strict) convex drawing will be produced, without edge crossings. Finally, the duplicate of the outer face and temporary edges inserted during the augmentation stage are removed from layout.

TUTTE's algorithm requires that vertices of the outer face are initially placed on the boundary of a convex polygon. In order to produce a more flexible layout, the present algorithm duplicates the outer face such that the subgraph induced by the vertices on both the outer face and its duplicate is a prism graph. The duplicates of the outer-face vertices form a fixed regular polygon, allowing the original beneath it to take a more natural shape, and are deleted once the layout is frozen.

The augmentation process consists of two stages. The first stage consists of decomposing  $G$  into biconnected components (blocks) by using depth-first search [33, p. 25] and decomposing each block into faces by using DEMOUCRON's algorithm (see [33, p. 88] and [57]). Embeddings obtained for each blocks are then combined by adding one temporary edge for each articulation point, joining the two corresponding blocks. Figure 6.1a shows the outer faces of two blocks  $B_1$  and  $B_2$ , connected by an articulation point (cut vertex). The temporary edge (shown in green) is added to join  $B_1$  and  $B_2$  into a single block. After "folding up" the tree of blocks, the algorithm picks the largest face in the resulting bi

connected graph to be the outer face of the planar embedding.

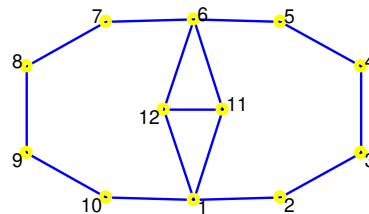
The second stage of the augmentation process consists of recursively decomposing each non-convex inner face into several convex polygons by adding temporary edges. An inner face  $f = (v_1, \dots, v_n)$  is non-convex if there exist  $k$  and  $l$  such that  $1 \leq k < l - 1 < n$  and either  $v_k v_l \in E$ , in which case the edge  $v_k v_l$  is a *chord* (see Figure 6.1b for an example) or there exists a face  $g = (w_1, w_2, \dots, v_k, \dots, v_l, \dots, w_{m-1}, w_m)$  such that the vertices  $v_{k+1}, \dots, v_{l-1}$  are not contained in  $g$  (see Figure 6.1c for an example). In Figure 6.1, temporary edges added by the algorithm are drawn in green.

This method of drawing planar graphs operates in  $O(|V|^2)$  time, which makes it usable for graphs with up to several thousands vertices. A drawback of this method is that it sometimes creates clusters of vertices which are very close to each other, resulting in a very high ratio of the area of the largest inner face to the area of the smallest inner face (not considering the outer, infinite-area face). In order to cope with this issue, `draw_graph` redraws the layout several times (unless the graph is triconnected), each time randomizing the graph augmentation, in order to minimize the above ratio. The number of redraws scales with  $\frac{1}{|V|}$ , hence `draw_graph` does not hang on large graphs. For  $|V| < 500$ , at least two redraws are performed. Of course, one can always call `draw_graph` repeatedly in attempt to obtain a better result. This strategy usually works well for biconnected graphs; however, non-biconnected, sparse graphs are often drawn poorly. In such cases consider using the `spring` option.

```
> G:=graph(trail(1,2,3,4,5,6,7,8,9,10,1),trail(11,12,6,11,1,12))
```

an undirected unweighted graph with 12 vertices and 15 edges

```
> draw_graph(G,planar)
```



Note that the inner diamond-like shape in the above drawing would end up flattened—making the two triangular faces invisible—if the input graph was not augmented; since the vertices with labels 11 and 12 are “attracted” to each other (namely, the two large faces are “inflating” themselves to become convex), they would end up in the same position.

In the second example the input graph is connected but not biconnected (it has two articulation points). It is obtained by removing a vertex from the Sierpiński triangle graph  $ST_3^3$ . Note that the syntax mode is set to XCAS in this example, so the first vertex label is zero.

