

---

# **pygmtools Documentation**

**Runzhong Wang, Ziao Guo**

**Oct 23, 2022**



# CONTENTS

<b>1</b>	<b>Installation</b>	<b>3</b>
<b>2</b>	<b>Available Graph Matching Solvers</b>	<b>5</b>
<b>3</b>	<b>Available Backends</b>	<b>7</b>
<b>4</b>	<b>The Deep Graph Matching Benchmark</b>	<b>9</b>
<b>5</b>	<b>Chat with the Community</b>	<b>11</b>
<b>6</b>	<b>Contributing</b>	<b>13</b>
<b>7</b>	<b>Developers and Maintainers</b>	<b>15</b>
<b>8</b>	<b>References</b>	<b>17</b>
<b>9</b>	<b>Contents of Official Documentation</b>	<b>19</b>
	<b>Python Module Index</b>	<b>177</b>
	<b>Index</b>	<b>179</b>





---

pygmtools provides graph matching solvers in Python and is easily accessible via:

```
$ pip install pygmtools
```

Official documentation: <https://pygmtools.readthedocs.io>

Source code: <https://github.com/Thinklab-SJTU/pygmtools>

Graph matching is a fundamental yet challenging problem in pattern recognition, data mining, and others. Graph matching aims to find node-to-node correspondence among multiple graphs, by solving an NP-hard combinatorial optimization problem.

Doing graph matching in Python used to be difficult, and this library wants to make researchers' lives easier. To highlight, pygmtools has the following features:

- *Support various solvers*, including traditional combinatorial solvers (including linear, quadratic, and multi-graph) and novel deep learning-based solvers;
- *Support various backends*, including `numpy` which is universally accessible, and some state-of-the-art deep learning architectures with GPU support: `pytorch`, `paddle`, `jittor`.
- *Deep learning friendly*, the operations are designed to best preserve the gradient during computation and batched operations support for the best performance.



## INSTALLATION

You can install the stable release on PyPI:

```
$ pip install pygmtools
```

or get the latest version by running:

```
$ pip install -U https://github.com/Thinklab-SJTU/pygmtools/archive/master.zip # with --  
→user for user install (no root)
```

Now the pygmtools is available with the numpy backend.

The following packages are required, and shall be automatically installed by pip:

```
Python >= 3.5  
requests >= 2.25.1  
scipy >= 1.4.1  
Pillow >= 7.2.0  
numpy >= 1.18.5  
easydict >= 1.7  
appdirs >= 1.4.4  
tqdm >= 4.64.1
```



## AVAILABLE GRAPH MATCHING SOLVERS

This library offers user-friendly API for the following solvers:

- **Two-Graph Matching Solvers**
  - Linear assignment solvers including the differentiable soft [Sinkhorn algorithm](#) [1], and the exact solver [Hungarian](#) [2].
  - Soft and differentiable quadratic assignment solvers, including [spectral graph matching](#) [3] and [random-walk-based graph matching](#) [4].
  - Discrete (non-differentiable) quadratic assignment solver [integer projected fixed point method](#) [5].
- **Multi-Graph Matching Solvers**
  - [Composition based Affinity Optimization \(CAO\)](#) solver [6] by optimizing the affinity score, meanwhile gradually infusing the consistency.
  - Multi-Graph Matching based on [Floyd shortest path algorithm](#) [7].
  - [Graduated-assignment based multi-graph matching solver](#) [8][9] by graduated annealing of Sinkhorn’s temperature.
- **Neural Graph Matching Solvers**
  - Intra-graph and cross-graph embedding based neural graph matching solvers [PCA-GM](#) and [IPCA-GM](#) [10] for matching individual graphs.
  - [Channel independent embedding \(CIE\)](#) [11] based neural graph matching solver for matching individual graphs.
  - [Neural graph matching solver \(NGM\)](#) [12] for the general quadratic assignment formulation.



## AVAILABLE BACKENDS

This library is designed to support multiple backends with the same set of API. Please follow the official instructions to install your backend.

The following backends are available:

- [Numpy](#) (**default** backend, CPU only)
- [PyTorch](#) (**recommended** backend, GPU friendly, deep learning friendly)
- [PaddlePaddle](#) (GPU friendly, deep learning friendly)
- [Jittor](#) (GPU friendly, deep learning friendly)

For more details, please [read the documentation](#).





## THE DEEP GRAPH MATCHING BENCHMARK

`pygmtools` is also featured with a standard data interface of several graph matching benchmarks. We also maintain a repository containing non-trivial implementation of deep graph matching models, please check out [ThinkMatch](#) if you are interested!



## CHAT WITH THE COMMUNITY

If you have any questions, or if you are experiencing any issues, feel free to raise an issue on GitHub.

We also offer the following chat rooms if you are more comfortable with them:

- Discord (for English users):

```
:raw-html-m2r: ``  
<https://discord.gg/8m6n7rRz9T>`_
```

- QQ Group (for Chinese users)/QQ(): 696401889

```
:raw-html-m2r: `` <https://qm.qq.com/cgi-bin/qm/qr?k=NlPuwwvaFaHzEWD8w7jSOTzoqSLIM80V&`  
jump_from=webapi&authKey=chI2htrWDujQed6VtVid3V1NXEoJvwz3MVwruax6x5lQIvLsC8BmpmzBJOCzhtQd>`_
```



## CONTRIBUTING

Any contributions/ideas/suggestions from the community is welcomed! Before starting your contribution, please read the [Contributing Guide](#).



## DEVELOPERS AND MAINTAINERS

`pygmtools` is currently developed and maintained by members from [ThinkLab](#) at Shanghai Jiao Tong University.





## REFERENCES

- [1] Sinkhorn, Richard, and Paul Knopp. "Concerning nonnegative matrices and doubly stochastic matrices." *Pacific Journal of Mathematics* 21.2 (1967): 343-348.
- [2] Munkres, James. "Algorithms for the assignment and transportation problems." *Journal of the society for industrial and applied mathematics* 5.1 (1957): 32-38.
- [3] Leordeanu, Marius, and Martial Hebert. "A spectral technique for correspondence problems using pairwise constraints." *International Conference on Computer Vision* (2005).
- [4] Cho, Minsu, Jungmin Lee, and Kyoung Mu Lee. "Reweighted random walks for graph matching." *European conference on Computer vision*. Springer, Berlin, Heidelberg, 2010.
- [5] Leordeanu, Marius, Martial Hebert, and Rahul Sukthankar. "An integer projected fixed point method for graph matching and map inference." *Advances in neural information processing systems* 22 (2009).
- [6] Yan, Junchi, et al. "Multi-graph matching via affinity optimization with graduated consistency regularization." *IEEE transactions on pattern analysis and machine intelligence* 38.6 (2015): 1228-1242.
- [7] Jiang, Zetian, Tianzhe Wang, and Junchi Yan. "Unifying offline and online multi-graph matching via finding shortest paths on supergraph." *IEEE transactions on pattern analysis and machine intelligence* 43.10 (2020): 3648-3663.
- [8] Solé-Ribalta, Albert, and Francesc Serratos. "Graduated assignment algorithm for multiple graph matching based on a common labeling." *International Journal of Pattern Recognition and Artificial Intelligence* 27.01 (2013): 1350001.
- [9] Wang, Runzhong, Junchi Yan, and Xiaokang Yang. "Graduated assignment for joint multi-graph matching and clustering with application to unsupervised graph matching network learning." *Advances in Neural Information Processing Systems* 33 (2020): 19908-19919.
- [10] Wang, Runzhong, Junchi Yan, and Xiaokang Yang. "Combinatorial learning of robust deep graph matching: an embedding based approach." *IEEE Transactions on Pattern Analysis and Machine Intelligence* (2020).
- [11] Yu, Tianshu, et al. "Learning deep graph matching with channel-independent embedding and hungarian attention." *International conference on learning representations*. 2019.
- [12] Wang, Runzhong, Junchi Yan, and Xiaokang Yang. "Neural graph matching network: Learning lawler's quadratic assignment problem with extension to hypergraph and multiple-graph matching." *IEEE Transactions on Pattern Analysis and Machine Intelligence* (2021).



## CONTENTS OF OFFICIAL DOCUMENTATION

### 9.1 Introduction and Guidelines

This page provides a brief introduction to graph matching and some guidelines for using `pygmtools`. If you are seeking some background information, this is the right place!

---

**Note:** For more technical details, we recommend the following two surveys.

About **learning-based** deep graph matching: Junchi Yan, Shuang Yang, Edwin Hancock. “[Learning Graph Matching and Related Combinatorial Optimization Problems](#).” *IJCAI 2020*.

About **non-learning** two-graph matching and multi-graph matching: Junchi Yan, Xu-Cheng Yin, Weiyao Lin, Cheng Deng, Hongyuan Zha, Xiaokang Yang. “[A Short Survey of Recent Advances in Graph Matching](#).” *ICMR 2016*.”

---

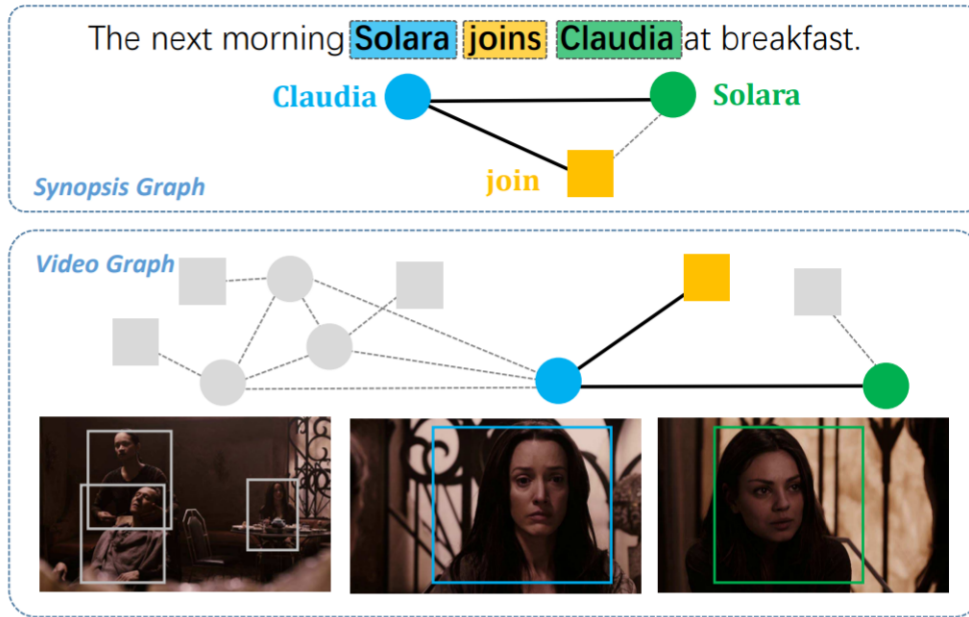
#### 9.1.1 Why Graph Matching?

Graph Matching (GM) is a fundamental yet challenging problem in pattern recognition, data mining, and others. GM aims to find node-to-node correspondence among multiple graphs, by solving an NP-hard combinatorial problem. Recently, there is growing interest in developing deep learning-based graph matching methods.

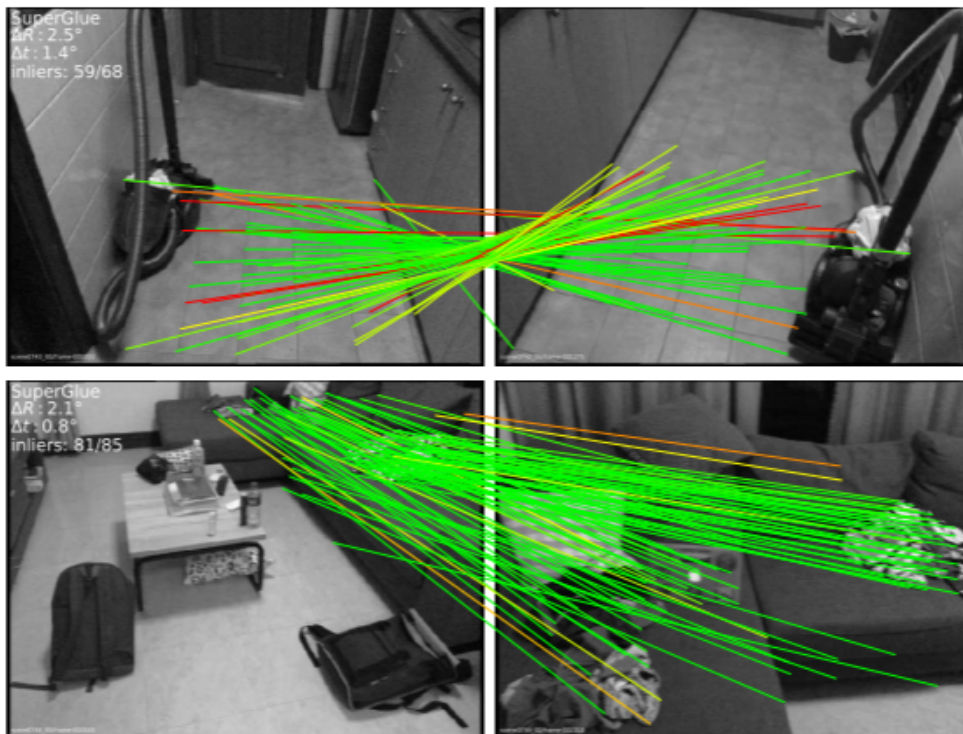
Compared to other straight-forward matching methods e.g. greedy matching, graph matching methods are more reliable because it is based on an optimization form. Besides, graph matching methods exploit both node affinity and edge affinity, thus graph matching methods are usually more robust to noises and outliers. The recent line of deep graph matching methods also enables many graph matching solvers to be integrated into a deep learning pipeline.

Graph matching techniques have been applied to the following applications:

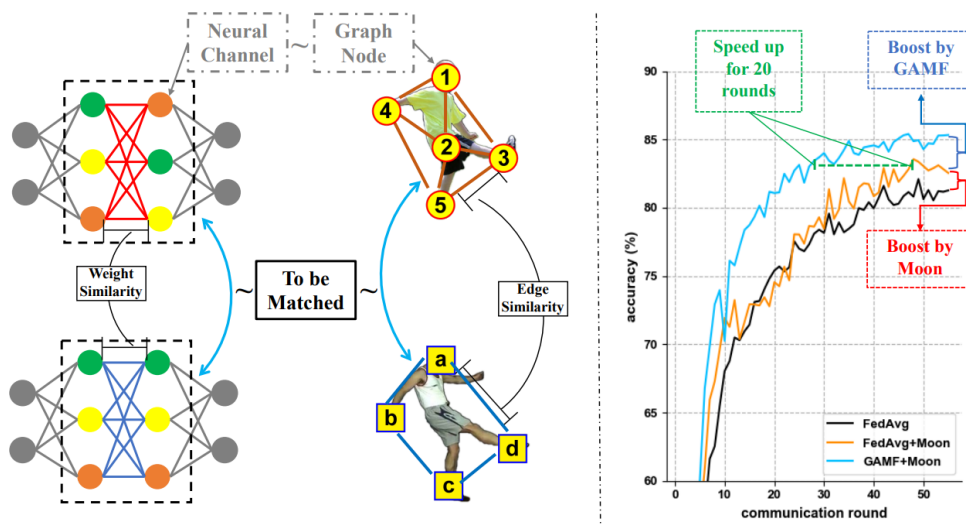
- [Bridging movie and synopses](#)



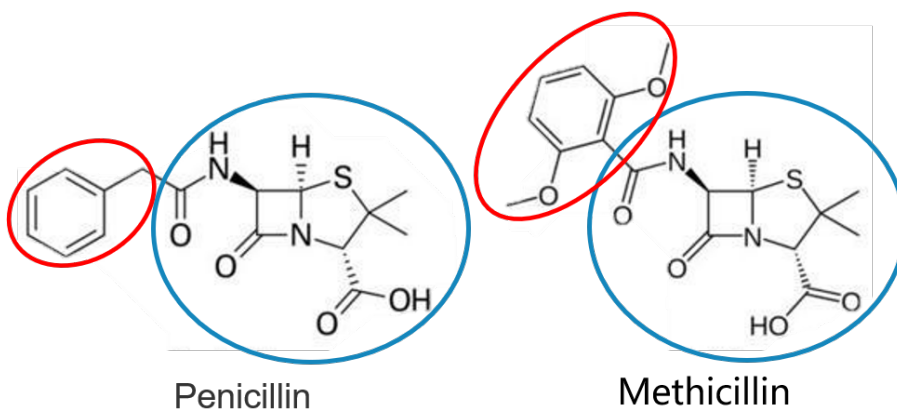
- Image correspondence



- Model ensemble and federated learning



- Molecules matching



- and more...

If your task involves matching two or more graphs, you should try the solvers in pygmtools!

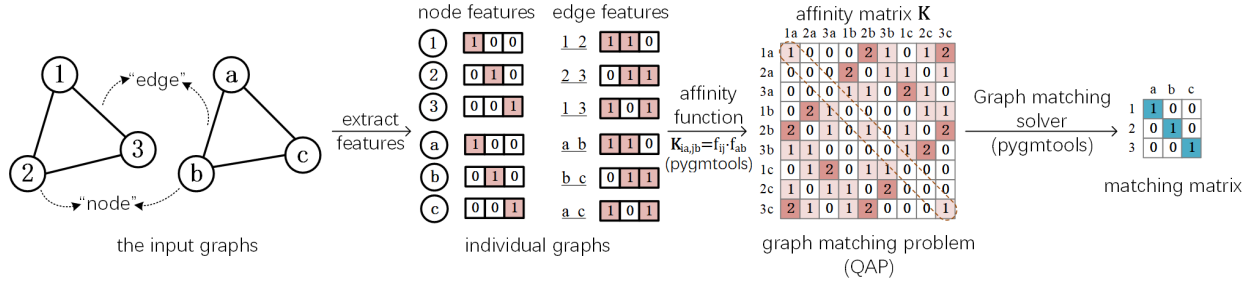
## 9.1.2 What is Graph Matching?

### The Graph Matching Pipeline

Solving a real-world graph-matching problem may involve the following steps:

1. Extract node/edge features from the graphs you want to match.
2. Build an affinity matrix from node/edge features.
3. Solve the graph matching problem with GM solvers.

And Step 1 may be done by methods depending on your application, Step 2&3 can be handled by pygmtools. The following plot illustrates a standard deep graph matching pipeline.



