

GraphDating - a Tool for Graph Alignments

Christina Kuhn, Jens-Tilman Rau, Aljoscha Rydzyk and Johann Wurz

University of Leipzig - Department of Computer Science
Härtelstraße 16-18, 04107 Leipzig - Germany

2019
Oktober

Abstract

Comparing the similarity of two or more graphs due to graph alignments has a broad spectra of applications. GraphDating is a software to generate multiple graph alignments, but is also able to find cliques of single graphs. The program has many additional functions for further specifications of special use-cases. GraphDating is written in Python 3 in a modular structure, to maintain the opportunity to specify or expand certain functions. It is available on [GitHub \(/tick-trick-and-clique/BestesRepository\)](#). GraphDating is described in the following manual. The first part characterizes the utilized main functions and algorithms, but also the applied graph format. The second part describes the application of GraphDating by explaining parameters and functions with command-line examples.

Contents

| | | |
|----------|---|-----------|
| 1 | Functions and implemented algorithms | 3 |
| 1.1 | Graph format | 3 |
| 1.2 | Parser | 4 |
| 1.3 | Construction of random graphs | 4 |
| 1.4 | Guide trees | 5 |
| 1.5 | Graph alignments | 5 |
| 1.6 | Graph representation | 6 |
| 2 | Command-line declarations | 7 |
| 2.1 | Inputs | 7 |
| 2.2 | Outputs | 8 |
| 2.3 | Operations | 9 |
| 3 | Profiling | 16 |
| 3.1 | Performance | 16 |
| 3.2 | Benchmarking | 16 |
| A | Help message | 18 |
| B | Example graphs | 21 |

1 Functions and implemented algorithms

A description of the most important functions and implemented algorithms is given in the following section, to create an overview of the program's features and how they are connected to each other.

1.1 Graph format

The presented graph format will be needed as input (besides *json* format) and is produced as output (if an output is desired). The file format compromises plain text and is induced with *.graph* at its end (e.g *example.graph*). The data format does not necessarily have to be *.graph*. GraphDating can use other formats too, if it is at least in plain text in the following structure. The presented graph format will be called standard graph format in the following for simplicity.

The required format is organised in three simple blocks - header, vertices and edges - separated from each other by an empty line (newline). The single parts are described in the following section. Specific examples are located in the appendix B. The presented example is *graph6.graph*.

Header

The header consists of five lines, each line has a parameter and a attribute separated by a semicolon. The parameters and attributes in correct order are:

1. number of nodes;Integer
2. number of edges;Integer
3. Information if nodes are labelled;Boolean
4. Information if edges are labelled;Boolean
5. Information if graph is directed;Boolean

Here is an example for a properly created header:

```
#nodes;3
#edges;3
nodes labelled;True
edges labelled;True
directed graph;True
```

Vertices

The vertex section consists of as many lines as vertices the graph consists of. The lines begin with ascending integers, the first vertex is named **1**. If the vertices are labelled, the integer is followed by a semicolon and the desired label. There is an example for a labelled vertex section appropriate to the already described header:

```
1;a
2;b
3;c
```

Edges

The edge section consists of as many lines as edges the graph consists of. The lines begin with the integers of vertices, the edges connects, separated by a semicolon. If the edges are labelled, the two integers are followed by a semicolon and the desired label. There is an example for a labelled edge section appropriate to the already described header and vertex section:

```
1;2;a
2;1;b
2;3;c
```

Please remember that in the full format, the single sections are separated by an empty line (newline). See appendix B for examples in full format.

1.2 Parser

There are different parsers implemented in GraphDating to maintain integrity. The presented graph format is usually transferred into an internal structure of several classes. The graph class consists of the vertex and the edge class. To generate an output, the internal graph structure is in most cases again transferred in the readable graph format. This basic parser also intercepts many small issues and calls exceptions. It does work as a control feature for inputs and outputs too, e.g. checking the number of vertices in the header with the number of lines of vertices.

1.3 Construction of random graphs

The construction of random graphs was implemented to test GraphDatings performance and to play around with its functions. It was also integrated for users, who do not bring their own graphs or who are to convenient to transfer their own graphs in the advised graph format. All randomly created graphs are without any labels. There are two possibilities to create your own random graphs.