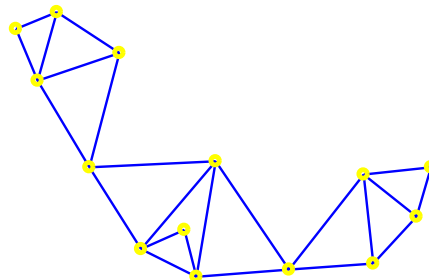
```
> G:=sierpinski_graph(3,3,triangle)
```

an undirected unweighted graph with 15 vertices and 27 edges

```
> G:=delete_vertex(G,3)
```

an undirected unweighted graph with 14 vertices and 23 edges

```
> draw_graph(G,planar,labels=false)
```



### 6.1.5 Circular graph drawings

The drawing method selected by specifying the option `circle=L` or `convexhull=L` when calling `draw_graph` on a triconnected graph  $G(V, E)$ , where  $L \subset V$  is a set of vertices in  $G$ , uses the following strategy. First, positions of the vertices from  $L$  are fixed so that they form a regular polygon on the unit circle. Other vertices, i.e. all vertices from  $V \setminus L$ , are placed in origin. Then an iterative force-directed algorithm [65], similar to TUTTE’s barycentric method, is applied to obtain the final layout.

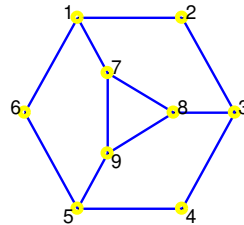
This approach gives best results for symmetrical graphs such as generalized Petersen graphs. In addition, if the input graph is planar and triconnected and the outer hull represents a face in a planar embedding, then the drawing will contain no edge crossings. Some very short edges may, however, end up crossing each other since the number of force-update iterations is limited.

The following example is entered in `xcas` mode, where the vertices are numbered starting from 0.

```
> G:=graph([1,2,3,4,5,6,7,8,9],%{[1,2],[1,6],[1,7],[2,3],[3,4],[3,8],[4,5],[5,6],[5,9],[7,8],[7,9],[8,9]%})
```

an undirected unweighted graph with 9 vertices and 12 edges

```
> draw_graph(G,circle=[1,2,3,4,5,6])
```



To draw a planar triconnected graph, one should pass one of its faces as the outer hull. In the following example we draw a circular planar layout of the Frucht graph.

```
> G:=graph("frucht")
```

an undirected unweighted graph with 12 vertices and 18 edges

Get the list of faces:

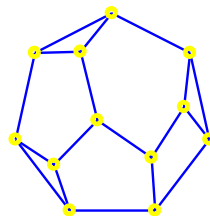
```
> purge(F); is_planar(G,F)
```

"Done", true

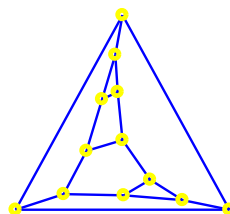
```
> apply(length,F)
```

[7, 4, 3, 5, 3, 5, 3, 6]

```
> draw_graph(G,circle=F[0],labels=false)
```



```
> draw_graph(G,circle=F[6],labels=false)
```



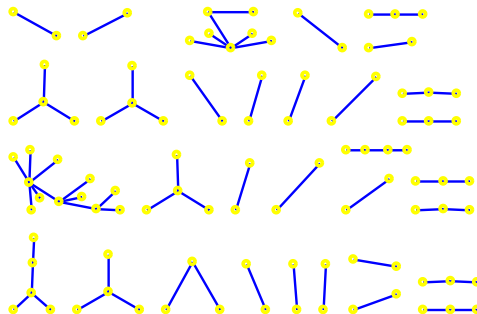
### 6.1.6 Drawing disconnected graphs

When the input graph has two or more connected components, each component is drawn separately and the drawings are subsequently arranged such that the bounding box of the whole drawing has the smallest perimeter under condition that as little space as possible is wasted inside the box.

```
> G:=random_planar_graph(100,0.9,0)
```

an undirected unweighted graph with 100 vertices and 68 edges

```
> draw_graph(G,planar)
```



### 6.1.7 Setting layout position, size, and title

Graph drawings may be moved around, scaled, and resized using optional arguments. This is useful for combining several drawings in one figure or adding graph drawings to larger graphical scenes. Individual drawings may also be given a title. Note that the graph attribute `name`, when one is provided, is used as the title in case the latter is not set.

Below we draw the first two discovered snarks in one figure.