## The Math Form

Let's involve a little bit of math to better understand the graph matching pipeline. In general, graph matching is of the following form, known as **Quadratic Assignment Problem (QAP)**:

$$\begin{aligned} \max_{\mathbf{X}} \quad & \text{vec}(\mathbf{X})^\top \mathbf{K} \text{vec}(\mathbf{X}) \\ \text{s.t.} \quad & \mathbf{X} \in \{0, 1\}^{n_1 \times n_2}, \mathbf{X}\mathbf{1} = \mathbf{1}, \mathbf{X}^\top \mathbf{1} \leq \mathbf{1} \end{aligned}$$

The notations are explained as follows:

- $\mathbf{X}$  is known as the **permutation matrix** which encodes the matching result. It is also the decision variable in graph matching problem.  $\mathbf{X}_{i,a} = 1$  means node  $i$  in graph 1 is matched to node  $a$  in graph 2, and  $\mathbf{X}_{i,a} = 0$  means non-matched. Without loss of generality, it is assumed that  $n_1 \leq n_2$ .  $\mathbf{X}$  has the following constraints:
  - The sum of each row must be equal to 1:  $\mathbf{X}\mathbf{1} = \mathbf{1}$ ;
  - The sum of each column must be equal to, or smaller than 1:  $\mathbf{X}^\top \mathbf{1} \leq \mathbf{1}$ .
- $\text{vec}(\mathbf{X})$  means the column-wise vectorization form of  $\mathbf{X}$ .
- $\mathbf{1}$  means a column vector whose elements are all 1s.
- $\mathbf{K}$  is known as the **affinity matrix** which encodes the information of the input graphs. Both node-wise and edge-wise affinities are encoded in  $\mathbf{K}$ :
  - The diagonal element  $\mathbf{K}_{i+a \times n_1, i+a \times n_1}$  means the node-wise affinity of node  $i$  in graph 1 and node  $a$  in graph 2;
  - The off-diagonal element  $\mathbf{K}_{i+a \times n_1, j+b \times n_1}$  means the edge-wise affinity of edge  $ij$  in graph 1 and edge  $ab$  in graph 2.

### 9.1.3 Graph Matching Best Practice

We need to understand the advantages and limitations of graph matching solvers. As discussed above, the major advantage of graph matching solvers is that they are more robust to noises and outliers. Graph matching also utilizes edge information, which is usually ignored in linear matching methods. The major drawback of graph matching solvers is their efficiency and scalability since the optimization problem is NP-hard. Therefore, to decide which matching method is most suitable, one needs to balance between the required matching accuracy and the affordable time and memory cost according to his/her application.

---

**Note:** Anyway, it does no harm to try graph matching first!

---

## When to use pygmtools

pygmtools is recommended for the following cases, and you could benefit from the friendly API:

- If you want to integrate graph matching as a step of your pipeline (either learning or non-learning).
- If you want a quick benchmarking and profiling of the graph matching solvers available in pygmtools.
- If you do not want to dive too deep into the algorithm details and do not need to modify the algorithm.

We offer the following guidelines for your reference:

- If you want to integrate graph matching solvers into your end-to-end supervised deep learning pipeline, try [neural\\_solvers](#).
- If no ground truth label is available for the matching step, try [classic\\_solvers](#).
- If there are multiple graphs to be jointly matched, try [multi\\_graph\\_solvers](#).
- If time and memory cost of the above methods are unacceptable for your task, try [linear\\_solvers](#).

## When not to use pygmtools

As a highly packed toolkit, pygmtools lacks some flexibilities in the implementation details, especially for experts in graph matching. If you are researching new graph matching algorithms or developing next-generation deep graph matching neural networks, pygmtools may not be suitable. We recommend [ThinkMatch](#) as the protocol for academic research.

### 9.1.4 What's Next

Please read the [Get Started](#) guide.

## 9.2 Get Started

### 9.2.1 Basic Install by pip

You can install the stable release on PyPI:

```
$ pip install pygmtools
```

or get the latest version by running:

```
$ pip install -U https://github.com/Thinklab-SJTU/pygmtools/archive/master.zip # with --
↪user for user install (no root)
```

Now the pygmtools is available with the numpy backend:



You may jump to [Example: Matching Isomorphic Graphs](#) if you do not need other backends.

The following packages are required, and shall be automatically installed by pip:

```
Python >= 3.5
requests >= 2.25.1
scipy >= 1.4.1
Pillow >= 7.2.0
numpy >= 1.18.5
easydict >= 1.7
appdirs >= 1.4.4
tqdm >= 4.64.1
```

### 9.2.2 Install Other Backends

Currently, we also support deep learning architectures `pytorch`, `paddle`, `jittor` which are GPU-friendly and deep learning-friendly.

Once the backend is ready, you may switch to the backend globally by the following command:

```
>>> import pygmtools as pygm
>>> pygm.BACKEND = 'pytorch' # replace 'pytorch' by other backend names
```

#### PyTorch Backend



PyTorch is an open-source machine learning framework developed and maintained by Meta Inc./Linux Foundation. PyTorch is popular, especially among the deep learning research community. The PyTorch backend of `pygmtools` is designed to support GPU devices and facilitate deep learning research.

Please follow [the official PyTorch installation guide](#).

This package is developed with `torch==1.6.0` and shall work with any PyTorch versions `>=1.6.0`.

How to enable PyTorch backend:

```
>>> import pygmtools as pygm
>>> import torch
>>> pygm.BACKEND = 'pytorch'
```

#### Paddle Backend



PaddlePaddle is an open-source deep learning platform originated from industrial practice, which is developed and maintained by Baidu Inc. The Paddle backend of `pygmtools` is designed to support GPU devices and deep learning applications.

Please follow [the official PaddlePaddle installation guide](#).



This package is developed with paddlepaddle==2.3.1 and shall work with any PaddlePaddle versions >=2.3.1.

How to enable Paddle backend:

```
>>> import pygmtools as pygm
>>> import paddle
>>> pygm.BACKEND = 'paddle'
```

## Jittor Backend



Jittor is an open-source deep learning platform based on just-in-time (JIT) for high performance, which is developed and maintained by the [CSCG group](#) from Tsinghua University. The Jittor backend of pygmtools is designed to support GPU devices and deep learning applications.

Please follow [the official Jittor installation guide](#).

This package is developed with jittor==1.3.4.16 and shall work with any Jittor versions >=1.3.4.16.

How to enable Jittor backend:

```
>>> import pygmtools as pygm
>>> import jittor
>>> pygm.BACKEND = 'jittor'
```

### 9.2.3 Example: Matching Isomorphic Graphs

Here we provide a basic example of matching two isomorphic graphs (i.e. two graphs have the same nodes and edges, but the node permutations are unknown).

Step 0: Import packages and set backend

```
>>> import numpy as np
>>> import pygmtools as pygm
>>> pygm.BACKEND = 'numpy'
>>> np.random.seed(1)
```

Step 1: Generate a batch of isomorphic graphs

```
>>> batch_size = 3
>>> X_gt = np.zeros((batch_size, 4, 4))
>>> X_gt[:, np.arange(0, 4, dtype=np.int64), np.random.permutation(4)] = 1
>>> A1 = np.random.rand(batch_size, 4, 4)
>>> A2 = np.matmul(np.matmul(X_gt.transpose((0, 2, 1)), A1), X_gt)
>>> n1 = n2 = np.repeat([4], batch_size)
```

Step 2: Build an affinity matrix and select an affinity function

```
>>> conn1, edge1, ne1 = pygm.utils.dense_to_sparse(A1)
>>> conn2, edge2, ne2 = pygm.utils.dense_to_sparse(A2)
>>> import functools
>>> gaussian_aff = functools.partial(pygm.utils.gaussian_aff_fn, sigma=1.) # set_
↳affinity function
>>> K = pygm.utils.build_aff_mat(None, edge1, conn1, None, edge2, conn2, n1, ne1, n2,
↳ne2, edge_aff_fn=gaussian_aff)
```

Step 3: Solve graph matching by RRWM

```
>>> X = pygm.rrwm(K, n1, n2, beta=100)
>>> X = pygm.hungarian(X)
>>> X # X is the permutation matrix
[[[0. 0. 0. 1.]
  [0. 0. 1. 0.]
  [1. 0. 0. 0.]
  [0. 1. 0. 0.]]

 [[0. 0. 0. 1.]
  [0. 0. 1. 0.]
  [1. 0. 0. 0.]
  [0. 1. 0. 0.]]

 [[0. 0. 0. 1.]
  [0. 0. 1. 0.]
  [1. 0. 0. 0.]
  [0. 1. 0. 0.]]]
```

Final Step: Evaluate the accuracy

```
>>> (X * X_gt).sum() / X_gt.sum()
1.0
```

## 9.2.4 What's Next

Please checkout [Examples Gallery](#) to see how to apply pygmtools to tackle real-world problems. You may see [API and Modules](#) for the API documentation.

## 9.3 Graph Matching Benchmark

**pygmtools** also provides a protocol to fairly compare existing deep graph matching algorithms under different datasets & experiment settings. The Benchmark module provides a unified data interface and an evaluating platform for different datasets.

If you are interested in the performance and the full deep learning pipeline, please refer to our [ThinkMatch project](#).

### 9.3.1 Evaluation Metrics and Results

Our evaluation metrics include **matching\_precision (p)**, **matching\_recall (r)** and **f1\_score (f1)**. Also, to measure the reliability of the evaluation result, we define **coverage (cvg)** for each class in the dataset as *the number of evaluated pairs in the class/number of all possible pairs in the class*. Therefore, larger coverage refers to higher reliability.

An example of evaluation result ( $p=r=f1$  because this evaluation does not involve partial matching/outliers):

```
Matching accuracy
Car: p = 0.8395±0.2280, r = 0.8395±0.2280, f1 = 0.8395±0.2280, cvg = 1.0000
Duck: p = 0.7713±0.2255, r = 0.7713±0.2255, f1 = 0.7713±0.2255, cvg = 1.0000
Face: p = 0.9656±0.0913, r = 0.9656±0.0913, f1 = 0.9656±0.0913, cvg = 0.2612
Motorbike: p = 0.8821±0.1821, r = 0.8821±0.1821, f1 = 0.8821±0.1821, cvg = 1.0000
Winebottle: p = 0.8929±0.1569, r = 0.8929±0.1569, f1 = 0.8929±0.1569, cvg = 0.9662
average accuracy: p = 0.8703±0.1767, r = 0.8703±0.1767, f1 = 0.8703±0.1767
Evaluation complete in 1m 55s
```

### 9.3.2 Available Datasets

Dataset can be automatically downloaded and unzipped, but you can also download the dataset yourself, and make sure it in the right path.

#### PascalVOC-Keypoint Dataset

1. Download [VOC2011 dataset](#) and make sure it looks like data/PascalVOC/TrainVal/VOCdevkit/VOC2011
1. Download keypoint annotation for VOC2011 from [Berkeley server](#) or [google drive](#) and make sure it looks like data/PascalVOC/annotations
1. Download the [train/test split file](#) and make sure it looks like data/PascalVOC/voc2011\_pairs.npz

Please cite the following papers if you use PascalVOC-Keypoint dataset:

```
@article{EveringhamIJCV10,
  title={The pascal visual object classes (voc) challenge},
  author={Everingham, Mark and Van Gool, Luc and Williams, Christopher KI and Winn, John
↵and Zisserman, Andrew},
  journal={International Journal of Computer Vision},
  volume={88},
  pages={303-338},
  year={2010}
}

@inproceedings{BourdevICCV09,
  title={Poselets: Body part detectors trained using 3d human pose annotations},
  author={Bourdev, L. and Malik, J.},
  booktitle={International Conference on Computer Vision},
  pages={1365--1372},
  year={2009},
  organization={IEEE}
}
```

### Willow-Object-Class Dataset

1. Download [Willow-ObjectClass dataset](#)

1. Unzip the dataset and make sure it looks like data/WillowObject/WILLOW-ObjectClass

Please cite the following paper if you use Willow-Object-Class dataset:

```
@inproceedings{ChoICCV13,
  author={Cho, Minsu and Alahari, Karteek and Ponce, Jean},
  title = {Learning Graphs to Match},
  booktitle = {International Conference on Computer Vision},
  pages={25--32},
  year={2013}
}
```

### CUB2011 Dataset

1. Download [CUB-200-2011 dataset](#).

1. Unzip the dataset and make sure it looks like data/CUB\_200\_2011/CUB\_200\_2011

Please cite the following report if you use CUB2011 dataset:

```
@techreport{CUB2011,
  Title = {{The Caltech-UCSD Birds-200-2011 Dataset}},
  Author = {Wah, C. and Branson, S. and Welinder, P. and Perona, P. and Belongie, S.},
  Year = {2011},
  Institution = {California Institute of Technology},
  Number = {CNS-TR-2011-001}
}
```

### IMC-PT-SparseGM Dataset

1. Download the IMC-PT-SparseGM dataset from [google drive](#) or [baidu drive](#) (code: 0576)

1. Unzip the dataset and make sure it looks like data/IMC\_PT\_SparseGM/annotations

Please cite the following papers if you use IMC-PT-SparseGM dataset:

```
@article{JinIJCV21,
  title={Image Matching across Wide Baselines: From Paper to Practice},
  author={Jin, Yuhe and Mishkin, Dmytro and Mishchuk, Anastasiia and Matas, Jiri and Fua,
  ↪ Pascal and Yi, Kwang Moo and Trulls, Eduard},
  journal={International Journal of Computer Vision},
  pages={517--547},
  year={2021}
}
```

### 9.3.3 API Reference

See *the API doc of Benchmark module* and *the API doc of datasets* for details.

### 9.3.4 File Organization

- `dataset.py`: The file includes 5 dataset classes, used to automatically download the dataset and process the dataset into a json file, and also save the training set and the testing set.
- `benchmark.py`: The file includes Benchmark class that can be used to fetch data from the json file and evaluate prediction results.
- `dataset_config.py`: The default dataset settings, mostly dataset path and classes.

### 9.3.5 Example

```
import pygmtools as pygm
from pygm.benchmark import Benchmark

# Define Benchmark on PascalVOC.
bm = Benchmark(name='PascalVOC', sets='train',
               obj_resize=(256, 256), problem='2GM',
               filter='intersection')

# Random fetch data and ground truth.
data_list, gt_dict, _ = bm.rand_get_data(cls=None, num=2)
```

## 9.4 API and Modules

<code>linear_solvers</code>	Classic (learning-free) <b>linear assignment problem</b> solvers.
<code>classic_solvers</code>	Classic (learning-free) <b>two-graph matching</b> solvers.
<code>multi_graph_solvers</code>	Classic (learning-free) <b>multi-graph matching</b> solvers.
<code>neural_solvers</code>	<b>Neural network-based</b> graph matching solvers.
<code>utils</code>	Utility functions: problem formulating, data processing, and beyond.
<code>benchmark</code>	The Benchmark module with a unified data interface to evaluate graph matching methods.
<code>dataset</code>	The implementations of data loading and data processing.

### 9.4.1 pygmtools.linear\_solvers

Classic (learning-free) **linear assignment problem** solvers. These linear assignment solvers are recommended to solve matching problems with only nodes (i.e. linear matching problems), or large-scale graph matching problems where the cost of QAP formulation is too high.

The linear assignment problem only considers nodes, and is also known as bipartite graph matching and linear matching:

$$\begin{aligned} & \max_{\mathbf{X}} \text{tr}(\mathbf{X}^\top \mathbf{S}) \\ \text{s.t. } & \mathbf{X} \in \{0, 1\}^{n_1 \times n_2}, \mathbf{X}\mathbf{1} = \mathbf{1}, \mathbf{X}^\top \mathbf{1} \leq \mathbf{1} \end{aligned}$$

#### Functions

<i>hungarian</i>	Solve optimal LAP permutation by hungarian algorithm.
<i>sinkhorn</i>	Sinkhorn algorithm turns the input matrix into a doubly-stochastic matrix.

#### pygmtools.linear\_solvers.hungarian

`pygmtools.linear_solvers.hungarian(s, n1=None, n2=None, unmatched1=None, unmatched2=None, nproc: int = 1, backend=None)`

Solve optimal LAP permutation by hungarian algorithm. The time cost is  $O(n^3)$ .

##### Parameters

- **s** – ( $b \times n_1 \times n_2$ ) input 3d tensor. *b*: batch size. Non-batched input is also supported if *s* is of size ( $n_1 \times n_2$ )
- **n1** – (*b*) (optional) number of objects in dim1
- **n2** – (*b*) (optional) number of objects in dim2
- **unmatched1** – (optional, new in 0.3.0) ( $b \times n_1$ ) the scores indicating the objects in dim1 is unmatched
- **unmatched2** – (optional, new in 0.3.0) ( $b \times n_1$ ) the scores indicating the objects in dim2 is unmatched
- **nproc** – (default: 1, i.e. no parallel) number of parallel processes
- **backend** – (default: `pygmtools.BACKEND` variable) the backend for computation.

##### Returns

( $b \times n_1 \times n_2$ ) optimal permutation matrix

---

**Note:** The parallelization is based on multi-processing workers that run on multiple CPU cores.

---



---

**Note:** For all backends, `scipy.optimize.linear_sum_assignment` is called to solve the LAP, therefore the computation is based on `numpy` and `scipy`. The `backend` argument of this function only affects the input-output data type.

---

**Note:** We support batched instances with different number of nodes, therefore `n1` and `n2` are required to specify the exact number of objects of each dimension in the batch. If not specified, we assume the batched matrices are not padded and all elements in `n1` are equal, all in `n2` are equal.

**Warning:** This function can work with or without maximal inlier matching:

- **With maximal inlier matching** (the default mode). If `unmatch1=None` and `unmatch2=None`, the solver aims to match as many nodes as possible. The corresponding linear assignment problem is

$$\begin{aligned} \max_{\mathbf{X}} \quad & \text{tr}(\mathbf{X}^\top \mathbf{S}) \\ \text{s.t.} \quad & \mathbf{X} \in \{0, 1\}^{n_1 \times n_2}, \mathbf{X}\mathbf{1} = \mathbf{1}, \mathbf{X}^\top \mathbf{1} \leq \mathbf{1} \end{aligned}$$

where the constraint  $\mathbf{X}\mathbf{1} = \mathbf{1}$  urges the solver to match as many inlier nodes as possible.