Standard

To create a standard graph you need to supply three attributes. You can choose the number of vertices (integer), the mean relative connectivity (float, $0.0 < p \leq 1.0$) and the parameter, if your randomly created graph should be directed or undirected (boolean).

Cluster

To create a clustered graph you need to supply four attributes. You can choose the number of vertices (integer), the degree at each vertex (integer), the number of deleted vertices (integer) and the number of deleted edges (integer). It is an interesting task to align clustered graphs, because the runtime of many graph algorithms (e.g. Bron-Kerbosch algorithm) is supposed to expand enormously.

1.4 Guide trees

The application of guide trees is important for progressive alignments. They define the chronological sequence of pairwise alignments to gain a multiple alignment. Therefore GraphDating is able to calculate an guide tree from the supplied input graphs. The program calculates it by comparing the densities from the supplied graphs or by the greatest subgraph isomorphism. The densest graphs or graphs with maximal number of vertices in subgraphs will be aligned first. The user can also implement an own comparison function and pass it to GraphDating (see 2.3 **Guide trees** for details). The resulting guide tree is saved in the *newick* format and can be output too. The user can also submit an own guide tree in *newick* format for a graph alignment.

1.5 Graph alignments

The focus of GraphDating is the calculation of graph alignments. They are done by progressive alignments - a progression of pairwise alignments in a defined order to gain a multiple alignment. The chronological sequence of pairwise alignments can be set by a guide tree, which can be calculated by GraphDating or which can be supplied by the user. There are two possibilities to create such an alignment.

Bron-Kerbosch algorithm and modular product of graphs^[1]

The Bron-Kerbosch algorithm is a backtracking algorithm to find maximal cliques of an undirected graph. It can be accelerated by choosing a pivot element, but works also without pivoting. There are two options of choosing a pivot element implemented: selecting randomly a vertex as pivot or selecting the vertex with

highest cardinality as pivot. It is also possible to supply a so called anchor graph, where you have to distinguish between anchors for the bron-kerbosch algorithm alone and anchors for graph alignments with the bron-kerbosch algorithm. For the first case: The anchor has to be a clique, which the algorithm would expand if possible. For the second case: The anchor does not necessarily have to be a clique. For both cases: The anchor has to be a subgraph of one of the input graphs.

For finding similarity of graphs in a graph alignment, the Bron-Kerbosch algorithm is applied to the modular product of two graphs. It is also possible to run this algorithm to a supplied graph, just for clique finding. The modular product of two graphs G and H is the cartesian product (G, H) of these two graphs. This creates a new graph with all combinations of vertices of the two given graphs. In this new graph, edges between vertices (a,b) and (a',b') are formed if and only if either a is adjacent to a' and b is adjacent to b' **or** a is not adjacent to a' and b is not adjacent to b' . By applying the Bron-Kerbosch algorithm on (G, H) , you find the maximal common induced subgraph of the two original graphs. A pairwise graph alignment is done and can be developed to a multiple graph alignment by building the modular product of (G, H) and another graph. A guidetree can be used for defining the running order of the multiple graph alignment.

Cordella algorithm^[2]

The Cordella algorithm implements an improved version of a graph matching algorithm and can be applied to directed or undirected graphs. It was especially designed for matching large graphs. The algorithm implements a mapping M of vertices of graph G and graph H . $M(G,H)$ is called a graph-subgraph isomorphism if $M(G,H)$ is an isomorphism of H and a subgraph of G . Therefore it is important, that H consists of less or the same number vertices as G . The Cordella algorithm claims to be more efficient especially for large, well structured graphs (cluster).

1.6 Graph representation

GraphDating is connected to Neo4j to visualize graphs and graph alignments. See 2.3 **Graph representation with Neo4j** for the application of Neo4j with GraphDating.

2 Command-line declarations

The use-cases of GraphDating will be presented in the following section, to declare the common syntax and to show off its skill set. All positions of parameters are exchangeable and the usage of absolute paths is also possible. We recommend to use pypy3 to run GraphDating, because it shortens the runtime tremendously. **Tip:** If you don't have any graphs or graphs in the used format, you can create random graphs with GraphDating or download them from databases e.g. PubChem. See the subsection 2.3 **Random graphs** for further informations. To read the help message, use parameter **-h** or see appendix A.