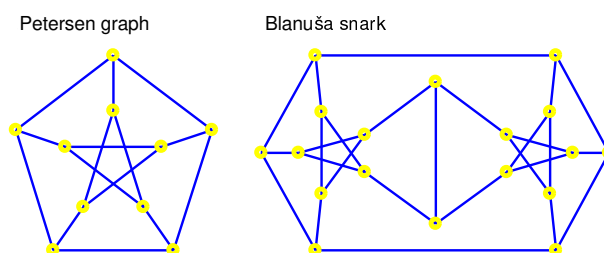
```
> P:=graph("petersen")
```

an undirected unweighted graph with 10 vertices and 15 edges

```
> B:=graph("blanusa")
```

an undirected unweighted graph with 18 vertices and 27 edges

```
> draw_graph(P,[0,0],size=[0,1],title="Petersen graph",labels=false);  
> draw_graph(B,[1.32,0],size=[0,1],title="Blanuša snark",labels=false)
```



If graph has a name, it is printed automatically. To override this behavior, one should set the `title` option to "" (empty string) in such cases.

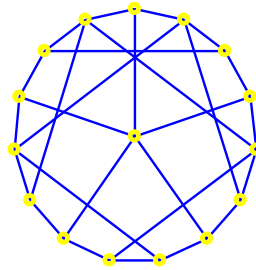
```
> S:=set_graph_attribute(graph("sousselier"),"name"="Sousselier graph")
```

Sousselier graph: an undirected unweighted graph with 16 vertices and 27 edges

```
> draw_graph(S,labels=false)
```



Sousselier graph



## 6.2 Vertex positions

### 6.2.1 Setting vertex positions

`set_vertex_positions(G,L)`

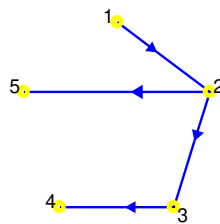
The command `set_vertex_positions` is used for assigning custom coordinates to vertices of a graph to be used when drawing the graph. It takes two arguments, a graph  $G(V, E)$  and the list  $L$  of positions to be assigned to vertices in order of `vertices(G)`. The positions may be complex numbers, lists of coordinates or points (geometrical objects created with the command `point`). `set_vertex_positions` returns the copy  $G'$  of  $G$  with the given layout stored in it.

Any subsequent call to `draw_graph` with  $G'$  as an argument and without specifying the drawing style will result in displaying vertices at the stored coordinates. However, if a drawing style is specified, the stored layout is ignored (although it remains stored in  $G'$ ).

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

a directed unweighted graph with 5 vertices and 4 arcs

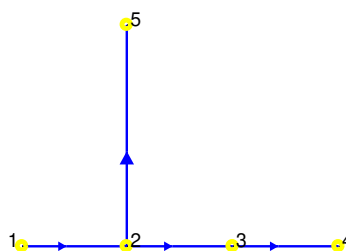
```
> draw_graph(G,circle)
```



```
> H:=set_vertex_positions(G,[[0,0],[0.5,0],[1.0,0],[1.5,0],[0.5,1]])
```

a directed unweighted graph with 5 vertices and 4 arcs

```
> draw_graph(H)
```



### 6.2.2 Generating vertex positions

Vertex positions can be generated for a particular graph  $G$  by using the `draw_graph` command with the additional argument  $P$  which should be an unassigned identifier. After the layout is obtained, it will be stored to  $P$  as a list of positions (complex numbers for 2D drawings or points for 3D drawings) for each vertex in order of `vertices(G)`.

This feature combines well with the `set_vertex_positions` command, as when one obtains the desired drawing of the graph  $G$  by calling `draw_graph`, the layout coordinates can be easily stored to the graph for future reference. In particular, each subsequent call of `draw_graph` with  $G$  as an argument will display the stored layout. The example below illustrates this property by setting a custom layout to the octahedral graph.

```
> G:=graph("octahedron")
```

an undirected unweighted graph with 6 vertices and 12 edges

```
> purge(P):: draw_graph(G,P,spring)::
```

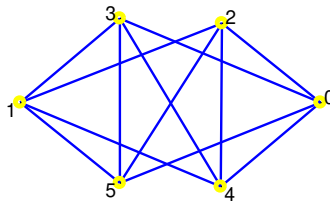
“Done”, “Done”

Now  $P$  contains vertex coordinates, which can be permanently stored to  $G$ :

```
> G:=set_vertex_positions(G,P)
```

an undirected unweighted graph with 6 vertices and 12 edges

```
> draw_graph(G)
```



It should be noted that, after a particular layout is fixed, it stays valid when some edges or vertices are removed or when an edge is contracted. The stored layout becomes invalid only if a new vertex is added to the graph (unless its position is specified by `set_vertex_attribute` upon the creation) or if the `position` attribute of an existing vertex is discarded.