- **Without maximal inlier matching** (new in 0.3.0). If `unmatch1` and `unmatch2` are not `None`, the solver is allowed to match nodes to void nodes, and the corresponding scores for matching to void nodes are specified by `unmatch1` and `unmatch2`. The following (modified) linear assignment problem is considered:

$$\begin{aligned} \max_{\mathbf{X}} \quad & \text{tr}(\mathbf{X}^\top \mathbf{S}') \\ \text{s.t.} \quad & \mathbf{X} \in \{0, 1\}^{n_1+1 \times n_2+1}, \mathbf{X}_{[0:n_1,:]} \mathbf{1} = \mathbf{1}, \mathbf{X}_{[:,0:n_2]}^\top \mathbf{1} \leq \mathbf{1} \end{aligned}$$

where the last column and last row of  $\mathbf{S}'$  are `unmatch1` and `unmatch2`, respectively.

For example, if you want to solve the following problem (note that both constraints are  $\leq$ )

$$\begin{aligned} \max_{\mathbf{X}} \quad & \text{tr}(\mathbf{X}^\top \mathbf{S}) \\ \text{s.t.} \quad & \mathbf{X} \in \{0, 1\}^{n_1 \times n_2}, \mathbf{X}\mathbf{1} \leq \mathbf{1}, \mathbf{X}^\top \mathbf{1} \leq \mathbf{1} \end{aligned}$$

you can simply set `unmatch1` and `unmatch2` as zero vectors.

## Numpy Example

```
>>> import numpy as np
>>> import pygmtools as pygm
>>> pygm.BACKEND = 'numpy'
>>> np.random.seed(0)

# 2-dimensional (non-batched) input
>>> s_2d = np.random.rand(5, 5)
>>> s_2d
array([[0.5488135 , 0.71518937, 0.60276338, 0.54488318, 0.4236548 ],
       [0.64589411, 0.43758721, 0.891773  , 0.96366276, 0.38344152],
       [0.79172504, 0.52889492, 0.56804456, 0.92559664, 0.07103606],
       [0.0871293 , 0.0202184 , 0.83261985, 0.77815675, 0.87001215],
       [0.97861834, 0.79915856, 0.46147936, 0.78052918, 0.11827443]])

>>> x = pygm.hungarian(s_2d)
>>> x
```

(continues on next page)

(continued from previous page)

```

array([[0., 1., 0., 0., 0.],
       [0., 0., 1., 0., 0.],
       [0., 0., 0., 1., 0.],
       [0., 0., 0., 0., 1.],
       [1., 0., 0., 0., 0.]])

# 3-dimensional (batched) input
>>> s_3d = np.random.rand(3, 5, 5)
>>> n1 = n2 = np.array([3, 4, 5])
>>> x = pygm.hungarian(s_3d, n1, n2)
>>> x
array([[0., 0., 1., 0., 0.],
       [0., 1., 0., 0., 0.],
       [1., 0., 0., 0., 0.],
       [0., 0., 0., 0., 0.],
       [0., 0., 0., 0., 0.]],

       [[1., 0., 0., 0., 0.],
        [0., 1., 0., 0., 0.],
        [0., 0., 1., 0., 0.],
        [0., 0., 0., 1., 0.],
        [0., 0., 0., 0., 0.]],

       [[0., 0., 1., 0., 0.],
        [1., 0., 0., 0., 0.],
        [0., 0., 0., 0., 1.],
        [0., 1., 0., 0., 0.],
        [0., 0., 0., 1., 0.]])

# allow matching to void nodes by setting unmatched1 and unmatched2
>>> s_2d = np.random.randn(5, 5)
>>> s_2d
array([[ -1.16514984,  0.90082649,  0.46566244, -1.53624369,  1.48825219],
       [ 1.89588918,  1.17877957, -0.17992484, -1.07075262,  1.05445173],
       [-0.40317695,  1.22244507,  0.20827498,  0.97663904,  0.3563664 ],
       [ 0.70657317,  0.01050002,  1.78587049,  0.12691209,  0.40198936],
       [ 1.8831507 , -1.34775906, -1.270485  ,  0.96939671, -1.17312341]])
>>> unmatched1 = np.random.randn(5)
>>> unmatched1
array([ 1.94362119, -0.41361898, -0.74745481,  1.92294203,  1.48051479])
>>> unmatched2 = np.random.randn(5)
>>> unmatched2
array([ 1.86755896,  0.90604466, -0.86122569,  1.91006495, -0.26800337])
>>> x = pygm.hungarian(s_2d, unmatched1=unmatched1, unmatched2=unmatched2)
>>> x
array([[0., 0., 0., 0., 1.],
       [1., 0., 0., 0., 0.],
       [0., 1., 0., 0., 0.],
       [0., 0., 1., 0., 0.],
       [0., 0., 0., 1., 0.]])

```



## Pytorch Example

```

>>> import torch
>>> import pygmtools as pygm
>>> pygm.BACKEND = 'pytorch'
>>> np.random.seed(0)

# 2-dimensional (non-batched) input
>>> s_2d = torch.from_numpy(np.random.rand(5, 5))
>>> s_2d
tensor([[0.5488, 0.7152, 0.6028, 0.5449, 0.4237],
        [0.6459, 0.4376, 0.8918, 0.9637, 0.3834],
        [0.7917, 0.5289, 0.5680, 0.9256, 0.0710],
        [0.0871, 0.0202, 0.8326, 0.7782, 0.8700],
        [0.9786, 0.7992, 0.4615, 0.7805, 0.1183]], dtype=torch.float64)
>>> x = pygm.hungarian(s_2d)
>>> x
tensor([[0., 1., 0., 0., 0.],
        [0., 0., 1., 0., 0.],
        [0., 0., 0., 1., 0.],
        [0., 0., 0., 0., 1.],
        [1., 0., 0., 0., 0.]], dtype=torch.float64)

# 3-dimensional (batched) input
>>> s_3d = torch.from_numpy(np.random.rand(3, 5, 5))
>>> n1 = n2 = torch.tensor([3, 4, 5])
>>> x = pygm.hungarian(s_3d, n1, n2)
>>> x
tensor([[[[0., 0., 1., 0., 0.],
          [0., 1., 0., 0., 0.],
          [1., 0., 0., 0., 0.],
          [0., 0., 0., 0., 0.],
          [0., 0., 0., 0., 0.]],
         [[1., 0., 0., 0., 0.],
          [0., 1., 0., 0., 0.],
          [0., 0., 1., 0., 0.],
          [0., 0., 0., 1., 0.],
          [0., 0., 0., 0., 0.]],
         [[0., 0., 1., 0., 0.],
          [1., 0., 0., 0., 0.],
          [0., 0., 0., 0., 1.],
          [0., 1., 0., 0., 0.],
          [0., 0., 0., 1., 0.]]], dtype=torch.float64)

# allow matching to void nodes by setting unmatched1 and unmatched2
>>> s_2d = torch.from_numpy(np.random.randn(5, 5))
>>> s_2d
tensor([[ -1.1651,  0.9008,  0.4657, -1.5362,  1.4883],
        [ 1.8959,  1.1788, -0.1799, -1.0708,  1.0545],
        [-0.4032,  1.2224,  0.2083,  0.9766,  0.3564],
        [ 0.7066,  0.0105,  1.7859,  0.1269,  0.4020],

```

(continues on next page)

(continued from previous page)

```

        [ 1.8832, -1.3478, -1.2705,  0.9694, -1.1731]], dtype=torch.float64)
>>> unmatched1 = torch.from_numpy(np.random.randn(5))
>>> unmatched1
tensor([ 1.9436, -0.4136, -0.7475,  1.9229,  1.4805], dtype=torch.float64)
>>> unmatched2 = torch.from_numpy(np.random.randn(5))
>>> unmatched2
tensor([ 1.8676,  0.9060, -0.8612,  1.9101, -0.2680], dtype=torch.float64)
>>> x = pygm.hungarian(s_2d, unmatched1=unmatched1, unmatched2=unmatched2)
>>> x
tensor([[0., 0., 0., 0., 0.],
        [0., 0., 0., 0., 1.],
        [0., 0., 1., 0., 0.],
        [0., 0., 0., 0., 0.],
        [0., 0., 0., 0., 0.]], dtype=torch.float64)

```

## Paddle Example

```

>>> import paddle
>>> import pygmtools as pygm
>>> pygm.BACKEND = 'paddle'
>>> np.random.seed(0)

# 2-dimensional (non-batched) input
>>> s_2d = paddle.to_tensor(np.random.rand(5, 5))
>>> s_2d
Tensor(shape=[5, 5], dtype=float64, place=Place(cpu), stop_gradient=True,
       [[0.54881350, 0.71518937, 0.60276338, 0.54488318, 0.42365480],
        [0.64589411, 0.43758721, 0.89177300, 0.96366276, 0.38344152],
        [0.79172504, 0.52889492, 0.56804456, 0.92559664, 0.07103606],
        [0.08712930, 0.02021840, 0.83261985, 0.77815675, 0.87001215],
        [0.97861834, 0.79915856, 0.46147936, 0.78052918, 0.11827443]])
>>> x = pygm.hungarian(s_2d)
>>> x
Tensor(shape=[5, 5], dtype=float64, place=Place(cpu), stop_gradient=True,
       [[0., 1., 0., 0., 0.],
        [0., 0., 1., 0., 0.],
        [0., 0., 0., 1., 0.],
        [0., 0., 0., 0., 1.],
        [1., 0., 0., 0., 0.]])

# 3-dimensional (batched) input
>>> s_3d = paddle.to_tensor(np.random.rand(3, 5, 5))
>>> n1 = n2 = paddle.to_tensor([3, 4, 5])
>>> x = pygm.hungarian(s_3d, n1, n2)
>>> x
Tensor(shape=[3, 5, 5], dtype=float64, place=Place(cpu), stop_gradient=True,
       [[[0., 0., 1., 0., 0.],
         [0., 1., 0., 0., 0.],
         [1., 0., 0., 0., 0.],
         [0., 0., 0., 0., 0.],
         [0., 0., 0., 0., 0.]]])

```

(continues on next page)

(continued from previous page)

```

        [0., 0., 0., 0., 0.]],

        [[1., 0., 0., 0., 0.],
         [0., 1., 0., 0., 0.],
         [0., 0., 1., 0., 0.],
         [0., 0., 0., 1., 0.],
         [0., 0., 0., 0., 0.]],

        [[0., 0., 1., 0., 0.],
         [1., 0., 0., 0., 0.],
         [0., 0., 0., 0., 1.],
         [0., 1., 0., 0., 0.],
         [0., 0., 0., 1., 0.]])

# allow matching to void nodes by setting unmatched1 and unmatched2
>>> s_2d = paddle.to_tensor(np.random.randn(5, 5))
>>> s_2d
Tensor(shape=[5, 5], dtype=float64, place=Place(cpu), stop_gradient=True,
       [[-1.16514984,  0.90082649,  0.46566244, -1.53624369,  1.48825219],
        [ 1.89588918,  1.17877957, -0.17992484, -1.07075262,  1.05445173],
        [-0.40317695,  1.22244507,  0.20827498,  0.97663904,  0.35636640],
        [ 0.70657317,  0.01050002,  1.78587049,  0.12691209,  0.40198936],
        [ 1.88315070, -1.34775906, -1.27048500,  0.96939671, -1.17312341]])
>>> unmatched1 = paddle.to_tensor(np.random.randn(5))
>>> unmatched1
Tensor(shape=[5], dtype=float64, place=Place(cpu), stop_gradient=True,
       [ 1.94362119, -0.41361898, -0.74745481,  1.92294203,  1.48051479])
>>> unmatched2 = paddle.to_tensor(np.random.randn(5))
>>> unmatched2
Tensor(shape=[5], dtype=float64, place=Place(cpu), stop_gradient=True,
       [ 1.86755896,  0.90604466, -0.86122569,  1.91006495, -0.26800337])
>>> x = pygm.hungarian(s_2d, unmatched1=unmatched1, unmatched2=unmatched2)
>>> x
Tensor(shape=[5, 5], dtype=float64, place=Place(cpu), stop_gradient=True,
       [[0., 0., 0., 0., 0.],
        [0., 0., 0., 0., 1.],
        [0., 0., 1., 0., 0.],
        [0., 0., 0., 0., 0.],
        [0., 0., 0., 0., 0.]])

```

### Jittor Example

```

>>> import jittor as jt
>>> import pygmtools as pygm
>>> pygm.BACKEND = 'jittor'
>>> np.random.seed(0)

# 2-dimensional (non-batched) input
>>> s_2d = pygm.utils.from_numpy(np.random.rand(5, 5))

```

(continues on next page)

(continued from previous page)

```

>>> s_2d
jt.Var([[0.5488135  0.71518934 0.60276335 0.5448832  0.4236548 ]
        [0.6458941  0.4375872  0.891773   0.96366274 0.3834415 ]
        [0.79172504 0.5288949  0.56804454 0.92559665 0.07103606]
        [0.0871293  0.0202184  0.83261985 0.77815676 0.87001216]
        [0.9786183  0.7991586  0.46147937 0.7805292  0.11827443]], dtype=float32)
>>> x = pygm.hungarian(s_2d)
>>> x
jt.Var([[0. 1. 0. 0. 0.]
        [0. 0. 1. 0. 0.]
        [0. 0. 0. 1. 0.]
        [0. 0. 0. 0. 1.]
        [1. 0. 0. 0. 0.]], dtype=float32)

# 3-dimensional (batched) input
>>> s_3d = pygm.utils.from_numpy(np.random.rand(3, 5, 5))
>>> n1 = n2 = jt.Var([3, 4, 5])
>>> x = pygm.hungarian(s_3d, n1, n2)
>>> x
jt.Var([[[[0. 0. 1. 0. 0.]
           [0. 1. 0. 0. 0.]
           [1. 0. 0. 0. 0.]
           [0. 0. 0. 0. 0.]
           [0. 0. 0. 0. 0.]]
          [[1. 0. 0. 0. 0.]
           [0. 1. 0. 0. 0.]
           [0. 0. 1. 0. 0.]
           [0. 0. 0. 1. 0.]
           [0. 0. 0. 0. 0.]]
          [[0. 0. 1. 0. 0.]
           [1. 0. 0. 0. 0.]
           [0. 0. 0. 0. 1.]
           [0. 1. 0. 0. 0.]
           [0. 0. 0. 1. 0.]]]], dtype=float32)

# allow matching to void nodes by setting unmatched1 and unmatched2
>>> s_2d = pygm.utils.from_numpy(np.random.randn(5, 5))
>>> s_2d
jt.Var([[-1.1651498  0.9008265  0.46566245 -1.5362437  1.4882522 ]
        [ 1.8958892  1.1787796 -0.17992483 -1.0707526  1.0544517 ]
        [-0.40317693  1.222445  0.20827498  0.97663903  0.3563664 ]
        [ 0.7065732  0.01050002  1.7858706  0.12691209  0.40198937]
        [ 1.8831507 -1.347759 -1.270485  0.9693967 -1.1731234 ]],
dtype=float32)
>>> unmatched1 = pygm.utils.from_numpy(np.random.randn(5))
>>> unmatched1
jt.Var([ 1.9436212 -0.41361898 -0.7474548  1.922942  1.4805148 ], dtype=float32)
>>> unmatched2 = pygm.utils.from_numpy(np.random.randn(5))
>>> unmatched2
jt.Var([ 1.867559  0.90604466 -0.86122566  1.9100649 -0.26800337], dtype=float32)

```

(continues on next page)

(continued from previous page)

```
>>> x = pygm.hungarian(s_2d, unmatched1=unmatched1, unmatched2=unmatched2)
>>> x
jt.Var([[0. 0. 0. 0. 0.]
        [0. 0. 0. 0. 1.]
        [0. 0. 1. 0. 0.]
        [0. 0. 0. 0. 0.]
        [0. 0. 0. 0. 0.]], dtype=float32)
```

**Note:** If you find this graph matching solver useful for your research, please cite:

```
@article{hungarian,
  title={Algorithms for the assignment and transportation problems},
  author={Munkres, James},
  journal={Journal of the society for industrial and applied mathematics},
  volume={5},
  number={1},
  pages={32--38},
  year={1957},
  publisher={SIAM}
}
```

### pygmtools.linear\_solvers.sinkhorn

`pygmtools.linear_solvers.sinkhorn(s, n1=None, n2=None, unmatched1=None, unmatched2=None, dummy_row: bool = False, max_iter: int = 10, tau: float = 1.0, batched_operation: bool = False, backend=None)`

Sinkhorn algorithm turns the input matrix into a doubly-stochastic matrix.

Sinkhorn algorithm firstly applies an `exp` function with temperature  $\tau$ :

$$S_{i,j} = \exp\left(\frac{S_{i,j}}{\tau}\right)$$

And then turns the matrix into doubly-stochastic matrix by iterative row- and column-wise normalization:

$$\begin{aligned} S &= S \oslash (\mathbf{1}_{n_2} \mathbf{1}_{n_2}^\top \cdot S) \\ S &= S \oslash (S \cdot \mathbf{1}_{n_2} \mathbf{1}_{n_2}^\top) \end{aligned}$$

where  $\oslash$  means element-wise division,  $\mathbf{1}_n$  means a column-vector with length  $n$  whose elements are all 1s.

#### Parameters

- **s** – ( $b \times n_1 \times n_2$ ) input 3d tensor. *b*: batch size. Non-batched input is also supported if **s** is of size ( $n_1 \times n_2$ )
- **n1** – (optional) (*b*) number of objects in dim1
- **n2** – (optional) (*b*) number of objects in dim2
- **unmatched1** – (optional, new in 0.3.0) ( $b \times n_1$ ) the scores indicating the objects in dim1 is unmatched
- **unmatched2** – (optional, new in 0.3.0) ( $b \times n_1$ ) the scores indicating the objects in dim2 is unmatched

- **dummy\_row** – (default: False) whether to add dummy rows (rows whose elements are all 0) to pad the matrix to square matrix.
- **max\_iter** – (default: 10) maximum iterations
- **tau** – (default: 1) the hyper parameter  $\tau$  controlling the temperature
- **batched\_operation** – (default: False) apply batched\_operation for better efficiency (but may cause issues for back-propagation)
- **backend** – (default: `pygmtools.BACKEND` variable) the backend for computation.