2.1 Inputs

Files and formats

To supply one or several input graphs, you use the flag **-i**. You have to put a space character between submitted graph files, if you want to input more than one graph. It is also possible, to use chemical structures directly from PubChem. Therefore you need to download the 2D structure of a particular molecule in *json* format. To supply graphs in *json* format, you need to specify the input by using the flag **-if json**. You can also neglect all hydrogen atoms from *json* inputs by adding the flag **-nh**. To be more precise: by using **-nh** you neglect all atoms with the label "1" in *json* format. It is not possible to read graphs in *json* format and the displayed graph format at the same time.

If you want to read several graphs in standard format, your command-line could look like this:

```
python3 Main.py -i graph2.graph graph3.graph
```

If you want to read a single graph in *json* format and neglect all found hydrogen atoms, your command-line could look like this:

```
python3 Main.py -if json -i Ethane.json -nh
```

Please note, that the usage of flags **-i** and **-if** without any additional parameters will not calculate anything. It will only show some information about the inputs.

Anchors

You can supply a so called anchor graph for clique finding or graph alignments with the bron-kerbosch algorithm to append an already known clique or an already known alignment. Therefore you use the flag **-a**. GraphDating will only return reasonable outputs, if the passed anchor is an induced subgraph of the first input file and is included structurally in all other input files. The input anchor needs to be in the standard graph format.

If you want to read several graphs in standard format and also supply an anchor, your command-line could look like this:

```
python3 Main.py -i graph3.graph graph6.graph -a graph2.graph
```

Please note, that it is not possible to use anchor graphs in *json* format or to apply anchors for the cordella algorithm.

2.2 Outputs

Calculated graphs and subgraphs

To output calculated graphs and subgraphs, you use the flags **-go** and **-sgo**. Here is the specification of graph- and subgraph outputs very important. You want to save the entire graph (**-go**) from the calculation of random graphs and the modular product. But you want to save one or several subgraphs (**-sgo**) from clique finding and graph alignments. You can specify a file name for graph outputs and subgraph outputs. By default, subgraph outputs will have "_Subgraph_" followed by an ascending number in its file name. You can also choose the number of subgraph outputs by supplying an integer behind the **-sgo** flag. You can also combine input and output functions to reformat *json* files in *graph* files. You will find further information to the output of a particular function in the description of these function in 2.3.

If you want to format a *json* file to a standard graph file, your command-line could look like this:

```
python3 Main.py -i Ethane.json -if json -go ethane_pubchem.graph
```

Please note, that you can not save graphs or subgraphs in *json* format. Also note, that the labels of vertices of reformatted files from PubChem represent the particular atomic number. The labels from the associated edges represent the bonding type (e.g. 1 = single bond, 2 = double bond, 3 = triple bond, 7 = ionic bond, ...).

Newick format

GraphDating can calculate guide trees and save them in *newick* format for later usage. Therefore you need to use the flag **-no**. You find further information in 2.3 in the section about guide trees.

2.3 Operations

Random graphs

To calculate random graphs, you use the flags **-rg** or **-rc**. You also need to supply several attributes. For standard graphs you can choose the number of vertices, the relative connectivity and if your randomly created graph should be directed or undirected. For clustered graphs you can choose the number of vertices, the desired degree at each vertex, how many vertices you want to delete from the cluster and how many edges you want to delete from the cluster. Clustered graphs are undirected by default.

If you want to create a random standard graph, your command-line could look like this:

```
python3 Main.py -rg 10 0.5 False -go my_random_graph1.graph
```

If you want to create a random clustered graph, your command-line could look like this:

```
python3 Main.py -rc 20 3 2 2 -go my_random_graph1.graph
```

To create a lot of random graphs simultaneously at once, you can use the provided Nextflow file **create_random_graphs.nf**. The application and changeable parameters are described in the source code of the Nextflow file.

Clique finding

To find cliques of a graph, you use the flag **-bk**. GraphDating uses the algorithm of Bron and Kerbosch for clique finding. Therefore you want to supply an input file in the *graph* or *json* format. You can supply the maximum number of found cliques after the **-bk** flag (descending by the number of vertices of the clique). If you supply the number one, GraphDating will return only the largest found clique. You can also fasten the clique finding algorithm by applying a pivot element for the candidate choice. Therefore you use the flag **-p** and decide between the modes for maximum cardinality (**max**) or a random candidate (**random**).