### 6.2.3 Custom layout example: spectral graph drawing

In this section it is demonstrated how `set_vertex_positions` can be used to obtain spectral drawings of graphs.

Let  $G(V, E)$  be an undirected, connected graph with  $|V| = m$ . Furthermore, let  $\rho: V \rightarrow \mathbb{R}^n$  be a **graph drawing** of  $G$  in  $\mathbb{R}^n$ . The **matrix of a graph drawing**  $\rho$  is a  $m \times n$  matrix  $R$  whose  $i$ -th row corresponds to the row vector  $\rho(v_i)$  containing coordinates of the point representing  $v_i$  in  $\mathbb{R}^n$ . Typically, it is desired that  $n$  is (much) smaller than  $m$ . The drawing is **balanced** if sum of entries in each column of  $R$  equals to 1.

The **energy** of a drawing  $R$  is given by

$$\varepsilon(R) = \sum_{v_i v_j \in E} w_{ij} \|\rho(v_i) - \rho(v_j)\|^2,$$

where  $w_{ij}$  is the weight of  $v_i v_j$ . (If  $G$  is unweighted, then  $w_{ij} = 1$  for all  $1 \leq i, j \leq m$ .) A drawing is considered to be “good” if it minimizes the energy function  $\varepsilon$  under certain constraints which prevent vertices from occupying the same position. The function  $\varepsilon$  can be expressed in terms of the (non-normalized) Laplacian matrix  $L$ :

$$\varepsilon(R) = \text{tr}(R^T L R).$$

In order to avoid trivial minimum-energy layouts, it is reasonable to assume that the columns of  $R$  are pairwise orthogonal and that they have unit length. Therefore,

$$R^T R = I,$$

where  $I$  is identity matrix. A drawing which satisfies the above condition is called **orthogonal drawing**.

The following theorem provides a way to find minimum graph drawings under this condition. Note that, since  $G$  is undirected and connected, its Laplacian matrix has exactly one zero eigenvalue and  $m - 1$  strictly positive—but not necessarily distinct—eigenvalues (see Section 4.2.2). We assume that  $n < m$ . For details on spectral graph drawing, see [51].

**Theorem 6.1.** *Let the eigenvalues of  $L$  be  $0 = \lambda_1 < \lambda_2 \leq \lambda_3 \leq \dots \leq \lambda_m$ . Then the minimal energy of any balanced orthogonal drawing of  $G$  in  $\mathbb{R}^n$  is equal to  $\lambda_2 + \lambda_3 + \dots + \lambda_{n+1}$ . The  $m \times n$  matrix  $R$  whose columns are unit eigenvectors  $u_2, \dots, u_{n+1}$  associated with  $\lambda_2, \dots, \lambda_{n+1}$ , respectively, represents a balanced orthogonal drawing of minimal energy.*

In particular, for  $n = 2$  and  $n = 3$  one obtains graph drawings in the two- resp. three-dimensional Euclidean space. For example, we can write a function `spectral_layout` which takes  $G$  as its argument and returns a copy of  $G$  with spectral 2D layout stored to vertex positions. The code is given below.

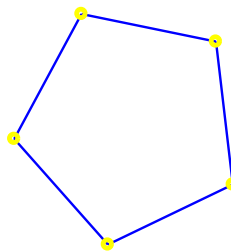
```
spectral_layout:=proc(G)
  local L,R,evals,ev,S,m,k;
  m:=number_of_vertices(G);
  L:=evalf(laplacian_matrix(G));           // Laplacian matrix (approx)
  evals:=[eigenvals(L)];                  // list of eigenvalues
  ev:=tran(eigenvectors(L));              // list of corresponding eigenvectors
  S:=sort(zip(evals,[k$(k=0..m-1)]));    // sort eigenvalues
  R:=tran([ev[S[1][1]],ev[S[2][1]]]);    // get the second and third eigenvector
  return set_vertex_positions(G,R);
end;
```