#### Returns

$(b \times n_1 \times n_2)$  the computed doubly-stochastic matrix

You need not dive too deep into the math details if you are simply using Sinkhorn. However, you should be aware of one important hyper parameter. `tau` controls the distance between the predicted doubly-stochastic matrix, and the discrete permutation matrix computed by Hungarian algorithm (see [hungarian\(\)](#)). Given a small `tau`, Sinkhorn performs more closely to Hungarian, at the cost of slower convergence speed and reduced numerical stability.

---

**Note:** We support batched instances with different number of nodes, therefore `n1` and `n2` are required to specify the exact number of objects of each dimension in the batch. If not specified, we assume the batched matrices are not padded and all elements in `n1` are equal, all in `n2` are equal.

---



---

**Note:** The original Sinkhorn algorithm only works for square matrices. To handle cases where the graphs to be matched have different number of nodes, it is a common practice to add dummy rows to construct a square matrix. After the row and column normalizations, the padded rows are discarded.

---



---

**Note:** Setting `batched_operation=True` may be preferred when you are doing inference with this module and do not need the gradient. It is assumed that `row number <= column number`. If not, the input matrix will be transposed.

---

**Warning:** This function can work with or without the maximal inlier matching:

- **With maximal inlier matching** (the default mode). If `unmatch1=None` and `unmatch2=None`, the solver aims to match as many nodes as possible. The corresponding linear assignment problem is

$$\begin{aligned} \max_{\mathbf{X}} \quad & \text{tr}(\mathbf{X}^\top \mathbf{S}) \\ \text{s.t.} \quad & \mathbf{X} \in [0, 1]^{n_1 \times n_2}, \mathbf{X}\mathbf{1} = \mathbf{1}, \mathbf{X}^\top \mathbf{1} \leq \mathbf{1} \end{aligned}$$

where the constraint  $\mathbf{X}\mathbf{1} = \mathbf{1}$  urges the solver to match as many inlier nodes as possible.  $\mathbf{X}$  is relaxed to continuous value in Sinkhorn.

- **Without maximal inlier matching** (new in 0.3.0). If `unmatch1` and `unmatch2` are not None, the solver is allowed to match nodes to void nodes, and the corresponding scores for matching to void nodes are specified by `unmatch1` and `unmatch2`. The following (modified) linear assignment problem is considered:

$$\begin{aligned} \max_{\mathbf{X}} \quad & \text{tr}(\mathbf{X}^\top \mathbf{S}') \\ \text{s.t.} \quad & \mathbf{X} \in [0, 1]^{n_1+1 \times n_2+1}, \mathbf{X}_{[0:n_1,:]} \mathbf{1} = \mathbf{1}, \mathbf{X}_{[:,0:n_2]}^\top \mathbf{1} \leq \mathbf{1} \end{aligned}$$

where the last column and last row of  $\mathbf{S}'$  are `unmatch1` and `unmatch2`, respectively.

For example, if you want to solve the following problem (note that both constraints are  $\leq$ )

$$\begin{aligned} \max_{\mathbf{X}} \quad & \text{tr}(\mathbf{X}^\top \mathbf{S}) \\ \text{s.t.} \quad & \mathbf{X} \in [0, 1]^{n_1 \times n_2}, \mathbf{X}\mathbf{1} \leq \mathbf{1}, \mathbf{X}^\top \mathbf{1} \leq \mathbf{1} \end{aligned}$$

you can simply set `unmatch1` and `unmatch2` as zero vectors.

## Numpy Example

```
>>> import numpy as np
>>> import pygmtools as pygm
>>> pygm.BACKEND = 'numpy'
>>> np.random.seed(0)

# 2-dimensional (non-batched) input
>>> s_2d = np.random.rand(5, 5)
>>> s_2d
array([[0.5488135 , 0.71518937, 0.60276338, 0.54488318, 0.4236548 ],
       [0.64589411, 0.43758721, 0.891773 , 0.96366276, 0.38344152],
       [0.79172504, 0.52889492, 0.56804456, 0.92559664, 0.07103606],
       [0.0871293 , 0.0202184 , 0.83261985, 0.77815675, 0.87001215],
       [0.97861834, 0.79915856, 0.46147936, 0.78052918, 0.11827443]])
>>> x = pygm.sinkhorn(s_2d)
>>> x
array([[0.18880224, 0.24990915, 0.19202217, 0.16034278, 0.20892366],
       [0.18945066, 0.17240445, 0.23345011, 0.22194762, 0.18274716],
       [0.23713583, 0.204348 , 0.18271243, 0.23114583, 0.1446579 ],
       [0.11731039, 0.1229692 , 0.23823909, 0.19961588, 0.32186549],
       [0.26730088, 0.2503692 , 0.15357619, 0.18694789, 0.1418058 ]])

# 3-dimensional (batched) input
>>> s_3d = np.random.rand(3, 5, 5)
>>> x = pygm.sinkhorn(s_3d)
>>> print('row_sum:', x.sum(2))
row_sum: [[1. 1. 1. 1. 1. ]
 [0.99999998 1.00000002 0.99999999 1.00000003 0.99999999]
 [1. 1. 1. 1. 1. ]]
>>> print('col_sum:', x.sum(1))
col_sum: [[1. 1. 1. 1. 1.]
 [1. 1. 1. 1. 1.]
 [1. 1. 1. 1. 1.]]

# If the 3-d tensor are with different number of nodes
>>> n1 = np.array([3, 4, 5])
>>> n2 = np.array([3, 4, 5])
>>> x = pygm.sinkhorn(s_3d, n1, n2)
>>> x[0] # non-zero size: 3x3
array([[0.36665934, 0.21498158, 0.41835906, 0. , 0. ],
       [0.27603621, 0.44270207, 0.28126175, 0. , 0. ],
       [0.35730445, 0.34231636, 0.3003792 , 0. , 0. ]],
```

(continues on next page)

(continued from previous page)

```

    [0.          , 0.          , 0.          , 0.          , 0.          ],
    [0.          , 0.          , 0.          , 0.          , 0.          ]])
>>> x[1] # non-zero size: 4x4
array([[0.28847831, 0.20583051, 0.34242091, 0.16327021, 0.          ],
       [0.22656752, 0.30153021, 0.19407969, 0.27782262, 0.          ],
       [0.25346378, 0.19649853, 0.32565049, 0.22438715, 0.          ],
       [0.23149039, 0.29614075, 0.13784891, 0.33452002, 0.          ],
       [0.          , 0.          , 0.          , 0.          , 0.          ]])
>>> x[2] # non-zero size: 5x5
array([[0.20147352, 0.19541986, 0.24942798, 0.17346397, 0.18021467],
       [0.21050732, 0.17620948, 0.18645469, 0.20384684, 0.22298167],
       [0.18319623, 0.18024007, 0.17619871, 0.1664133 , 0.29395169],
       [0.20754376, 0.2236443 , 0.19658101, 0.20570847, 0.16652246],
       [0.19727917, 0.22448629, 0.19133762, 0.25056742, 0.13632951]])

# non-squared input
>>> s_non_square = np.random.rand(4, 5)
>>> x = pygm.sinkhorn(s_non_square, dummy_row=True) # set dummy_row=True for non-
↳ squared cases
>>> print('row_sum:', x.sum(1), 'col_sum:', x.sum(0))
row_sum: [1. 1. 1. 1.] col_sum: [0.78239609 0.80485526 0.80165627 0.80004254 0.
↳ 81104984]

# allow matching to void nodes by setting unmatched1 and unmatched2
>>> s_2d = np.random.randn(5, 5)
>>> s_2d
array([[ 0.01050002,  1.78587049,  0.12691209,  0.40198936,  1.8831507 ],
       [-1.34775906, -1.270485 ,  0.96939671, -1.17312341,  1.94362119],
       [-0.41361898, -0.74745481,  1.92294203,  1.48051479,  1.86755896],
       [ 0.90604466, -0.86122569,  1.91006495, -0.26800337,  0.8024564 ],
       [ 0.94725197, -0.15501009,  0.61407937,  0.92220667,  0.37642553]])
>>> unmatched1 = np.random.randn(5)
>>> unmatched1
array([-1.09940079,  0.29823817,  1.3263859 , -0.69456786, -0.14963454])
>>> unmatched2 = np.random.randn(5)
>>> unmatched2
array([-0.43515355,  1.84926373,  0.67229476,  0.40746184, -0.76991607])
>>> x = pygm.sinkhorn(s_2d, unmatched1=unmatched1, unmatched2=unmatched2, max_iter=40)
>>> x
array([[0.12434101, 0.23913991, 0.05663597, 0.13943479, 0.31811425],
       [0.03084473, 0.01085787, 0.12689067, 0.02784578, 0.3260589 ],
       [0.03192548, 0.00745004, 0.13391025, 0.16087345, 0.12289304],
       [0.29820536, 0.01659601, 0.32997174, 0.06988242, 0.10573396],
       [0.29787774, 0.0322356 , 0.08654936, 0.22023996, 0.06619393]])
>>> print('row_sum:', x.sum(1), 'col_sum:', x.sum(0))
row_sum: [0.87766593 0.52249794 0.45705226 0.82038949 0.70309659] col_sum: [0.
↳ 78319431 0.30627943 0.733958 0.61827641 0.93899407]

```



## Pytorch Example

```

>>> import torch
>>> import pygmtools as pygm
>>> pygm.BACKEND = 'pytorch'
>>> np.random.seed(0)

# 2-dimensional (non-batched) input
>>> s_2d = torch.from_numpy(np.random.rand(5, 5))
>>> s_2d
tensor([[0.5488, 0.7152, 0.6028, 0.5449, 0.4237],
        [0.6459, 0.4376, 0.8918, 0.9637, 0.3834],
        [0.7917, 0.5289, 0.5680, 0.9256, 0.0710],
        [0.0871, 0.0202, 0.8326, 0.7782, 0.8700],
        [0.9786, 0.7992, 0.4615, 0.7805, 0.1183]], dtype=torch.float64)
>>> x = pygm.sinkhorn(s_2d)
>>> x
tensor([[0.1888, 0.2499, 0.1920, 0.1603, 0.2089],
        [0.1895, 0.1724, 0.2335, 0.2219, 0.1827],
        [0.2371, 0.2043, 0.1827, 0.2311, 0.1447],
        [0.1173, 0.1230, 0.2382, 0.1996, 0.3219],
        [0.2673, 0.2504, 0.1536, 0.1869, 0.1418]], dtype=torch.float64)
>>> print('row_sum:', x.sum(1), 'col_sum:', x.sum(0))
row_sum: tensor([1.0000, 1.0000, 1.0000, 1.0000, 1.0000], dtype=torch.float64)
col_sum: tensor([1.0000, 1.0000, 1.0000, 1.0000, 1.0000], dtype=torch.float64)

# 3-dimensional (batched) input
>>> s_3d = torch.from_numpy(np.random.rand(3, 5, 5))
>>> x = pygm.sinkhorn(s_3d)
>>> print('row_sum:', x.sum(2))
row_sum: tensor([[1.0000, 1.0000, 1.0000, 1.0000, 1.0000],
                 [1.0000, 1.0000, 1.0000, 1.0000, 1.0000],
                 [1.0000, 1.0000, 1.0000, 1.0000, 1.0000]], dtype=torch.float64)
>>> print('col_sum:', x.sum(1))
col_sum: tensor([[1.0000, 1.0000, 1.0000, 1.0000, 1.0000],
                 [1.0000, 1.0000, 1.0000, 1.0000, 1.0000],
                 [1.0000, 1.0000, 1.0000, 1.0000, 1.0000]], dtype=torch.float64)

# If the 3-d tensor are with different number of nodes
>>> n1 = torch.tensor([3, 4, 5])
>>> n2 = torch.tensor([3, 4, 5])
>>> x = pygm.sinkhorn(s_3d, n1, n2)
>>> x[0] # non-zero size: 3x3
tensor([[0.3667, 0.2150, 0.4184, 0.0000, 0.0000],
        [0.2760, 0.4427, 0.2813, 0.0000, 0.0000],
        [0.3573, 0.3423, 0.3004, 0.0000, 0.0000],
        [0.0000, 0.0000, 0.0000, 0.0000, 0.0000],
        [0.0000, 0.0000, 0.0000, 0.0000, 0.0000]], dtype=torch.float64)
>>> x[1] # non-zero size: 4x4
tensor([[0.2885, 0.2058, 0.3424, 0.1633, 0.0000],
        [0.2266, 0.3015, 0.1941, 0.2778, 0.0000],
        [0.2535, 0.1965, 0.3257, 0.2244, 0.0000],
        [0.2315, 0.2961, 0.1378, 0.3345, 0.0000],

```

(continues on next page)

(continued from previous page)

```

        [0.0000, 0.0000, 0.0000, 0.0000, 0.0000]], dtype=torch.float64)
>>> x[2] # non-zero size: 5x5
tensor([[0.2015, 0.1954, 0.2494, 0.1735, 0.1802],
        [0.2105, 0.1762, 0.1865, 0.2038, 0.2230],
        [0.1832, 0.1802, 0.1762, 0.1664, 0.2940],
        [0.2075, 0.2236, 0.1966, 0.2057, 0.1665],
        [0.1973, 0.2245, 0.1913, 0.2506, 0.1363]], dtype=torch.float64)

# non-squared input
>>> s_non_square = torch.from_numpy(np.random.rand(4, 5))
>>> x = pygm.sinkhorn(s_non_square, dummy_row=True) # set dummy_row=True for non-
→squared cases
>>> print('row_sum:', x.sum(1), 'col_sum:', x.sum(0))
row_sum: tensor([1.0000, 1.0000, 1.0000, 1.0000], dtype=torch.float64) col_sum:
→tensor([0.7824, 0.8049, 0.8017, 0.8000, 0.8110], dtype=torch.float64)

# allow matching to void nodes by setting unmatched1 and unmatched2
>>> s_2d = torch.from_numpy(np.random.randn(5, 5))
>>> s_2d
tensor([[ 0.0105,  1.7859,  0.1269,  0.4020,  1.8832],
        [-1.3478, -1.2705,  0.9694, -1.1731,  1.9436],
        [-0.4136, -0.7475,  1.9229,  1.4805,  1.8676],
        [ 0.9060, -0.8612,  1.9101, -0.2680,  0.8025],
        [ 0.9473, -0.1550,  0.6141,  0.9222,  0.3764]], dtype=torch.float64)
>>> unmatched1 = torch.from_numpy(np.random.randn(5))
>>> unmatched1
tensor([-1.0994,  0.2982,  1.3264, -0.6946, -0.1496], dtype=torch.float64)
>>> unmatched2 = torch.from_numpy(np.random.randn(5))
>>> unmatched2
tensor([-0.4352,  1.8493,  0.6723,  0.4075, -0.7699], dtype=torch.float64)
>>> x = pygm.sinkhorn(s_2d, unmatched1=unmatched1, unmatched2=unmatched2, max_iter=40)
>>> x
tensor([[0.1243, 0.2391, 0.0566, 0.1394, 0.3181],
        [0.0308, 0.0109, 0.1269, 0.0278, 0.3261],
        [0.0319, 0.0075, 0.1339, 0.1609, 0.1229],
        [0.2982, 0.0166, 0.3300, 0.0699, 0.1057],
        [0.2979, 0.0322, 0.0865, 0.2202, 0.0662]], dtype=torch.float64)
>>> print('row_sum:', x.sum(1), 'col_sum:', x.sum(0))
row_sum: tensor([0.8777, 0.5225, 0.4571, 0.8204, 0.7031], dtype=torch.float64) col_
→sum: tensor([0.7832, 0.3063, 0.7340, 0.6183, 0.9390], dtype=torch.float64)

```

## Paddle Example

```

>>> import paddle
>>> import pygmtools as pygm
>>> pygm.BACKEND = 'paddle'
>>> np.random.seed(0)

# 2-dimensional (non-batched) input
>>> s_2d = paddle.to_tensor(np.random.rand(5, 5))

```

(continues on next page)

(continued from previous page)

```

>>> s_2d
Tensor(shape=[5, 5], dtype=float64, place=Place(cpu), stop_gradient=True,
      [[0.54881350, 0.71518937, 0.60276338, 0.54488318, 0.42365480],
       [0.64589411, 0.43758721, 0.89177300, 0.96366276, 0.38344152],
       [0.79172504, 0.52889492, 0.56804456, 0.92559664, 0.07103606],
       [0.08712930, 0.02021840, 0.83261985, 0.77815675, 0.87001215],
       [0.97861834, 0.79915856, 0.46147936, 0.78052918, 0.11827443]])
>>> x = pygm.sinkhorn(s_2d)
>>> x
Tensor(shape=[5, 5], dtype=float64, place=Place(cpu), stop_gradient=True,
      [[0.18880224, 0.24990915, 0.19202217, 0.16034278, 0.20892366],
       [0.18945066, 0.17240445, 0.23345011, 0.22194762, 0.18274716],
       [0.23713583, 0.20434800, 0.18271243, 0.23114583, 0.14465790],
       [0.11731039, 0.12296920, 0.23823909, 0.19961588, 0.32186549],
       [0.26730088, 0.25036920, 0.15357619, 0.18694789, 0.14180580]])
>>> print('row_sum:', x.sum(1), 'col_sum:', x.sum(0))
row_sum: Tensor(shape=[5], dtype=float64, place=Place(cpu), stop_gradient=True,
      [1.00000000, 1.00000001, 0.99999998, 1.00000005, 0.99999997])
col_sum: Tensor(shape=[5], dtype=float64, place=Place(cpu), stop_gradient=True,
      [1.00000000, 1.00000000, 1.00000000, 1.          , 1.00000000])

# 3-dimensional (batched) input
>>> s_3d = paddle.to_tensor(np.random.rand(3, 5, 5))
>>> x = pygm.sinkhorn(s_3d)
>>> print('row_sum:', x.sum(2))
row_sum: Tensor(shape=[3, 5], dtype=float64, place=Place(cpu), stop_gradient=True,
      [[1.00000000, 1.00000000, 1.00000000, 1.00000000, 1.00000000],
       [0.99999998, 1.00000002, 0.99999999, 1.00000003, 0.99999999],
       [1.00000000, 1.00000000, 1.00000000, 1.00000000, 1.00000000]])
>>> print('col_sum:', x.sum(1))
col_sum: Tensor(shape=[3, 5], dtype=float64, place=Place(cpu), stop_gradient=True,
      [[1.00000000, 1.          , 1.          , 1.00000000, 1.00000000],
       [1.          , 1.          , 1.          , 1.          , 1.          ],
       [1.          , 1.          , 1.          , 1.          , 1.00000000]])

# If the 3-d tensor are with different number of nodes
>>> n1 = paddle.to_tensor([3, 4, 5])
>>> n2 = paddle.to_tensor([3, 4, 5])
>>> x = pygm.sinkhorn(s_3d, n1, n2)
>>> x[0] # non-zero size: 3x3
Tensor(shape=[5, 5], dtype=float64, place=Place(cpu), stop_gradient=True,
      [[0.36665934, 0.21498158, 0.41835906, 0.00000000, 0.00000000],
       [0.27603621, 0.44270207, 0.28126175, 0.00000000, 0.00000000],
       [0.35730445, 0.34231636, 0.30037920, 0.00000000, 0.00000000],
       [0.00000000, 0.00000000, 0.00000000, 0.00000000, 0.00000000],
       [0.00000000, 0.00000000, 0.00000000, 0.00000000, 0.00000000]])
>>> x[1] # non-zero size: 4x4
Tensor(shape=[5, 5], dtype=float64, place=Place(cpu), stop_gradient=True,
      [[0.28847831, 0.20583051, 0.34242091, 0.16327021, 0.00000000],
       [0.22656752, 0.30153021, 0.19407969, 0.27782262, 0.00000000],
       [0.25346378, 0.19649853, 0.32565049, 0.22438715, 0.00000000],
       [0.23149039, 0.29614075, 0.13784891, 0.33452002, 0.00000000],