If you want to find a clique from a graph and apply a pivot element of maximum cardinality, your command-line could look like this:


```
python3 Main.py -i graph3.graph -bk -p max
```

If you want to find a clique from a graph in standard format and save the three largest found cliques with an own file name, your command-line could look like this:

```
python3 Main.py -i graph6.graph -bk \  
-sgo my_subgraph_name.graph 3
```

Modular product

To calculate the modular product of two graphs, you use the flag **-mp**. Therefore you want to supply two input files in the *graph* or *json* format and pass the argument for the calculation of the modular product. If you calculate the modular product of two ~~similar~~ graphs and afterwards run the bron-kerbosch function for clique finding, one of the output cliques will be the initial graph. But please note, that you can not deduce which part from the modular product was which part from the initial graph.

 If you want to calculate the modular product of two graphs in *graph* format and save the output, your command-line could look like this:

```
python3 Main.py -i graph2.graph graph3.graph \  
-go mp_g2g3.graph -mp
```

Guide trees

To calculate a guide tree, you use the flag **-gt**. To save the result in *newick* format, you need to apply the flag **-no**. For guide tree construction you need to supply a list of input graphs and your choice of a comparison function, which are explained above in section 1.4 ("density", "pairwise_align", "custom"). The implemented default parameter for guide tree calculation is the graph density, but you can also choose an alignment by greatest subgraph isomorphism or supply your own comparison function and pass it to GraphDating. Please note: It is not possible to pass an anchor for the calculation of a guide tree via "pairwise_align".

For the application of a custom comparison function you also have to supply a *python* file (e.g. example.py). The function has to take two graphs as input parameters and has to return a float number, which represents the calculated distance of the two graphs. A small float number constitutes a small distance (consequently a high similarity) and vice versa. The pseudocode for the comparison function in *python* is given below.

```
def my_comparion_function(graph1, graph2):  
    calculate a float distance between graph1 and graph2  
    return distance
```

If you want to calculate a guide tree with graph density as the comparison parameter and save the output, your command-line could look like this:

```
python3 Main.py -i graph2.graph graph3.graph graph6.graph \  
-gt density -no res_g2g3g6.newick
```

If you want to calculate a guide tree with your own comparison function, your command-line could look like this:

```
python3 Main.py -i graph2.graph graph3.graph graph6.graph \  
-gt costum my_comparison_function.py -no res_g2g3g6.newick
```

Graph alignments

To make a graph alignment, you use the flag **-ga**. You can choose between the matching algorithms, which are explained above in section 1.5 ("bk" for matching by the modular product and clique finding, "mb" for matching by cordella algorithm). Therefore you want to supply a list of input files in the standard graph or *json* format. You also need to decide, if you want GraphDating to use your own guide tree, supplied in *newick* format or to calculate its own guide tree as described in 2.3 Guide trees above. Without any specifications GraphDating uses the density to calculate guide trees. The default value of the number of matchings per alignment is 1. Please note: if a compare function matches two vertices with different labels, the resulting matching graph vertex will either have the label from the first or the second matched vertex. You can specify this by an own label function.

If you want to make a graph alignment via the modular product and the Bron-Kerbosch algorithm by your own guide tree, your command-line could look like this:

```
python3 Main.py -i graph2.graph graph3.graph graph6.graph -sgo \  
-ga bk -gt my_guide_tree.newick
```



If you want to make a graph alignment via the Cordella algorithm and the guide tree is supposed to be calculated by your own comparison function, your command-line could look like this:

```
python3 Main.py -i graph2.graph graph3.graph graph6.graph \  
-gt costum my_comparison_function.py comparison_function_name \  
-go res_g2g3g6.graph -ga mb
```

Graph representation with Neo4j

To visualize graphs, you can do that via Neo4j by using the flag **-n**. Please note, that (strictly spoken) there are no undirected graphs in Neo4j. Undirected graphs are represented by Neo4j by multi-di-graphs, which means that an undirected edge is represented as two reverse directed edges. There are two possibilities for the visualization of graphs via Neo4j. You can either download the Neo4j desktop version or use a Neo4J sandbox online.