After compiling the above program in XCAS (by copying it into a programming cell which we create by pressing `(key|Alt+P)`), we demonstrate it in the following examples.

```
> C:=cycle_graph(5)
```

an undirected unweighted graph with 5 vertices and 5 edges

```
> draw_graph(spectral_layout(C),labels=false)
```



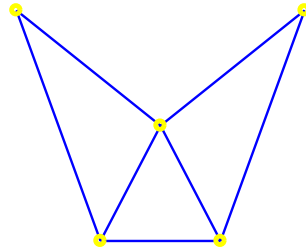
```
> A:=[[0,1,1,0,0],[1,0,1,1,1],[1,1,0,1,0],[0,1,1,0,1],[0,1,0,1,0]]
```

$$\begin{pmatrix} 0 & 1 & 1 & 0 & 0 \\ 1 & 0 & 1 & 1 & 1 \\ 1 & 1 & 0 & 1 & 0 \\ 0 & 1 & 1 & 0 & 1 \\ 0 & 1 & 0 & 1 & 0 \end{pmatrix}$$

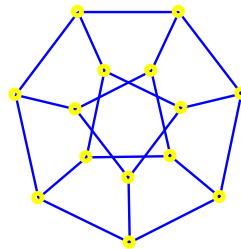
```
> G:=graph(A)
```

an undirected unweighted graph with 5 vertices and 7 edges

```
> draw_graph(spectral_layout(G),labels=false)
```



```
> draw_graph(spectral_layout(petersen_graph(7,2)),labels=false)
```



Unlike the methods used by `draw_graph` command, spectral graph layout takes edge weights into account. Assuming that all weights are positive, endpoints of edges with larger weights tend to get closer to each other, as in the next example.

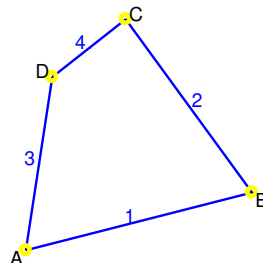
```
> W:=[[0,1,0,3],[1,0,2,0],[0,2,0,4],[3,0,4,0]]
```

$$\begin{pmatrix} 0 & 1 & 0 & 3 \\ 1 & 0 & 2 & 0 \\ 0 & 2 & 0 & 4 \\ 3 & 0 & 4 & 0 \end{pmatrix}$$

```
> purge(A,B,C,D); H:=graph([A,B,C,D],W)
```

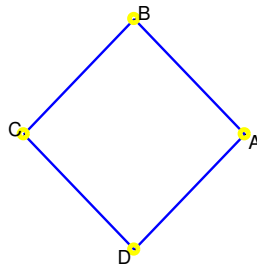
“Done”, an undirected weighted graph with 4 vertices and 4 edges

```
> draw_graph(spectral_layout(H))
```



On the other hand, the underlying graph of  $H$  is unweighted and hence drawn as a regular polygon.

```
> draw_graph(spectral_layout(underlying_graph(H)))
```



## 6.3 Highlighting parts of graphs

### 6.3.1 Highlighting vertices

```
highlight_vertex(G,v,<c>)
highlight_vertex(G,[v1,v2,...,vk],<c>)
highlight_vertex(G,[v1,v2,...,vk],[c1,c2,...,ck])
```

The command `highlight_vertex` changes color of one or more vertices in a graph. It takes two or three arguments: a graph  $G(V, E)$ , a vertex  $v \in V$  or a list of vertices  $v_1, v_2, \dots, v_k \in V$  and optionally the new color  $c$  or a list of colors  $c_1, c_2, \dots, c_k$  for the selected vertices (the default is green). It returns a modified copy of  $G$  in which the specified vertices are colored with the specified color(s).