```

(continues on next page)

(continued from previous page)

```

[0.00000000, 0.00000000, 0.00000000, 0.00000000, 0.00000000]])
>>> x[2] # non-zero size: 5x5
Tensor(shape=[5, 5], dtype=float64, place=Place(cpu), stop_gradient=True,
[[0.20147352, 0.19541986, 0.24942798, 0.17346397, 0.18021467],
 [0.21050732, 0.17620948, 0.18645469, 0.20384684, 0.22298167],
 [0.18319623, 0.18024007, 0.17619871, 0.16641330, 0.29395169],
 [0.20754376, 0.22364430, 0.19658101, 0.20570847, 0.16652246],
 [0.19727917, 0.22448629, 0.19133762, 0.25056742, 0.13632951]])

# non-squared input
>>> s_non_square = paddle.to_tensor(np.random.rand(4, 5))
>>> x = pygm.sinkhorn(s_non_square, dummy_row=True) # set dummy_row=True for non-
→squared cases
>>> print('row_sum:', x.sum(1), 'col_sum:', x.sum(0))
row_sum: Tensor(shape=[4], dtype=float64, place=Place(cpu), stop_gradient=True,
[1.00000000, 1.00000000, 1.00000000, 1.00000000])
col_sum: Tensor(shape=[5], dtype=float64, place=Place(cpu), stop_gradient=True,
[0.78239609, 0.80485526, 0.80165627, 0.80004254, 0.81104984])

# allow matching to void nodes by setting unmatched1 and unmatched2
>>> s_2d = paddle.to_tensor(np.random.randn(5, 5))
>>> s_2d
Tensor(shape=[5, 5], dtype=float64, place=Place(cpu), stop_gradient=True,
[[ 0.01050002,  1.78587049,  0.12691209,  0.40198936,  1.88315070],
 [-1.34775906, -1.27048500,  0.96939671, -1.17312341,  1.94362119],
 [-0.41361898, -0.74745481,  1.92294203,  1.48051479,  1.86755896],
 [ 0.90604466, -0.86122569,  1.91006495, -0.26800337,  0.80245640],
 [ 0.94725197, -0.15501009,  0.61407937,  0.92220667,  0.37642553]])
>>> unmatched1 = paddle.to_tensor(np.random.randn(5))
>>> unmatched1
Tensor(shape=[5], dtype=float64, place=Place(cpu), stop_gradient=True,
[-1.09940079,  0.29823817,  1.32638590, -0.69456786, -0.14963454])
>>> unmatched2 = paddle.to_tensor(np.random.randn(5))
>>> unmatched2
Tensor(shape=[5], dtype=float64, place=Place(cpu), stop_gradient=True,
[-0.43515355,  1.84926373,  0.67229476,  0.40746184, -0.76991607])
>>> x = pygm.sinkhorn(s_2d, unmatched1=unmatched1, unmatched2=unmatched2, max_iter=40)
>>> x
Tensor(shape=[5, 5], dtype=float64, place=Place(cpu), stop_gradient=True,
[[0.12434101, 0.23913991, 0.05663597, 0.13943479, 0.31811425],
 [0.03084473, 0.01085787, 0.12689067, 0.02784578, 0.32605890],
 [0.03192548, 0.00745004, 0.13391025, 0.16087345, 0.12289304],
 [0.29820536, 0.01659601, 0.32997174, 0.06988242, 0.10573396],
 [0.29787774, 0.03223560, 0.08654936, 0.22023996, 0.06619393]])
>>> print('row_sum:', x.sum(1), 'col_sum:', x.sum(0))
row_sum: Tensor(shape=[5], dtype=float64, place=Place(cpu), stop_gradient=True,
[0.87766593, 0.52249794, 0.45705226, 0.82038949, 0.70309659])
col_sum: Tensor(shape=[5], dtype=float64, place=Place(cpu), stop_gradient=True,
[0.78319431, 0.30627943, 0.73395800, 0.61827641, 0.93899407])

```

## Jittor Example

```

>>> import jittor as jt
>>> import pygmtools as pygm
>>> pygm.BACKEND = 'jittor'
>>> np.random.seed(0)

# 2-dimensional (non-batched) input
>>> s_2d = pygm.utils.from_numpy(np.random.rand(5, 5))
>>> s_2d
jt.Var([[0.5488135  0.71518934 0.60276335 0.5448832  0.4236548 ]
        [0.6458941  0.4375872  0.891773   0.96366274 0.3834415 ]
        [0.79172504 0.5288949  0.56804454 0.92559665 0.07103606]
        [0.0871293  0.0202184  0.83261985 0.77815676 0.87001216]
        [0.9786183  0.7991586  0.46147937 0.7805292  0.11827443]], dtype=float32)
>>> x = pygm.sinkhorn(s_2d)
>>> x
jt.Var([[0.18880227 0.24990915 0.19202219 0.1603428  0.20892365]
        [0.18945065 0.17240447 0.23345011 0.22194763 0.18274714]
        [0.23713583 0.20434798 0.18271242 0.23114584 0.1446579 ]
        [0.11731039 0.1229692  0.23823905 0.19961584 0.3218654 ]
        [0.2673009  0.2503692  0.1535762  0.1869479  0.1418058 ]], dtype=float32)
>>> print('row_sum:', x.sum(1), 'col_sum:', x.sum(0))
row_sum: jt.Var([1.00000001 0.99999994 1.          0.9999999  1.          ],
↳dtype=float32)
col_sum: jt.Var([1.          1.          1.          1.          0.9999999],
↳dtype=float32)

# 3-dimensional (batched) input
>>> s_3d = pygm.utils.from_numpy(np.random.rand(3, 5, 5))
>>> x = pygm.sinkhorn(s_3d)
>>> print('row_sum:', x.sum(2))
row_sum: jt.Var([[1.00000001 0.9999999 0.99999994 1.          0.99999994]
                 [1.          1.00000001 1.          0.99999994 1.          ]
                 [1.          1.          0.99999994 0.99999994 1.          ]],
↳dtype=float32)
>>> print('col_sum:', x.sum(1))
col_sum: jt.Var([[1.          0.99999994 1.          0.99999994 1.          ]
                 [1.          1.          1.00000001 1.          0.9999999 ]
                 [0.99999994 1.00000001 0.9999999  1.          1.          ]],
↳dtype=float32)

# If the 3-d tensor are with different number of nodes
>>> n1 = jt.Var([3, 4, 5])
>>> n2 = jt.Var([3, 4, 5])
>>> x = pygm.sinkhorn(s_3d, n1, n2)
>>> x[0] # non-zero size: 3x3
jt.Var([[0.3666593  0.21498157 0.41835907 0.          0.          ]
        [0.2760362  0.44270205 0.28126174 0.          0.          ]
        [0.35730445 0.34231633 0.30037922 0.          0.          ]
        [0.          0.          0.          0.          0.          ]
        [0.          0.          0.          0.          0.          ]], dtype=float32)
>>> x[1] # non-zero size: 4x4

```

(continues on next page)

(continued from previous page)

```

jt.Var([[0.28847834 0.20583051 0.34242094 0.16327024 0.
        [0.22656752 0.3015302 0.1940797 0.2778226 0.
        [0.2534638 0.1964985 0.32565048 0.22438715 0.
        [0.23149039 0.2961407 0.13784888 0.33452 0.
        [0. 0. 0. 0. 0. ]], dtype=float32)
>>> x[2] # non-zero size: 5x5
jt.Var([[0.20147353 0.19541988 0.24942797 0.17346397 0.18021466]
        [0.21050733 0.1762095 0.18645467 0.20384683 0.22298168]
        [0.18319622 0.18024008 0.17619869 0.16641329 0.2939517 ]
        [0.20754376 0.2236443 0.19658099 0.20570846 0.16652244]
        [0.19727917 0.2244863 0.1913376 0.25056744 0.13632952]], dtype=float32)

# non-squared input
>>> s_non_square = pygm.utils.from_numpy(np.random.rand(4, 5))
>>> x = pygm.sinkhorn(s_non_square, dummy_row=True) # set dummy_row=True for non-
↳ squared cases
>>> print('row_sum:', x.sum(1), 'col_sum:', x.sum(0))
row_sum: jt.Var([1. 1. 1. 0.99999994], dtype=float32)
col_sum: jt.Var([0.78239614 0.8048552 0.80165625 0.8000425 0.8110498],
↳ dtype=float32)

# allow matching to void nodes by setting unmatched1 and unmatched2
>>> s_2d = pygm.utils.from_numpy(np.random.randn(5, 5))
>>> s_2d
jt.Var([[ 0.01050002 1.7858706 0.12691209 0.40198937 1.8831507 ]
        [-1.347759 -1.270485 0.9693967 -1.1731234 1.9436212 ]
        [-0.41361898 -0.7474548 1.922942 1.4805148 1.867559 ]
        [ 0.90604466 -0.86122566 1.9100649 -0.26800337 0.8024564 ]
        [ 0.947252 -0.15501009 0.61407936 0.9222067 0.37642553]],
↳ dtype=float32)
>>> unmatched1 = pygm.utils.from_numpy(np.random.randn(5))
>>> unmatched1
jt.Var([-1.0994008 0.2982382 1.3263859 -0.69456786 -0.14963454], dtype=float32)
>>> unmatched2 = pygm.utils.from_numpy(np.random.randn(5))
>>> unmatched2
jt.Var([-0.43515354 1.8492638 0.67229474 0.40746182 -0.76991606], dtype=float32)
>>> x = pygm.sinkhorn(s_2d, unmatched1=unmatched1, unmatched2=unmatched2, max_iter=40)
>>> x
jt.Var([[0.12434097 0.23913991 0.05663597 0.13943481 0.3181142 ]
        [0.03084473 0.01085788 0.12689069 0.02784578 0.32605886]
        [0.03192548 0.00745005 0.13391027 0.16087341 0.12289305]
        [0.2982054 0.01659602 0.32997176 0.06988242 0.10573398]
        [0.29787776 0.0322356 0.08654935 0.22023994 0.06619392]], dtype=float32)
>>> print('row_sum:', x.sum(1), 'col_sum:', x.sum(0))
row_sum: jt.Var([0.8776659 0.52249795 0.45705223 0.8203896 0.70309657],
↳ dtype=float32) col_sum: jt.Var([0.7831943 0.30627945 0.73395807 0.61827636 0.
↳ 938994 ], dtype=float32)

```

**Note:** If you find this graph matching solver useful for your research, please cite:

@article{sinkhorn,

(continues on next page)

(continued from previous page)

```

title={Concerning nonnegative matrices and doubly stochastic matrices},
author={Sinkhorn, Richard and Knopp, Paul},
journal={Pacific Journal of Mathematics},
volume={21},
number={2},
pages={343--348},
year={1967},
publisher={Mathematical Sciences Publishers}
}

```

## 9.4.2 pygmtools.classic\_solvers

Classic (learning-free) **two-graph matching** solvers. These two-graph matching solvers are recommended to solve matching problems with two explicit graphs, or problems formulated as Quadratic Assignment Problem (QAP).

The two-graph matching problem considers both nodes and edges, formulated as a QAP:

$$\begin{aligned}
 & \max_{\mathbf{X}} \text{vec}(\mathbf{X})^\top \mathbf{K} \text{vec}(\mathbf{X}) \\
 & s.t. \quad \mathbf{X} \in \{0, 1\}^{n_1 \times n_2}, \mathbf{X}\mathbf{1} = \mathbf{1}, \mathbf{X}^\top \mathbf{1} \leq \mathbf{1}
 \end{aligned}$$

### Functions

<i>ipfp</i>	Integer Projected Fixed Point (IPFP) method for graph matching (QAP).
<i>rrwm</i>	Reweighted Random Walk Matching (RRWM) solver for graph matching (QAP).
<i>sm</i>	Spectral Graph Matching solver for graph matching (QAP).

### pygmtools.classic\_solvers.ipfp

`pygmtools.classic_solvers.ipfp(K, n1=None, n2=None, n1max=None, n2max=None, x0=None, max_iter: int = 50, backend=None)`

Integer Projected Fixed Point (IPFP) method for graph matching (QAP).

#### Parameters

- **K** – ( $b \times n_1 n_2 \times n_1 n_2$ ) the input affinity matrix,  $b$ : batch size.
- **n1** – ( $b$ ) number of nodes in graph1 (optional if **n1max** is given, and all  $n1=n1max$ ).
- **n2** – ( $b$ ) number of nodes in graph2 (optional if **n2max** is given, and all  $n2=n2max$ ).
- **n1max** – ( $b$ ) max number of nodes in graph1 (optional if **n1** is given, and  $n1max=\max(n1)$ ).
- **n2max** – ( $b$ ) max number of nodes in graph2 (optional if **n2** is given, and  $n2max=\max(n2)$ ).
- **x0** – ( $b \times n_1 \times n_2$ ) an initial matching solution for warm-start. If not given, **x0** will filled with  $\frac{1}{n_1 n_2}$ .
- **max\_iter** – (default: 50) max number of iterations in IPFP. More iterations will be lead to more accurate result, at the cost of increased inference time.

- **backend** – (default: `pygmtools.BACKEND` variable) the backend for computation.

**Returns**

$(b \times n_1 \times n_2)$  the solved matching matrix

---

**Note:** Either `n1` or `n1max` should be specified because it cannot be inferred from the input tensor size. Same for `n2` or `n2max`.

---



---

**Note:** We support batched instances with different number of nodes, therefore `n1` and `n2` are required to specify the exact number of objects of each dimension in the batch. If not specified, we assume the batched matrices are not padded and all elements in `n1` are equal, all in `n2` are equal.

---



---

**Note:** This function also supports non-batched input, by ignoring all batch dimensions in the input tensors.

---



---

**Note:** This solver is non-differentiable. The output is a discrete matching matrix (i.e. permutation matrix).

---

**Numpy Example**

```
>>> import numpy as np
>>> import pygmtools as pygm
>>> pygm.BACKEND = 'numpy'
>>> np.random.seed(1)

# Generate a batch of isomorphic graphs
>>> batch_size = 10
>>> X_gt = np.zeros((batch_size, 4, 4))
>>> X_gt[:, np.arange(0, 4, dtype=np.int64), np.random.permutation(4)] = 1
>>> A1 = np.random.rand(batch_size, 4, 4)
>>> A2 = np.matmul(np.matmul(X_gt.transpose((0, 2, 1)), A1), X_gt)
>>> n1 = n2 = np.repeat([4], batch_size)

# Build affinity matrix
>>> conn1, edge1, ne1 = pygm.utils.dense_to_sparse(A1)
>>> conn2, edge2, ne2 = pygm.utils.dense_to_sparse(A2)
>>> import functools
>>> gaussian_aff = functools.partial(pygm.utils.gaussian_aff_fn, sigma=1.) # set_
↪affinity function
>>> K = pygm.utils.build_aff_mat(None, edge1, conn1, None, edge2, conn2, n1, None,
↪n2, None, edge_aff_fn=gaussian_aff)

# Solve by IPFP
>>> X = pygm.ipfp(K, n1, n2)
>>> X[0]
array([[0., 0., 0., 1.],
       [0., 0., 1., 0.],
       [1., 0., 0., 0.],
       [0., 1., 0., 0.]])
```

(continues on next page)



(continued from previous page)

```
# Accuracy
>>> (pygm.hungarian(X) * X_gt).sum() / X_gt.sum()
1.0
```

### Pytorch Example

```
>>> import torch
>>> import pygmtools as pygm
>>> pygm.BACKEND = 'pytorch'
>>> _ = torch.manual_seed(1)

# Generate a batch of isomorphic graphs
>>> batch_size = 10
>>> X_gt = torch.zeros(batch_size, 4, 4)
>>> X_gt[:, torch.arange(0, 4, dtype=torch.int64), torch.randperm(4)] = 1
>>> A1 = torch.rand(batch_size, 4, 4)
>>> A2 = torch.bmm(torch.bmm(X_gt.transpose(1, 2), A1), X_gt)
>>> n1 = torch.tensor([4] * batch_size)
>>> n2 = torch.tensor([4] * batch_size)

# Build affinity matrix
>>> conn1, edge1, ne1 = pygm.utils.dense_to_sparse(A1)
>>> conn2, edge2, ne2 = pygm.utils.dense_to_sparse(A2)
>>> import functools
>>> gaussian_aff = functools.partial(pygm.utils.gaussian_aff_fn, sigma=1.) # set_
↳affinity function
>>> K = pygm.utils.build_aff_mat(None, edge1, conn1, None, edge2, conn2, n1, None,
↳n2, None, edge_aff_fn=gaussian_aff)

# Solve by IPFP
>>> X = pygm.ipfp(K, n1, n2)
>>> X[0]
tensor([[0., 1., 0., 0.],
        [0., 0., 0., 1.],
        [0., 0., 1., 0.],
        [1., 0., 0., 0.]])

# Accuracy
>>> (pygm.hungarian(X) * X_gt).sum() / X_gt.sum()
tensor(1.)
```