The first option is to download Neo4j Dektop. Both here and in the online version you have to create a user profile. You can now create a project in the user interface and create a new local database using "Add Graph" and "Add local Graph" (we use version 3.5.9 for this). You choose a name and a password to start the database. Under "Manage - Details" you can now read the HTTP port you need to connect to. This information is passed to the program together with the password. The function call then looks like this: `-n "http://localhost:7474" "neo4j" "1234"` (Default user name is neo4j). (The easy way is to copy the information about the HTTP port from Figure 1). To see your uploaded data in the database open the Neo4j Browser.

HTTP port 7474 

Figure 1: Information about the HTTP port.

If you want to visualize graphs with the Neo4j desktop version, your command-line could look like this:

```
python3 Main.py -i graph1.graph \  
-n "http://localhost:7474" "neo4j" "1234"
```

The second possibility is to use Neo4j online. For this you have to log in on the website <https://neo4j.com/sandbox-v2/>. Now you launch a new "Blank Sandbox", because we want to upload our own data. You find all necessary connection data (Direct Neo4j HTTP, Username, Password) under "Details" (see Figure 2). This information have to be given to the function call. Then you can Launch the Browser under "Get Started".

If you want to visualize graphs with the Neo4j browser version, your command-line could look like this:

```
python3 Main.py -i graph1.graph \  
-n "HTTP" "USERNAME" "PASSWORD"
```

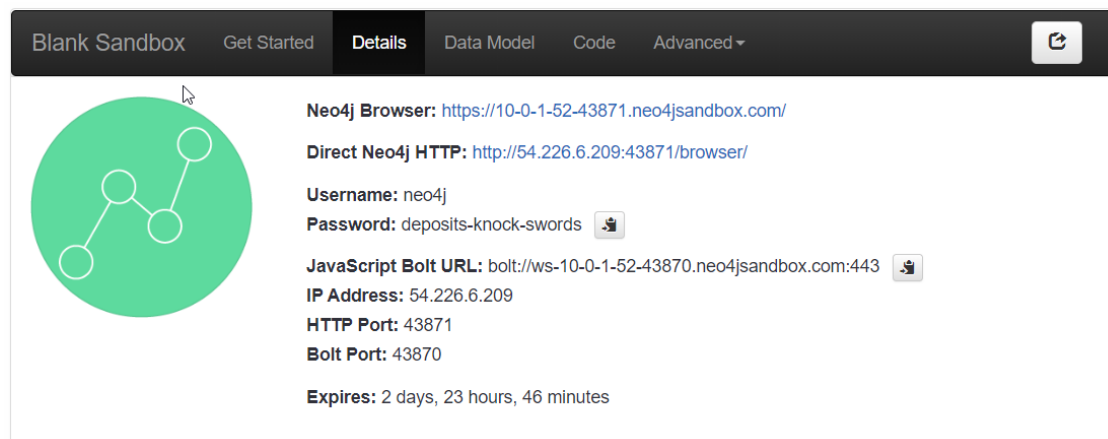


Figure 2: Example of the details description, where you find the Direct Neo4j HTTP, the username and the password, which you need to use the Neo4j browser version.

Other

There are some other useful functions implemented in GraphDating. They are described in the following section.

You can sort your output of graph alignments by supplying a custom sort function (similar to the custom function for the guide tree construction). Therefore you use the flag **-ms**. The function has to take a matching graph as input parameter

and has to return a float number. A high float number constitutes a high priority and vice versa. The pseudocode for the comparison function in *python* is given below.

```
def my_sorting_function(matching_graph):  
    calculate a float priority from matching_graph  
    return priority
```

If you want to sort your output from clique finding, your command-line could look like this:

```
python3 Main.py -i graph1.graph -bk -sgo \  
-ms my_sorting_function.py
```

You can cut off matchings, which are redundant relating to stereo isomerism. Therefore you use the flag **-nsi**. If you align methane to ethane for example and use **-nsi**, GraphDating will return two matchings instead of 18 whereby 17 of them would be redundant to each other.