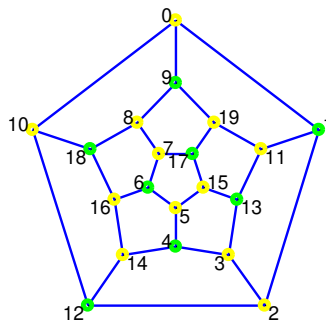
```
> G:=graph("dodecahedron")
```

an undirected unweighted graph with 20 vertices and 30 edges

```
> L:=maximum_independent_set(G)
```

```
[1, 4, 6, 9, 12, 13, 17, 18]
```

```
> draw_graph(highlight_vertex(G,L))
```



### 6.3.2 Highlighting edges and trails

```
highlight_edges(G,e,<c>)
highlight_edges(G,[e1,e2,...,ek],<c>)
highlight_edges(G,[e1,e2,...,ek],[c1,c2,...,ck])
highlight_trail(G,T,<c>)
highlight_trail(G,[T1,T2,...,Tk],<c>)
highlight_trail(G,[T1,T2,...,Tk],[c1,c2,...,ck])
```

To highlight an edge or a set of edges in a graph, use the `highlight_edges` command. If the edges form a trail, it is usually more convenient to use the `highlight_trail` command.

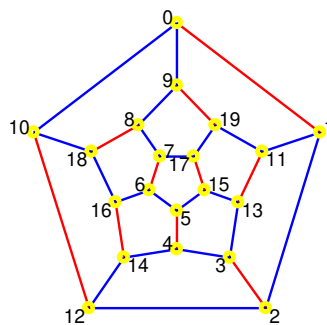
`highlight_edges` takes two or three arguments: a graph  $G(V, E)$ , an edge  $e \in E$  or a list of edges  $e_1, e_2, \dots, e_k \in E$  and optionally the new color  $c$  or a list of colors  $c_1, c_2, \dots, c_k$  for the selected edges (the default color is red). It returns a modified copy of  $G$  in which the specified edges are colored with the specified color.

`highlight_trail` takes two or three arguments: a graph  $G(V, E)$ , a trail  $T$  or a list of trails  $T_1, T_2, \dots, T_k$  and optionally the new color  $c$  or a list of colors  $c_1, c_2, \dots, c_k$ . The command returns the copy of  $G$  in which edges between consecutive vertices in each of the given trails are highlighted with color  $c$  (by default red) or the trail  $T_i$  is highlighted with color  $c_i$  for  $i = 1, 2, \dots, k$ .

```
> M:=maximum_matching(G)
```

```
[[0, 1], [2, 3], [4, 5], [6, 7], [8, 18], [9, 19], [10, 12], [11, 13], [14, 16], [15, 17]]
```

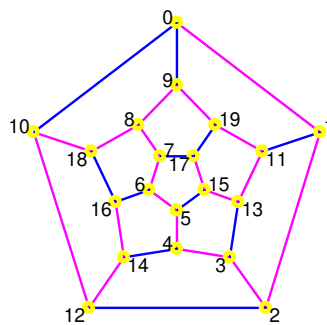
```
> draw_graph(highlight_edges(G,M))
```



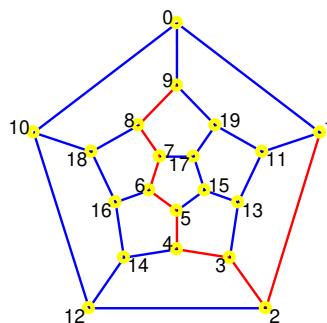
```
> S:=spanning_tree(G)
```

an undirected unweighted graph with 20 vertices and 19 edges

```
> draw_graph(highlight_edges(G,edges(S),magenta))
```



```
> draw_graph(highlight_trail(G,[1,2,3,4,5,6,7,8,9]))
```



```
> draw_graph(highlight_trail(G,shortest_path(G,1,[19,12]),[green,magenta]))
```