## Paddle Example

```
>>> import paddle
>>> import pygmtools as pygm
>>> pygm.BACKEND = 'paddle'
>>> _ = paddle.seed(1)

# Generate a batch of isomorphic graphs
>>> batch_size = 10
>>> X_gt = paddle.zeros((batch_size, 4, 4))
>>> X_gt[:, paddle.arange(0, 4, dtype=paddle.int64), paddle.randperm(4)] = 1
>>> A1 = paddle.rand((batch_size, 4, 4))
>>> A2 = paddle.bmm(paddle.bmm(X_gt.transpose((0, 2, 1)), A1), X_gt)
>>> n1 = paddle.to_tensor([4] * batch_size)
>>> n2 = paddle.to_tensor([4] * batch_size)

# Build affinity matrix
>>> conn1, edge1, ne1 = pygm.utils.dense_to_sparse(A1)
>>> conn2, edge2, ne2 = pygm.utils.dense_to_sparse(A2)
>>> import functools
>>> gaussian_aff = functools.partial(pygm.utils.gaussian_aff_fn, sigma=1.) # set_
↪affinity function
>>> K = pygm.utils.build_aff_mat(None, edge1, conn1, None, edge2, conn2, n1, None,
↪n2, None, edge_aff_fn=gaussian_aff)

# Solve by IPFP
>>> X = pygm.ipfp(K, n1, n2)
>>> X[0]
Tensor(shape=[4, 4], dtype=float32, place=Place(cpu), stop_gradient=True,
      [[0., 1., 0., 0.],
       [0., 0., 0., 1.],
       [0., 0., 1., 0.],
       [1., 0., 0., 0.]])

# Accuracy
>>> (pygm.hungarian(X) * X_gt).sum() / X_gt.sum()
Tensor(shape=[1], dtype=float32, place=Place(cpu), stop_gradient=True, [1.]
```

## Jittor Example

```
>>> import jittor as jt
>>> import pygmtools as pygm
>>> pygm.BACKEND = 'jittor'
>>> _ = jt.seed(1)

# Generate a batch of isomorphic graphs
>>> batch_size = 10
>>> X_gt = jt.zeros((batch_size, 4, 4))
>>> X_gt[:, jt.arange(0, 4, dtype=jt.int64), jt.randperm(4)] = 1
>>> A1 = jt.rand(batch_size, 4, 4)
>>> A2 = jt.bmm(jt.bmm(X_gt.transpose(1, 2), A1), X_gt)
```

(continues on next page)

(continued from previous page)

```

>>> n1 = jt.Var([4] * batch_size)
>>> n2 = jt.Var([4] * batch_size)

# Build affinity matrix
>>> conn1, edge1, ne1 = pygm.utils.dense_to_sparse(A1)
>>> conn2, edge2, ne2 = pygm.utils.dense_to_sparse(A2)
>>> import functools
>>> gaussian_aff = functools.partial(pygm.utils.gaussian_aff_fn, sigma=1.) # set_
    ↳affinity function
>>> K = pygm.utils.build_aff_mat(None, edge1, conn1, None, edge2, conn2, n1, None,
    ↳n2, None, edge_aff_fn=gaussian_aff)

# Solve by IPFP
>>> X = pygm.ipfp(K, n1, n2)
>>> X[0]
jt.Var([[1. 0. 0. 0.]
        [0. 0. 1. 0.]
        [0. 0. 0. 1.]
        [0. 1. 0. 0.]], dtype=float32)

# Accuracy
>>> (pygm.hungarian(X) * X_gt).sum() / X_gt.sum()
jt.Var([1.], dtype=float32)

```

**Note:** If you find this graph matching solver useful in your research, please cite:

```

@article{ipfp,
  title={An integer projected fixed point method for graph matching and map_
    ↳inference},
  author={Leordeanu, Marius and Hebert, Martial and Sukthankar, Rahul},
  journal={Advances in neural information processing systems},
  volume={22},
  year={2009}
}

```

## pygmtools.classic\_solvers.rrwm

`pygmtools.classic_solvers.rrwm(K, n1=None, n2=None, n1max=None, n2max=None, x0=None, max_iter: int = 50, sk_iter: int = 20, alpha: float = 0.2, beta: float = 30, backend=None)`

Rewighted Random Walk Matching (RRWM) solver for graph matching (QAP). This algorithm is implemented by power iteration with Sinkhorn reweighted jumps.

The official matlab implementation is available at <https://cv.snu.ac.kr/research/~RRWM/>

### Parameters

- **K** – ( $b \times n_1 n_2 \times n_1 n_2$ ) the input affinity matrix,  $b$ : batch size.
- **n1** – ( $b$ ) number of nodes in graph1 (optional if  $n1max$  is given, and all  $n1=n1max$ ).
- **n2** – ( $b$ ) number of nodes in graph2 (optional if  $n2max$  is given, and all  $n2=n2max$ ).

- **n1max** – ( $b$ ) max number of nodes in graph1 (optional if  $n1$  is given, and  $n1max=\max(n1)$ ).
- **n2max** – ( $b$ ) max number of nodes in graph2 (optional if  $n2$  is given, and  $n2max=\max(n2)$ ).
- **x0** – ( $b \times n_1 \times n_2$ ) an initial matching solution for warm-start. If not given,  $x0$  will filled with  $\frac{1}{n_1 n_2}$ .
- **max\_iter** – (default: 50) max number of iterations (i.e. number of random walk steps) in RRWM. More iterations will be lead to more accurate result, at the cost of increased inference time.
- **sk\_iter** – (default: 20) max number of Sinkhorn iterations. More iterations will be lead to more accurate result, at the cost of increased inference time.
- **alpha** – (default: 0.2) the parameter controlling the importance of the reweighted jump.  $\alpha$  should lie between 0 and 1. If  $\alpha=0$ , it means no reweighted jump; if  $\alpha=1$ , the reweighted jump provides all information.
- **beta** – (default: 30) the temperature parameter of exponential function before the Sinkhorn operator.  $\beta$  should be larger than 0. A larger  $\beta$  means more confidence in the jump. A larger  $\beta$  will usually require a larger **sk\_iter**.
- **backend** – (default: `pygmtools.BACKEND` variable) the backend for computation.

**Returns**

( $b \times n_1 \times n_2$ ) the solved matching matrix

---

**Note:** Either  $n1$  or  $n1max$  should be specified because it cannot be inferred from the input tensor size. Same for  $n2$  or  $n2max$ .

---

---

**Note:** We support batched instances with different number of nodes, therefore  $n1$  and  $n2$  are required to specify the exact number of objects of each dimension in the batch. If not specified, we assume the batched matrices are not padded and all elements in  $n1$  are equal, all in  $n2$  are equal.

---

---

**Note:** This function also supports non-batched input, by ignoring all batch dimensions in the input tensors.

---

---

**Note:** This solver is differentiable and supports gradient back-propagation.

---

**Warning:** The solver's output is normalized with a sum of 1, which is in line with the original implementation. If a doubly- stochastic matrix is required, please call `sinkhorn()` after this. If a discrete permutation matrix is required, please call `hungarian()`. Note that the Hungarian algorithm will truncate the gradient and the Sinkhorn algorithm will not.

## Numpy Example

```
>>> import numpy as np
>>> import pygmtools as pygm
>>> pygm.BACKEND = 'numpy'
>>> np.random.seed(1)

# Generate a batch of isomorphic graphs
>>> batch_size = 10
>>> X_gt = np.zeros((batch_size, 4, 4))
>>> X_gt[:, np.arange(0, 4, dtype=np.int64), np.random.permutation(4)] = 1
>>> A1 = np.random.rand(batch_size, 4, 4)
>>> A2 = np.matmul(np.matmul(X_gt.transpose((0, 2, 1)), A1), X_gt)
>>> n1 = n2 = np.repeat([4], batch_size)

# Build affinity matrix
>>> conn1, edge1, ne1 = pygm.utils.dense_to_sparse(A1)
>>> conn2, edge2, ne2 = pygm.utils.dense_to_sparse(A2)
>>> import functools
>>> gaussian_aff = functools.partial(pygm.utils.gaussian_aff_fn, sigma=1.) # set
↪affinity function
>>> K = pygm.utils.build_aff_mat(None, edge1, conn1, None, edge2, conn2, n1, None,
↪n2, None, edge_aff_fn=gaussian_aff)

# Solve by RRWM. Note that X is normalized with a sum of 1
>>> X = pygm.rrwm(K, n1, n2, beta=100)
>>> X.sum(axis=(1, 2))
array([1., 1., 1., 1., 1., 1., 1., 1., 1., 1.])

# Accuracy
>>> (pygm.hungarian(X) * X_gt).sum() / X_gt.sum()
1.0
```

## Pytorch Example

```
>>> import torch
>>> import pygmtools as pygm
>>> pygm.BACKEND = 'pytorch'
>>> _ = torch.manual_seed(1)

# Generate a batch of isomorphic graphs
>>> batch_size = 10
>>> X_gt = torch.zeros(batch_size, 4, 4)
>>> X_gt[:, torch.arange(0, 4, dtype=torch.int64), torch.randperm(4)] = 1
>>> A1 = torch.rand(batch_size, 4, 4)
>>> A2 = torch.bmm(torch.bmm(X_gt.transpose(1, 2), A1), X_gt)
>>> n1 = n2 = torch.tensor([4] * batch_size)

# Build affinity matrix
>>> conn1, edge1, ne1 = pygm.utils.dense_to_sparse(A1)
>>> conn2, edge2, ne2 = pygm.utils.dense_to_sparse(A2)
```

(continues on next page)

(continued from previous page)

```

>>> import functools
>>> gaussian_aff = functools.partial(pygm.utils.gaussian_aff_fn, sigma=1.) # set_
↳affinity function
>>> K = pygm.utils.build_aff_mat(None, edge1, conn1, None, edge2, conn2, n1, None,
↳n2, None, edge_aff_fn=gaussian_aff)

# Solve by RRWM. Note that X is normalized with a sum of 1
>>> X = pygm.rrwm(K, n1, n2, beta=100)
>>> X.sum(dim=(1, 2))
tensor([1.0000, 1.0000, 1.0000, 1.0000, 1.0000, 1.0000, 1.0000, 1.0000, 1.0000,
        1.0000])

# Accuracy
>>> (pygm.hungarian(X) * X_gt).sum() / X_gt.sum()
tensor(1.)

# This solver supports gradient back-propagation
>>> K = K.requires_grad_(True)
>>> pygm.rrwm(K, n1, n2, beta=100).sum().backward()
>>> len(torch.nonzero(K.grad))
272

```

## Paddle Example

```

>>> import paddle
>>> import pygmtools as pygm
>>> pygm.BACKEND = 'paddle'
>>> _ = paddle.seed(1)

# Generate a batch of isomorphic graphs
>>> batch_size = 10
>>> X_gt = paddle.zeros((batch_size, 4, 4))
>>> X_gt[:, paddle.arange(0, 4, dtype=paddle.int64), paddle.randperm(4)] = 1
>>> A1 = paddle.rand((batch_size, 4, 4))
>>> A2 = paddle.bmm(paddle.bmm(X_gt.transpose((0, 2, 1)), A1), X_gt)
>>> n1 = n2 = paddle.to_tensor([4] * batch_size)

# Build affinity matrix
>>> conn1, edge1, ne1 = pygm.utils.dense_to_sparse(A1)
>>> conn2, edge2, ne2 = pygm.utils.dense_to_sparse(A2)
>>> import functools
>>> gaussian_aff = functools.partial(pygm.utils.gaussian_aff_fn, sigma=1.) # set_
↳affinity function
>>> K = pygm.utils.build_aff_mat(None, edge1, conn1, None, edge2, conn2, n1, None,
↳n2, None, edge_aff_fn=gaussian_aff)

# Solve by RRWM. Note that X is normalized with a sum of 1
>>> X = pygm.rrwm(K, n1, n2, beta=100)
>>> X.sum(axis=(1, 2))
Tensor(shape=[10], dtype=float32, place=Place(cpu), stop_gradient=True,

```

(continues on next page)

(continued from previous page)

```

[0.99999988, 0.99999988, 0.99999994, 0.99999994, 1.
 1.          , 1.          , 1.00000012, 1.00000012, 1.
                                     ])

# Accuracy
>>> (pygm.hungarian(X) * X_gt).sum() / X_gt.sum()
Tensor(shape=[1], dtype=float32, place=Place(cpu), stop_gradient=True, [1.])

# This solver supports gradient back-propagation
>>> K.stop_gradient = False
>>> pygm.rrwm(K, n1, n2, beta=100).sum().backward()
>>> len(paddle.nonzero(K.grad))
544

```

### Jittor Example

```

>>> import jittor as jt
>>> import pygmtools as pygm
>>> pygm.BACKEND = 'jittor'
>>> _ = jt.seed(1)

# Generate a batch of isomorphic graphs
>>> batch_size = 10
>>> X_gt = jt.zeros((batch_size, 4, 4))
>>> X_gt[:, jt.arange(0, 4, dtype=jt.int64), jt.randperm(4)] = 1
>>> A1 = jt.rand(batch_size, 4, 4)
>>> A2 = jt.bmm(jt.bmm(X_gt.transpose(1, 2), A1), X_gt)
>>> n1 = n2 = jt.Var([4] * batch_size)

# Build affinity matrix
>>> conn1, edge1, ne1 = pygm.utils.dense_to_sparse(A1)
>>> conn2, edge2, ne2 = pygm.utils.dense_to_sparse(A2)
>>> import functools
>>> gaussian_aff = functools.partial(pygm.utils.gaussian_aff_fn, sigma=1.) # set_
↳affinity function
>>> K = pygm.utils.build_aff_mat(None, edge1, conn1, None, edge2, conn2, n1, None,
↳n2, None, edge_aff_fn=gaussian_aff)

# Solve by RRWM. Note that X is normalized with a sum of 1
>>> X = pygm.rrwm(K, n1, n2, beta=100)
>>> X.sum(dims=(1, 2))
jt.Var([1.          1.0000001  1.          0.99999976 1.
 1.          1.          1.0000001  0.99999994 1.
                                     ], dtype=float32)

# Accuracy
>>> (pygm.hungarian(X) * X_gt).sum() / X_gt.sum()
jt.Var([1.], dtype=float32)

```

**Note:** If you find this graph matching solver useful in your research, please cite:

```
@inproceedings{rrwm,
  title={Reweighted random walks for graph matching},
  author={Cho, Minsu and Lee, Jungmin and Lee, Kyoung Mu},
  booktitle={European conference on Computer vision},
  pages={492--505},
  year={2010},
  organization={Springer}
}
```

---

## pygmtools.classic\_solvers.sm

`pygmtools.classic_solvers.sm(K, n1=None, n2=None, n1max=None, n2max=None, x0=None, max_iter: int = 50, backend=None)`

Spectral Graph Matching solver for graph matching (QAP). This algorithm is also known as Power Iteration method, because it works by computing the leading eigenvector of the input affinity matrix by power iteration.

For each iteration,

$$\mathbf{v}_{k+1} = \mathbf{K}\mathbf{v}_k / \|\mathbf{K}\mathbf{v}_k\|_2$$

### Parameters

- **K** – ( $b \times n_1 n_2 \times n_1 n_2$ ) the input affinity matrix,  $b$ : batch size.
- **n1** – ( $b$ ) number of nodes in graph1 (optional if **n1max** is given, and all  $n1=n1max$ ).
- **n2** – ( $b$ ) number of nodes in graph2 (optional if **n2max** is given, and all  $n2=n2max$ ).
- **n1max** – ( $b$ ) max number of nodes in graph1 (optional if **n1** is given, and  $n1max=\max(n1)$ ).
- **n2max** – ( $b$ ) max number of nodes in graph2 (optional if **n2** is given, and  $n2max=\max(n2)$ ).
- **x0** – ( $b \times n_1 \times n_2$ ) an initial matching solution for warm-start. If not given, **x0** will be randomly generated.
- **max\_iter** – (default: 50) max number of iterations. More iterations will help the solver to converge better, at the cost of increased inference time.
- **backend** – (default: `pygmtools.BACKEND` variable) the backend for computation.

### Returns

( $b \times n_1 \times n_2$ ) the solved doubly-stochastic matrix

---

**Note:** Either **n1** or **n1max** should be specified because it cannot be inferred from the input tensor size. Same for **n2** or **n2max**.

---

---

**Note:** We support batched instances with different number of nodes, therefore **n1** and **n2** are required to specify the exact number of objects of each dimension in the batch. If not specified, we assume the batched matrices are not padded and all elements in **n1** are equal, all in **n2** are equal.

---

---

**Note:** This function also supports non-batched input, by ignoring all batch dimensions in the input tensors.

---



---

**Note:** This solver is differentiable and supports gradient back-propagation.

---

**Warning:** The solver's output is normalized with a squared sum of 1, which is in line with the original implementation. If a doubly-stochastic matrix is required, please call `sinkhorn()` after this. If a discrete permutation matrix is required, please call `hungarian()`. Note that the Hungarian algorithm will truncate the gradient and the Sinkhorn algorithm will not.