You can cut off matchings, which are not connected, by using the flag **-cc**.

~~You can use an own label comparison function by using the flags **-vle** (vertices) and/or **-ele** (edges). Function takes two strings, return boolean~~

```
def my_label_function(label1, label2):  
    decision if label1 and label2 match (True) or not (False)  
    return decision
```

3 Profiling

3.1 Performance

Clique finding

- clique finding mit bk von graphen verschiedener groesse und density:
 - density 0.3, 0.6, 0.9
 - anzahl knoten 10, 20, 50

Guide tree construction

- anwendungsbezogenes beispiel?

3.2 Benchmarking

- realistische beispiele fuer alignments?
 - evtl input von 9 standard random graphen (je density je knotenanzahl, siehe unten)
 - und input von 9 mesh random graphen (je density je knotenzahl, siehe unten)
- vergleich alignments mit mp+bk vs cordella:
 - standard random graphen:
 - * density 0.3, 0.6, 0.9
 - * anzahl knoten 10, 20, 50
 - mesh random graphen:
 - * ...parameter?

References

- [1] C. Bron and J. Kerbosch, Finding All Cliques of an Undirected Graph, Communications of the ACM, 16(9):575-577, ACM, 1973.
- [2] L. P. Cordella, P. Foggia, C. Sansone and M. Vento, An Improved Algorithm for Matching Large Graphs, 2001.

A Help message

usage: Software for graph analysis

positional arguments:

 syntax

optional arguments:

- h, --help show this help message and exit
- a , --anchor Supply anchor graph file (path) for an anchor to the first graph in the input graphs.NOTE: Anchor option is not available for anchor graphs in json format!
- bk [[...]], --bron-kerbosch [[...]]
 Invokes maximal clique finding on input graph.
 Optionally, you may pass a file name together clique sorting function name in that file.
- cc, --check_connection
 If selected, only connected subgraphs will be the output of graph alignment!
- ga [[...]], --graph_alignment [[...]]
 Choose matching algorithm: Either 'bk' for bron-kerbosch or 'mb' for matching-based. You may also provide the number of matched subgraphs in previous pairwise alignments on which the the alignment should be expanded (e.g. 'bk 5'). Default is one subgraph only. If matching-based was chosen,you may provide a margin in percent to what extend the smaller graph may be reduced for subgraph isomorphism search (e.g. 'mb 5 0.2').
- go [], --graph_output []
 Saves graph as .graph file. If a path (in quotation marks!) is provided, graph will be saved there. If a .graph file name is provided, it will be saved with that name in the current working directory. Else it will be saved in the current working directory using its name attribute.
- gt [[...]], --guide_tree [[...]]
 Choose either a comparison function/attribute for guide tree construction (Keywords for available graph characteristics to base the comparison on: 'density' for graph density, 'pairwise_align' for greatest subgraph isomorphisms, i.e. maximal number of nodes in subgraphs). Alternatively, pass a preconstructed guide tree as '.newick' file or pass the keyword 'custom' together with a .py file and the name of the comparison function in that file. For detailed requirements of the custom comparison functions see the manual! If not selected, default is a heuristic construction of a guide tree by graph density.NOTE:

For pairwise alignment add a second argument 'only' ('pairwise_align' 'only'). Also, you need to pass the '-ga' command line keyword and required parameters.

-i [[...]], --input [[...]]
 Supply input path(s) of input file(s).

-if {graph,json}, --input_format {graph,json}
 Specify type of input files. For .graph files pass 'graph' and for .json files pass 'json'. 'graph' is default. NOTE: Data in json files is supposed to be of the structure of PubChem 2D json files!

-vlc [[...]], --vertex_label_comparison [[...]]
 For custom matching-conditions of vertex-labels, pass a file name together with a function in that file that will take two strings (see manual) and returns a boolean value. If return is TRUE, two distinct VERTEX-objects with relative strings as labels are possible matches.

-elc [[...]], --edge_label_comparison [[...]]
 For custom matching-conditions of edge-labels, pass a file name together with a function in that file that will take two strings (labels) and returns a boolean value. If return is TRUE, two distinct EDGE-objects with relative strings as labels are possible matches.

-mp, --modular_product
 Forms the modular product of two graphs.