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# Command Index

add_arc	64	get_edge_attribute	69
add_edge	64	get_edge_weight	65
add_vertex	62	get_graph_attribute	67
adjacency_matrix	85	get_vertex_attribute	68
allpairs_distance	118	girth	121
antiprism_graph	26	goldberg_snark	29
arrivals	82	graph	13
articulation_points	107	graph_automorphisms	94
assign_edge_weights	60	graph_charpoly	89
bellman_ford	152	graph_complement	39
betweenness_centrality	140	graph_equal	78
biconnected_components	104	graph_join	42
bipartite_matching	125	graph_power	43
canonical_labeling	94	graph_rank	106
cartesian_product	44	graph_spectrum	90
chromatic_index	147	graph_union	41
chromatic_number	144	graph_vertices	77
chromatic_polynomial	100	greedy_clique	132
clique_cover	134	greedy_color	143
clique_cover_number	135	greedy_independent_set	132
clique_number	131	grid_graph	26
closeness_centrality	140	haar_graph	31
clustering_coefficient	138	harmonic_centrality	140
communicability_betweenness_centrality	140	has_arc	82
complete_binary_tree	20	has_edge	82
complete_graph	19	highlight_edges	173
complete_kary_tree	20	highlight_subgraph	175
condensation	124	highlight_trail	173
connected_components	104	highlight_vertex	173
contract_edge	65	hypercube_graph	24
contract_subgraph	63	identify_graph	97
cycle_basis	36	import_graph	71
cycle_graph	18	incidence_matrix	88
degree_centrality	140	incident_edges	85
degree_sequence	79	independence_number	132
delete_arc	64	induced_subgraph	36
delete_edge	64	information_centrality	140
delete_vertex	62	interval_graph	22
departures	82	is_acyclic	121
digraph	15	is_arborescence	114
dijkstra	152	is_biconnected	104
discard_edge_attribute	69	is_bipartite	84
discard_graph_attribute	67	is_clique	129
discard_vertex_attribute	68	is_connected	104
disjoint_union	42	is_cut_set	109
draw_graph	161	is_directed	77
edge_connectivity	108	is_eulerian	149
edges	77	is_forest	111
export_graph	74	is_graphic_sequence	21
find_cliques	130	is_hamiltonian	150
find_cycles	39	is_integer_graph	91
find_vertex_cover	127	is_isomorphic	91
flow_polynomial	101	is_network	114
flower_snark	29	is_planar	46
fundamental_cycle	36	is_reachable	160

is_regular	80	random_digraph	49
is_split_graph	135	random_graph	49
is_strongly_connected	107	random_network	58
is_strongly_regular	81	random_planar_graph	55
is_subgraph_isomorphic	95	random_regular_graph	58
is_tournament	83	random_sequence_graph	57
is_tree	110	random_tournament	58
is_triangle_free	136	random_tree	53
is_triconnected	104	reachable	160
is_two_edge_connected	109	relabel_vertices	35
is_vertex_colorable	146	reliability_polynomial	101
is_weighted	77	reverse_graph	41
isomorphic_copy	33	seidel_spectrum	90
katz centrality	140	seidel_switch	40
kneser_graph	22	sequence_graph	21
kspaths	154	set_edge_attribute	69
laplacian_matrix	86	set_edge_weight	65
lcf_graph	32	set_graph_attribute	67
line_graph	45	set_vertex_attribute	68
list_edge_attributes	69	set_vertex_positions	169
list_graph_attributes	67	shortest_path	152
list_vertex_attributes	68	sierpinski_graph	28
lowest_common_ancestor	113	simplicial_vertices	135
make_directed	61	spanning_tree	158
make_weighted	61	st_ordering	122
maxflow	115	star_graph	24
maximum_clique	131	strongly_connected_components	107
maximum_degree	79	subdivide_edges	66
maximum_independent_set	132	subgraph	35
maximum_matching	125	tensor_product	44
minimal_edge_coloring	147	topologic_sort	122
minimal_spanning_tree	158	topological_sort	122
minimal_vertex_coloring	143	torus_grid_graph	26
minimum_cut	117	trail	19
minimum_degree	79	trail2edges	19
minimum_vertex_cover	128	transitive_closure	45
mycielski	145	traveling_salesman	154
neighbors	82	tree_height	111
network_transitivity	139	truncate_graph	48
number_of_edges	77	tutte_polynomial	98
number_of_spanning_trees	159	two_edge_connected_components	109
number_of_vertices	77	underlying_graph	36
odd_girth	121	vertex_connectivity	106
odd_graph	22	vertex_cover_number	128
paley_graph	30	vertex_degree	79
path_graph	18	vertex_distance	118
permute_vertices	34	vertex_in_degree	79
petersen_graph	28	vertex_out_degree	79
plane_dual	46	vertices	77
prism_graph	25	web_graph	25
pruefer_code	112	weight_matrix	89
random_bipartite_graph	53	wheel_graph	25