## Numpy Example

```
>>> import numpy as np
>>> import pygmtools as pygm
>>> pygm.BACKEND = 'numpy'
>>> np.random.seed(1)

# Generate a batch of isomorphic graphs
>>> batch_size = 10
>>> X_gt = np.zeros((batch_size, 4, 4))
>>> X_gt[:, np.arange(0, 4, dtype=np.int64), np.random.permutation(4)] = 1
>>> A1 = np.random.rand(batch_size, 4, 4)
>>> A2 = np.matmul(np.matmul(X_gt.transpose((0, 2, 1)), A1), X_gt)
>>> n1 = n2 = np.repeat([4], batch_size)

# Build affinity matrix
>>> conn1, edge1, ne1 = pygm.utils.dense_to_sparse(A1)
>>> conn2, edge2, ne2 = pygm.utils.dense_to_sparse(A2)
>>> import functools
>>> gaussian_aff = functools.partial(pygm.utils.gaussian_aff_fn, sigma=1.) # set_
↳affinity function
>>> K = pygm.utils.build_aff_mat(None, edge1, conn1, None, edge2, conn2, n1, None,
↳n2, None, edge_aff_fn=gaussian_aff)

# Solve by SM. Note that X is normalized with a squared sum of 1
>>> X = pygm.sm(K, n1, n2)
>>> (X ** 2).sum(axis=(1, 2))
array([1., 1., 1., 1., 1., 1., 1., 1., 1., 1.])

# Accuracy
>>> (pygm.hungarian(X) * X_gt).sum() / X_gt.sum()
1.0
```

## Pytorch Example

```
>>> import torch
>>> import pygmtools as pygm
>>> pygm.BACKEND = 'pytorch'
>>> _ = torch.manual_seed(1)

# Generate a batch of isomorphic graphs
>>> batch_size = 10
>>> X_gt = torch.zeros(batch_size, 4, 4)
>>> X_gt[:, torch.arange(0, 4, dtype=torch.int64), torch.randperm(4)] = 1
>>> A1 = torch.rand(batch_size, 4, 4)
>>> A2 = torch.bmm(torch.bmm(X_gt.transpose(1, 2), A1), X_gt)
>>> n1 = n2 = torch.tensor([4] * batch_size)

# Build affinity matrix
>>> conn1, edge1, ne1 = pygm.utils.dense_to_sparse(A1)
>>> conn2, edge2, ne2 = pygm.utils.dense_to_sparse(A2)
>>> import functools
>>> gaussian_aff = functools.partial(pygm.utils.gaussian_aff_fn, sigma=1.) # set_
↪affinity function
>>> K = pygm.utils.build_aff_mat(None, edge1, conn1, None, edge2, conn2, n1, None,
↪n2, None, edge_aff_fn=gaussian_aff)

# Solve by SM. Note that X is normalized with a squared sum of 1
>>> X = pygm.sm(K, n1, n2)
>>> (X ** 2).sum(dim=(1, 2))
tensor([1.0000, 1.0000, 1.0000, 1.0000, 1.0000, 1.0000, 1.0000, 1.0000,
        1.0000])

# Accuracy
>>> (pygm.hungarian(X) * X_gt).sum() / X_gt.sum()
tensor(1.)

# This solver supports gradient back-propagation
>>> K = K.requires_grad_(True)
>>> pygm.sm(K, n1, n2).sum().backward()
>>> len(torch.nonzero(K.grad))
2560
```

## Paddle Example

```
>>> import paddle
>>> import pygmtools as pygm
>>> pygm.BACKEND = 'paddle'
>>> _ = paddle.seed(1)

# Generate a batch of isomorphic graphs
>>> batch_size = 10
>>> X_gt = paddle.zeros((batch_size, 4, 4))
>>> X_gt[:, paddle.arange(0, 4, dtype=paddle.int64), paddle.randperm(4)] = 1
```

(continues on next page)

(continued from previous page)

```

>>> A1 = paddle.rand((batch_size, 4, 4))
>>> A2 = paddle.bmm(paddle.bmm(X_gt.transpose((0, 2, 1)), A1), X_gt)
>>> n1 = n2 = paddle.to_tensor([4] * batch_size)

# Build affinity matrix
>>> conn1, edge1, ne1 = pygm.utils.dense_to_sparse(A1)
>>> conn2, edge2, ne2 = pygm.utils.dense_to_sparse(A2)
>>> import functools
>>> gaussian_aff = functools.partial(pygm.utils.gaussian_aff_fn, sigma=1.) # set_
↳affinity function
>>> K = pygm.utils.build_aff_mat(None, edge1, conn1, None, edge2, conn2, n1, None,
↳n2, None, edge_aff_fn=gaussian_aff)

# Solve by SM. Note that X is normalized with a squared sum of 1
>>> X = pygm.sm(K, n1, n2)
>>> (X ** 2).sum(axis=(1, 2))
Tensor(shape=[10], dtype=float32, place=Place(cpu), stop_gradient=True,
      [1.          , 1.          , 0.99999994, 0.99999994, 1.00000012,
       1.          , 1.00000012, 1.          , 1.          , 0.99999994])

# Accuracy
>>> (pygm.hungarian(X) * X_gt).sum() / X_gt.sum()
Tensor(shape=[1], dtype=float32, place=Place(cpu), stop_gradient=True, [1.])

# This solver supports gradient back-propagation
>>> K.stop_gradient = False
>>> pygm.sm(K, n1, n2).sum().backward()
>>> len(paddle.nonzero(K.grad))
2560

```

### Jittor Example

```

>>> import jittor as jt
>>> import pygmtools as pygm
>>> pygm.BACKEND = 'jittor'
>>> _ = jt.seed(1)

# Generate a batch of isomorphic graphs
>>> batch_size = 10
>>> X_gt = jt.zeros((batch_size, 4, 4))
>>> X_gt[:, jt.arange(0, 4, dtype=jt.int64), jt.randperm(4)] = 1
>>> A1 = jt.rand(batch_size, 4, 4)
>>> A2 = jt.bmm(jt.bmm(X_gt.transpose(1, 2), A1), X_gt)
>>> n1 = n2 = jt.Var([4] * batch_size)

# Build affinity matrix
>>> conn1, edge1, ne1 = pygm.utils.dense_to_sparse(A1)
>>> conn2, edge2, ne2 = pygm.utils.dense_to_sparse(A2)
>>> import functools
>>> gaussian_aff = functools.partial(pygm.utils.gaussian_aff_fn, sigma=1.) # set_

```

(continues on next page)

(continued from previous page)

```

↪affinity function
>>> K = pygm.utils.build_aff_mat(None, edge1, conn1, None, edge2, conn2, n1, None,
↪n2, None, edge_aff_fn=gaussian_aff)

# Solve by SM. Note that X is normalized with a squared sum of 1
>>> X = pygm.sm(K, n1, n2)
>>> (X ** 2).sum(dim=1).sum(dim=1)
jt.Var([0.9999998  1.          0.9999999  1.00000001  1.          1.
        0.9999999  0.99999994 1.00000001  1.          ], dtype=float32)

# Accuracy
>>> (pygm.hungarian(X) * X_gt).sum() / X_gt.sum()
jt.Var([1.], dtype=float32)

```

**Note:** If you find this graph matching solver useful for your research, please cite:

```

@inproceedings{sm,
  title={A spectral technique for correspondence problems using pairwise
↪constraints},
  author={Leordeanu, Marius and Hebert, Martial},
  year={2005},
  pages={1482-1489},
  booktitle={International Conference on Computer Vision},
  publisher={IEEE}
}

```

### 9.4.3 pygmtools.multi\_graph\_solvers

Classic (learning-free) **multi-graph matching** solvers. These multi-graph matching solvers are recommended to solve the joint matching problem of multiple graphs.

#### Functions

<i>cao</i>	Composition based Affinity Optimization (CAO) solver for multi-graph matching.
<i>gamgm</i>	Graduated Assignment-based multi-graph matching solver.
<i>mgm_floyd</i>	Multi-Graph Matching based on Floyd shortest path algorithm.

**pygmtools.multi\_graph\_solvers.cao**

```
pygmtools.multi_graph_solvers.cao(K, x0=None, qap_solver=None, mode='accu', max_iter=6,
                                   lambda_init=0.3, lambda_step=1.1, lambda_max=1.0, iter_boost=2,
                                   backend=None)
```

Composition based Affinity Optimization (CAO) solver for multi-graph matching. This solver builds a super-graph for matching update to incorporate the two aspects by optimizing the affinity score, meanwhile gradually infusing the consistency.

Each update step is described as follows:

$$\arg \max_k (1 - \lambda) J(\mathbf{X}_{ik} \mathbf{X}_{kj}) + \lambda C_p(\mathbf{X}_{ik} \mathbf{X}_{kj})$$

where  $J(\mathbf{X}_{ik} \mathbf{X}_{kj})$  is the objective score, and  $C_p(\mathbf{X}_{ik} \mathbf{X}_{kj})$  measures a consistency score compared to other matchings. These two terms are balanced by  $\lambda$ , and  $\lambda$  starts from a smaller number and gradually grows.

**Parameters**

- **K** – ( $m \times m \times n^2 \times n^2$ ) the input affinity matrix, where  $K[i, j]$  is the affinity matrix of graph *i* and graph *j* (*m*: number of nodes)
- **x0** – (optional) ( $m \times m \times n \times n$ ) the initial two-graph matching result, where  $X[i, j]$  is the matching matrix result of graph *i* and graph *j*. If this argument is not given, `qap_solver` will be used to compute the two-graph matching result.
- **qap\_solver** – (default: `pygm.rwm`) a function object that accepts a batched affinity matrix and returns the matching matrices. It is suggested to use `functools.partial` and the QAP solvers provided in the [classic\\_solvers](#) module (see examples below).
- **mode** – (default: 'accu') the operation mode of this algorithm. Options: 'accu', 'c', 'fast', 'pc', where 'accu' is equivalent to 'c' (accurate version) and 'fast' is equivalent to 'pc' (fast version).
- **max\_iter** – (default: 6) max number of iterations
- **lambda\_init** – (default: 0.3) initial value of  $\lambda$ , with  $\lambda \in [0, 1]$
- **lambda\_step** – (default: 1.1) the increase step size of  $\lambda$ , updated by  $\lambda = \text{step} * \lambda$
- **lambda\_max** – (default: 1.0) the max value of  $\lambda$
- **iter\_boost** – (default: 2) to boost the convergence of the CAO algorithm,  $\lambda$  will be forced to update every `iter_boost` iterations.
- **backend** – (default: `pygmtools.BACKEND` variable) the backend for computation.

**Returns**

( $m \times m \times n \times n$ ) the multi-graph matching result

---

**Note:** The input graphs must have the same number of nodes for this algorithm to work correctly.

---



---

**Note:** Multi-graph matching methods process all graphs at once and do not support the additional batch dimension. Please note that this behavior is different from two-graph matching solvers in [classic\\_solvers](#).

---

## Pytorch Example

```

>>> import torch
>>> import pygmtools as pygm
>>> pygm.BACKEND = 'pytorch'
>>> _ = torch.manual_seed(1)

# Generate 10 isomorphic graphs
>>> graph_num = 10
>>> As, X_gt = pygm.utils.generate_isomorphic_graphs(node_num=4, graph_num=10)
>>> As_1, As_2 = [], []
>>> for i in range(graph_num):
...     for j in range(graph_num):
...         As_1.append(As[i])
...         As_2.append(As[j])
>>> As_1 = torch.stack(As_1, dim=0)
>>> As_2 = torch.stack(As_2, dim=0)

# Build affinity matrix
>>> conn1, edge1, ne1 = pygm.utils.dense_to_sparse(As_1)
>>> conn2, edge2, ne2 = pygm.utils.dense_to_sparse(As_2)
>>> import functools
>>> gaussian_aff = functools.partial(pygm.utils.gaussian_aff_fn, sigma=1.) # set_
↪ affinity function
>>> K = pygm.utils.build_aff_mat(None, edge1, conn1, None, edge2, conn2, None, None,
↪ None, None, edge_aff_fn=gaussian_aff)
>>> K = K.reshape(graph_num, graph_num, 4*4, 4*4)
>>> K.shape
torch.Size([10, 10, 16, 16])

# Solve the multi-matching problem
>>> X = pygm.cao(K)
>>> (X * X_gt).sum() / X_gt.sum()
tensor(1.)

# Use the IPFP solver for two-graph matching
>>> ipfp_func = functools.partial(pygmtools.ipfp, n1max=4, n2max=4)
>>> X = pygm.cao(K, qap_solver=ipfp_func)
>>> (X * X_gt).sum() / X_gt.sum()
tensor(1.)

# Run the faster version of CAO algorithm
>>> X = pygm.cao(K, mode='fast')
>>> (X * X_gt).sum() / X_gt.sum()
tensor(1.)

```

**Note:** If you find this graph matching solver useful in your research, please cite:

```

@article{cao,
  title={Multi-graph matching via affinity optimization with graduated consistency_
↪ regularization},
  author={Yan, Junchi and Cho, Minsu and Zha, Hongyuan and Yang, Xiaokang and Chu,

```

(continues on next page)

(continued from previous page)

```

↪Stephen M},
journal={IEEE transactions on pattern analysis and machine intelligence},
volume={38},
number={6},
pages={1228--1242},
year={2015},
publisher={IEEE}
}

```

### pygmtools.multi\_graph\_solvers.gamgm

```

pygmtools.multi_graph_solvers.gamgm(A, W, ns=None, n_univ=None, U0=None, sk_init_tau=0.5,
                                     sk_min_tau=0.1, sk_gamma=0.8, sk_iter=20, max_iter=100,
                                     param_lambda=1.0, converge_thresh=1e-05, outlier_thresh=-1,
                                     bb_smooth=0.1, verbose=False, backend=None)

```

Graduated Assignment-based multi-graph matching solver. Graduated assignment is a classic approach for hard assignment problems like graph matching, based on graduated annealing of Sinkhorn's temperature  $\tau$  to enforce the matching constraint.

The objective score is described as

$$\max_{\mathbf{X}_{i,j}, i,j \in [m]} \sum_{i,j \in [m]} (\lambda \operatorname{tr}(\mathbf{X}_{ij}^\top \mathbf{A}_i \mathbf{X}_{ij} \mathbf{A}_j) + \operatorname{tr}(\mathbf{X}_{ij}^\top \mathbf{W}_{ij}))$$

Once the algorithm converges at a fixed  $\tau$  value,  $\tau$  shrinks as:

$$\tau = \tau \times \gamma$$

and the iteration continues. At last, Hungarian algorithm is applied to ensure the result is a permutation matrix.

**Note:** This algorithm is based on the Koopmans-Beckmann's QAP formulation and you should input the adjacency matrices  $\mathbf{A}$  and node-wise similarity matrices  $\mathbf{W}$  instead of the affinity matrices.

#### Parameters

- $\mathbf{A}$  – ( $m \times n \times n$ ) the adjacency matrix ( $m$ : number of nodes). The graphs may have different number of nodes (specified by the `ns` argument).
- $\mathbf{W}$  – ( $m \times m \times n \times n$ ) the node-wise similarity matrix, where  $\mathbf{W}[i, j]$  is the similarity matrix
- `ns` – (optional) ( $m$ ) the number of nodes. If not given, it will be inferred based on the size of  $\mathbf{A}$ .
- `n_univ` – (optional) the size of the universe node set. If not given, it will be the largest number of nodes.
- `U0` – (optional) the initial multi-graph matching result. If not given, it will be randomly initialized.
- `sk_init_tau` – (default: 0.05) initial value of  $\tau$  for Sinkhorn algorithm
- `sk_min_tau` – (default: 1.0e-3) minimal value of  $\tau$  for Sinkhorn algorithm
- `sk_gamma` – (default: 0.8) the shrinking parameter of  $\tau$ :  $\tau = \tau \times \gamma$

- **sk\_iter** – (default: 200) max number of iterations for Sinkhorn algorithm
- **max\_iter** – (default: 1000) max number of iterations for graduated assignment
- **param\_lambda** – (default: 1) the weight  $\lambda$  of the quadratic term
- **converge\_thresh** – (default: 1e-5) if the Frobenius norm of the change of U is smaller than this, the iteration is stopped.
- **outlier\_thresh** – (default: -1) if  $> 0$ , pairs with node+edge similarity score smaller than this threshold will be discarded. This threshold is designed to handle outliers.
- **bb\_smooth** – (default: 0.1) the black-box differentiation smoothing parameter.
- **verbose** – (default: False) print verbose information for parameter tuning
- **backend** – (default: `pygmtools.BACKEND` variable) the backend for computation.

**Returns**

the multi-graph matching result (a *MultiMatchingResult* object)

---

**Note:** In PyTorch backend, this function is differentiable through the black-box trick. See the following paper for details:

Vlastelica M, Paulus A., Differentiation of Blackbox Combinatorial Solvers, ICLR, ↪2020

If you want to disable this differentiable feature, please detach the input tensors from the computational graph.

---

---

**Note:** Setting `verbose=True` may help you tune the parameters.

---

**Pytorch Example**

```
>>> import torch
>>> import pygmtools as pygm
>>> import itertools
>>> import time
>>> pygm.BACKEND = 'pytorch'
>>> _ = torch.manual_seed(1)

# Generate 10 isomorphic graphs
>>> graph_num = 10
>>> As, X_gt, Fs = pygm.utils.generate_isomorphic_graphs(node_num=4, graph_num=10, ↪
↪node_feat_dim=20)

# Compute node-wise similarity by inner-product and Sinkhorn
>>> W = torch.matmul(Fs.unsqueeze(1), Fs.transpose(1, 2).unsqueeze(0))
>>> W = pygm.sinkhorn(W.reshape(graph_num ** 2, 4, 4)).reshape(graph_num, graph_num,
↪ 4, 4)

# Solve the multi-matching problem
>>> X = pygm.gamgm(As, W)
>>> matched = 0
```

(continues on next page)



(continued from previous page)

```

>>> for i, j in itertools.product(range(graph_num), repeat=2):
...     matched += (X[i,j] * X_gt[i,j]).sum()
>>> acc = matched / X_gt.sum()
>>> acc
tensor(1.)

# This function is differentiable by the black-box trick
>>> W.requires_grad_(True) # tell PyTorch to track the gradients
>>> X = pygm.gamgm(As, W)
>>> matched = 0
>>> for i, j in itertools.product(range(graph_num), repeat=2):
...     matched += (X[i,j] * X_gt[i,j]).sum()
>>> acc = matched / X_gt.sum()

# Backward pass via black-box trick
>>> acc.backward()
>>> torch.sum(W.grad != 0)
tensor(128)

# This function supports graphs with different nodes (also known as partial_
↪ matching)
# In the following we ignore the last node from the last 5 graphs
>>> ns = torch.tensor([4, 4, 4, 4, 4, 3, 3, 3, 3, 3], dtype=torch.int)
>>> for i in range(graph_num):
...     As[i, ns[i]:, :] = 0
...     As[i, :, ns[i]:] = 0
>>> for i, j in itertools.product(range(graph_num), repeat=2):
...     X_gt[i, j, ns[i]:, :] = 0
...     X_gt[i, j, :, ns[j]:] = 0
...     W[i, j, ns[i]:, :] = 0
...     W[i, j, :, ns[j]:] = 0
>>> W = W.detach() # detach tensor if gradient is not needed

# Partial matching is challenging and the following parameters are carefully tuned
>>> X = pygm.gamgm(As, W, ns, n_univ=4, sk_init_tau=.1, sk_min_tau=0.01, param_
↪ lambda=0.3)

# Check the partial matching result
>>> matched = 0
>>> for i, j in itertools.product(range(graph_num), repeat=2):
...     matched += (X[i,j] * X_gt[i, j, :ns[i], :ns[j]]).sum()
>>> matched / X_gt.sum()
tensor(1.)