-ms [[...]], --matching_sort [[...]]
 For custom sorting of matching graphs, pass a file name together with a function in that file that will take a matching-GRAPH object (see manual) and returns a floating point value. Matching graphs will then be sorted in descending order. Default is sorting by descending number of vertices!

-n [], --neo4j []
 Visualize output using NEO4J!

-nh, --no_h_atoms
 Specifies json format parsing. If selected, all H-atoms will be neglected.

-no [], --newick_output []
 Saves guide tree representation as Newick string to .newick file. If a path (in quotation marks!) is provided, it will be saved there. If a .newick file name is provided, it will be saved with that name in the current working directory. Else it will be saved in the current working directory using a default name.

-nsi, --no_stereo_isomers
 If selected and if input is a molecule graph, output will be reduced neglecting multiple stereo isomers, i.e. matchings where the subset of vertices is the same for each input graph, respectively. Only one stereoisomer will be forwarded!

-p , --pivot Choose pivot mode: Either 'max' or 'random'.
 -rg , --random_graph Create a random graph. Supply the number of vertices
 (N, integer), the mean relative connectivity (p,
 float) and whether it should be directed (either
 'True' or 'False') as e.g. '10 0.8 True'.
 -rc [], --random_cluster [] Create a random clustered graph. Supply the number of
 vertices (N, integer), the desired degree at each node
 (d, integer), how many vertices you want to delete
 from the cluster (del_vert, int) and finally how many
 edges you want to delete (del_edges, int) e.g. '20 3 2
 2'.
 -sgo [[...]], --subgraph_output [[[...]]] Saves found subgraphs as .graph file. You may specify
 the number of matchings in your output (e.g. -sgo 5),
 default is all matchings. If a path (in quotation
 marks!) is provided, subgraphs will be saved there
 with an additional sequential number. If a .graph file
 name is provided, they will be saved with that name in
 the current working directory. Else they will be saved
 in the current working directory using a default name.

B Example graphs

graph1.graph

The first example is derived from the chemical *benzoic acid*. The graph is not directed but its vertices are labeled as chemical elements and the its edges as the bond types single/double.

```
#nodes;15
#edges;15
nodes labelled;True
edges labelled;True
directed graph;False
```

```
1;O
2;C
3;O
4;C
5;C
6;C
7;C
8;C
9;C
10;H
11;H
12;H
13;H
14;H
15;H
```

```
15;1;s
1;2;s
3;2;d
2;4;s
4;5;s
5;14;s
5;6;d
6;13;s
6;7;s
7;12;s
7;8;d
8;11;s
8;9;s
9;10;s
9;4;d
```

graph2.graph

```
#nodes;6
#edges;10
nodes labelled;True
edges labelled;False
directed graph;True
```

```
1;a
2;b
3;c
4;d
5;e
6;f
```

```
1;2
2;1
2;4
4;2
4;1
1;4
4;3
3;4
1;5
1;6
```

graph3.graph

```
#nodes;10
#edges;22
nodes labelled;False
edges labelled;False
directed graph;True
```

```
1
2
3
4
5
6
7
8
9
10
```

```
1;10
10;9
9;10
9;1
1;9
9;3
3;9
3;1
1;3
1;4
3;4
4;2
1;2
2;1
1;5
3;2
2;3
5;6
8;6
6;7
7;8
7;2
```

graph4.graph

Attention! The graph was created to challenge the format parser.

```
#nodes;0
#edges;2
nodes labelled;False
edges labelled;False
directed graph;False
```

```
1;2
2;1
```

graph5.graph

Attention! The graph was created to challenge the format parser.

```
#nodes;0
#edges;0
nodes labelled;False
edges labelled;False
directed graph;True
```

graph6.graph

```
#nodes;3
#edges;3
nodes labelled;True
edges labelled;True
directed graph;True
```

```
1;a
2;b
3;c
```

```
1;2;a
2;1;b
2;3;c
```


graph7.graph

```
#nodes;4
#edges;8
Nodes labelled;True
Edges labelled;True
Directed graph;True
```

```
1;one
2;two
3;three
4;four
```

```
1;2;a
1;3;b
2;1;a
2;3;c
2;4;d
3;1;b
3;2;c
4;2;d
```