```

**Note:** If you find this graph matching solver useful in your research, please cite:

```

@article{gamgm1,
  title={Graduated assignment algorithm for multiple graph matching based on a_
↪ common labeling},
  author={Sol{\`e}-Ribalta, Albert and Serratosa, Francesc},
  journal={International Journal of Pattern Recognition and Artificial Intelligence}

```

(continues on next page)

(continued from previous page)

```

↪,
    volume={27},
    number={01},
    pages={1350001},
    year={2013},
    publisher={World Scientific}
}

@article{gamgm2,
    title={Graduated assignment for joint multi-graph matching and clustering with_
↪application to unsupervised graph matching network learning},
    author={Wang, Runzhong and Yan, Junchi and Yang, Xiaokang},
    journal={Advances in Neural Information Processing Systems},
    volume={33},
    pages={19908--19919},
    year={2020}
}

```

This algorithm is originally proposed by paper gamgm1, and further improved by paper gamgm2 to fit modern computing architectures like GPU.

### pygmtools.multi\_graph\_solvers.mgm\_floyd

`pygmtools.multi_graph_solvers.mgm_floyd(K, x0=None, qap_solver=None, mode='accu', param_lambda=0.2, backend=None)`

Multi-Graph Matching based on Floyd shortest path algorithm. A supergraph is considered by regarding each input graph as a node, and the matching between graphs are regreded as edges in the supergraph. Floyd algorithm is used to discover a shortest path on this supergraph for matching update.

The length of edges on the supergraph is described as follows:

$$\arg \max_k (1 - \lambda) J(\mathbf{X}_{ik} \mathbf{X}_{kj}) + \lambda C_p(\mathbf{X}_{ik} \mathbf{X}_{kj})$$

where  $J(\mathbf{X}_{ik} \mathbf{X}_{kj})$  is the objective score, and  $C_p(\mathbf{X}_{ik} \mathbf{X}_{kj})$  measures a consistency score compared to other matchings. These two terms are balanced by  $\lambda$ .

#### Parameters

- **K** – ( $m \times m \times n^2 \times n^2$ ) the input affinity matrix, where  $K[i, j]$  is the affinity matrix of graph  $i$  and graph  $j$  ( $m$ : number of nodes)
- **x0** – (optional) ( $m \times m \times n \times n$ ) the initial two-graph matching result, where  $X[i, j]$  is the matching matrix result of graph  $i$  and graph  $j$ . If this argument is not given, `qap_solver` will be used to compute the two-graph matching result.
- **qap\_solver** – (default: `pygm.rwm`) a function object that accepts a batched affinity matrix and returns the matching matrices. It is suggested to use `functools.partial` and the QAP solvers provided in the `classic_solvers` module (see examples below).
- **mode** – (default: 'accu') the operation mode of this algorithm. Options: 'accu', 'c', 'fast', 'pc', where 'accu' is equivalent to 'c' (accurate version) and 'fast' is equivalent to 'pc' (fast version).
- **param\_lambda** – (default: 0.3) value of  $\lambda$ , with  $\lambda \in [0, 1]$

- **backend** – (default: `pygmtools.BACKEND` variable) the backend for computation.

#### Returns

$(m \times m \times n \times n)$  the multi-graph matching result

#### Pytorch Example

```
>>> import torch
>>> import pygmtools as pygm
>>> pygm.BACKEND = 'pytorch'
>>> _ = torch.manual_seed(1)

# Generate 10 isomorphic graphs
>>> graph_num = 10
>>> As, X_gt = pygm.utils.generate_isomorphic_graphs(node_num=4, graph_num=10)
>>> As_1, As_2 = [], []
>>> for i in range(graph_num):
...     for j in range(graph_num):
...         As_1.append(As[i])
...         As_2.append(As[j])
>>> As_1 = torch.stack(As_1, dim=0)
>>> As_2 = torch.stack(As_2, dim=0)

# Build affinity matrix
>>> conn1, edge1, ne1 = pygm.utils.dense_to_sparse(As_1)
>>> conn2, edge2, ne2 = pygm.utils.dense_to_sparse(As_2)
>>> import functools
>>> gaussian_aff = functools.partial(pygm.utils.gaussian_aff_fn, sigma=1.) # set_
↳ affinity function
>>> K = pygm.utils.build_aff_mat(None, edge1, conn1, None, edge2, conn2, None, None,
↳ None, None, edge_aff_fn=gaussian_aff)
>>> K = K.reshape(graph_num, graph_num, 4*4, 4*4)
>>> K.shape
torch.Size([10, 10, 16, 16])

# Solve the multi-matching problem
>>> X = pygm.mgm_floyd(K)
>>> (X * X_gt).sum() / X_gt.sum()
tensor(1.)

# Use the IPFP solver for two-graph matching
>>> ipfp_func = functools.partial(pygmtools.ipfp, n1max=4, n2max=4)
>>> X = pygm.mgm_floyd(K, qap_solver=ipfp_func)
>>> (X * X_gt).sum() / X_gt.sum()
tensor(1.)

# Run the faster version of CAO algorithm
>>> X = pygm.mgm_floyd(K, mode='fast')
>>> (X * X_gt).sum() / X_gt.sum()
tensor(1.)
```

**Note:** If you find this graph matching solver useful in your research, please cite:

```
@article{mgm_floyd,
  title={Unifying offline and online multi-graph matching via finding shortest_
↪paths on supergraph},
  author={Jiang, Zetian and Wang, Tianzhe and Yan, Junchi},
  journal={IEEE transactions on pattern analysis and machine intelligence},
  volume={43},
  number={10},
  pages={3648--3663},
  year={2020},
  publisher={IEEE}
}
```

#### 9.4.4 pygmtools.neural\_solvers

**Neural network-based** graph matching solvers. It is recommended to integrate these networks as modules into your existing deep learning pipeline (either supervised, unsupervised or reinforcement learning).

##### Functions

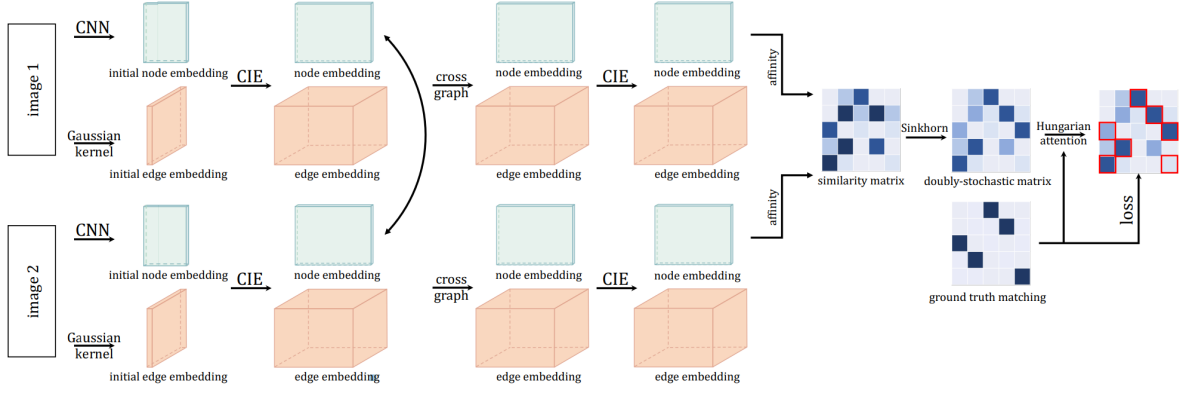
<i>cie</i>	The <b>CIE</b> (Channel Independent Embedding) graph matching neural network model for processing two individual graphs (KB-QAP).
<i>ipca_gm</i>	The <b>IPCA-GM</b> (Iterative Permutation loss and Cross-graph Affinity Graph Matching) neural network model for processing two individual graphs (KB-QAP).
<i>ngm</i>	The <b>NGM</b> (Neural Graph Matching) model for processing the affinity matrix (the most general form of Lawler's QAP).
<i>pca_gm</i>	The <b>PCA-GM</b> (Permutation loss and Cross-graph Affinity Graph Matching) neural network model for processing two individual graphs (KB-QAP).

##### pygmtools.neural\_solvers.cie

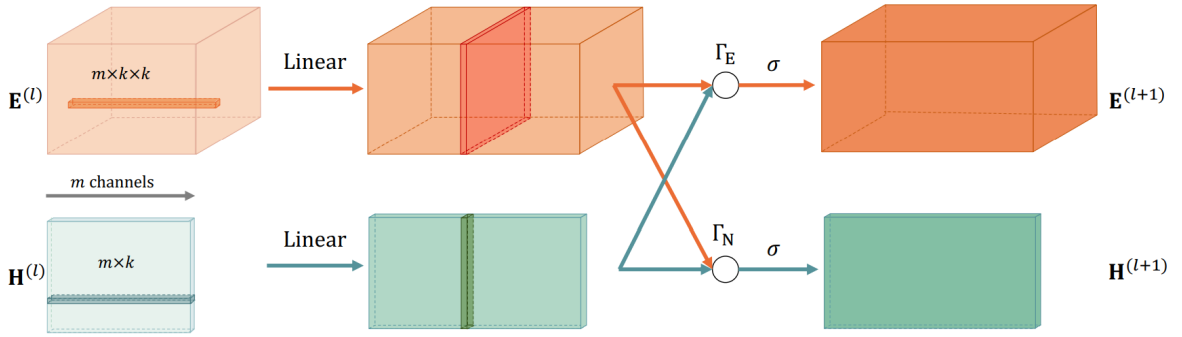
`pygmtools.neural_solvers.cie(feat_node1, feat_node2, A1, A2, feat_edge1, feat_edge2, n1=None, n2=None, in_node_channel=1024, in_edge_channel=1, hidden_channel=2048, out_channel=2048, num_layers=2, sk_max_iter=20, sk_tau=0.05, network=None, return_network=False, pretrain='voc', backend=None)`

The **CIE** (Channel Independent Embedding) graph matching neural network model for processing two individual graphs (KB-QAP). The graph matching module is composed of several intra-graph embedding layers, a cross-graph embedding layer, and a Sinkhorn matching layer. Only the second last layer has a cross-graph update layer. The graph embedding layers are based on channel-independent embedding, under the assumption that such a message passing scheme may offer higher model capacity especially with high-dimensional edge features.

See the following pipeline for an example, with application to visual graph matching:



The graph embedding layer (CIE layer) involves both node embedding and edge embedding:



See the following paper for more technical details: “Yu et al. Learning Deep Graph Matching with Channel-Independent Embedding and Hungarian Attention. ICLR 2020.”

#### Parameters

- **feat\_node1** – ( $b \times n_1 \times d_n$ ) input node feature of graph1
- **feat\_node2** – ( $b \times n_2 \times d_n$ ) input node feature of graph2
- **A1** – ( $b \times n_1 \times n_1$ ) input adjacency matrix of graph1
- **A2** – ( $b \times n_2 \times n_2$ ) input adjacency matrix of graph2
- **feat\_edge1** – ( $b \times n_1 \times n_1 \times d_e$ ) input edge feature of graph1
- **feat\_edge2** – ( $b \times n_2 \times n_2 \times d_e$ ) input edge feature of graph2
- **n1** – ( $b$ ) number of nodes in graph1. Optional if all equal to  $n_1$
- **n2** – ( $b$ ) number of nodes in graph2. Optional if all equal to  $n_2$
- **in\_node\_channel** – (default: 1024) Node channel size of the input layer. It must match the feature dimension ( $d_n$ ) of **feat\_node1**, **feat\_node2**. Ignored if the network object is given (ignored if **network**!=None)
- **in\_edge\_channel** – (default: 1) Edge channel size of the input layer. It must match the feature dimension ( $d_e$ ) of **feat\_edge1**, **feat\_edge2**. Ignored if the network object is given (ignored if **network**!=None)
- **hidden\_channel** – (default: 2048) Channel size of hidden layers (node channel == edge channel). Ignored if the network object is given (ignored if **network**!=None)
- **out\_channel** – (default: 2048) Channel size of the output layer (node channel == edge channel). Ignored if the network object is given (ignored if **network**!=None)

- **num\_layers** – (default: 2) Number of graph embedding layers. Must be  $\geq 2$ . Ignored if the network object is given (ignored if `network!=None`)
- **sk\_max\_iter** – (default: 20) Max number of iterations of Sinkhorn. See `sinkhorn()` for more details about this argument.
- **sk\_tau** – (default: 0.05) The temperature parameter of Sinkhorn. See `sinkhorn()` for more details about this argument.
- **network** – (default: None) The network object. If None, a new network object will be created, and load the model weights specified in `pretrain` argument.
- **return\_network** – (default: False) Return the network object (saving model construction time if calling the model multiple times).
- **pretrain** – (default: 'voc') If `network==None`, the pretrained model weights to be loaded. Available pretrained weights: `voc` (on Pascal VOC Keypoint dataset), `willow` (on Willow Object Class dataset), or `False` (no pretraining).
- **backend** – (default: `pygmtools.BACKEND` variable) the backend for computation.

### Returns

if `return_network==False`,  $(b \times n_1 \times n_2)$  the doubly-stochastic matching matrix

if `return_network==True`,  $(b \times n_1 \times n_2)$  the doubly-stochastic matching matrix, the network object

---

**Note:** You may need a proxy to load the pretrained weights if Google drive is not accessible in your country/region.

---



---

**Note:** This function also supports non-batched input, by ignoring all batch dimensions in the input tensors.

---

### PyTorch Example

```
>>> import torch
>>> import pygmtools as pygm
>>> pygm.BACKEND = 'pytorch'
>>> _ = torch.manual_seed(1)

# Generate a batch of isomorphic graphs
>>> batch_size = 10
>>> X_gt = torch.zeros(batch_size, 4, 4)
>>> X_gt[:, torch.arange(0, 4, dtype=torch.int64), torch.randperm(4)] = 1
>>> A1 = 1. * (torch.rand(batch_size, 4, 4) > 0.5)
>>> torch.diagonal(A1, dim1=1, dim2=2)[:,:] = 0 # discard self-loop edges
>>> e_feat1 = (torch.rand(batch_size, 4, 4) * A1).unsqueeze(-1) # shape: (10, 4, 4, 1)
>>> A2 = torch.bmm(torch.bmm(X_gt.transpose(1, 2), A1), X_gt)
>>> e_feat2 = torch.bmm(torch.bmm(X_gt.transpose(1, 2), e_feat1.squeeze(-1)), X_gt).
↳unsqueeze(-1)
>>> feat1 = torch.rand(batch_size, 4, 1024) - 0.5
>>> feat2 = torch.bmm(X_gt.transpose(1, 2), feat1)
>>> n1 = n2 = torch.tensor([4] * batch_size)
```

(continues on next page)

(continued from previous page)

```

# Match by CIE (load pretrained model)
>>> X, net = pygm.cie(feats1, feat2, A1, A2, e_feats1, e_feats2, n1, n2, return_
↳network=True)
Downloading to ~/.cache/pygmtools/cie_voc_pytorch.pt...
>>> (pygm.hungarian(X) * X_gt).sum() / X_gt.sum() # accuracy
tensor(1.)

# Pass the net object to avoid rebuilding the model again
>>> X = pygm.cie(feats1, feat2, A1, A2, e_feats1, e_feats2, n1, n2, network=net)

# You may also load other pretrained weights
>>> X, net = pygm.cie(feats1, feat2, A1, A2, e_feats1, e_feats2, n1, n2, return_
↳network=True, pretrain='willow')
Downloading to ~/.cache/pygmtools/cie_willow_pytorch.pt...

# You may configure your own model and integrate the model into a deep learning
↳pipeline. For example:
>>> net = pygm.utils.get_network(pygm.cie, in_node_channel=1024, in_edge_channel=1,
↳hidden_channel=2048, out_channel=512, num_layers=3, pretrain=False)
>>> optimizer = torch.optim.SGD(net.parameters(), lr=0.001, momentum=0.9)
# feats1/feat2/e_feats1/e_feats2 may be outputs by other neural networks
>>> X = pygm.cie(feats1, feat2, A1, A2, e_feats1, e_feats2, n1, n2, network=net)
>>> loss = pygm.utils.permutation_loss(X, X_gt)
>>> loss.backward()
>>> optimizer.step()

```

### Jittor Example

```

>>> import jittor as jt
>>> import pygmtools as pygm
>>> pygm.BACKEND = 'jittor'
>>> _ = jt.seed(1)

# Generate a batch of isomorphic graphs
>>> batch_size = 10
>>> X_gt = jt.zeros((batch_size, 4, 4))
>>> X_gt[:, jt.arange(0, 4, dtype=jt.int64), jt.randperm(4)] = 1
>>> A1 = 1. * (jt.rand(batch_size, 4, 4) > 0.5)
>>> for i in range(batch_size):
>>>     for j in range(4):
>>>         A1.data[i][j][j] = 0 # discard self-loop edges
>>> e_feats1 = (jt.rand(batch_size, 4, 4) * A1).unsqueeze(-1) # shape: (10, 4, 4, 1)
>>> A2 = jt.bmm(jt.bmm(X_gt.transpose(1, 2), A1), X_gt)
>>> e_feats2 = jt.bmm(jt.bmm(X_gt.transpose(1, 2), e_feats1.squeeze(-1)), X_gt).
↳unsqueeze(-1)
>>> feat1 = jt.rand(batch_size, 4, 1024) - 0.5
>>> feat2 = jt.bmm(X_gt.transpose(1, 2), feat1)
>>> n1 = n2 = jt.Var([4] * batch_size)

```

(continues on next page)

(continued from previous page)

```

# Match by CIE (load pretrained model)
>>> X, net = pygm.cie(featl1, feat2, A1, A2, e_feat1, e_feat2, n1, n2, return_
↳network=True)
Downloading to ~/.cache/pygmtools/cie_voc_jittor.pt...
>>> (pygm.hungarian(X) * X_gt).sum() / X_gt.sum() # accuracy
jt.Var([1.], dtype=float32)

# Pass the net object to avoid rebuilding the model again
>>> X = pygm.cie(featl1, feat2, A1, A2, e_feat1, e_feat2, n1, n2, network=net)

# You may also load other pretrained weights
>>> X, net = pygm.cie(featl1, feat2, A1, A2, e_feat1, e_feat2, n1, n2, return_
↳network=True, pretrain='willow')
Downloading to ~/.cache/pygmtools/cie_willow_jittor.pt...

# You may configure your own model and integrate the model into a deep learning
↳pipeline. For example:
>>> net = pygm.utils.get_network(pygm.cie, in_node_channel=1024, in_edge_channel=1,
↳hidden_channel=2048, out_channel=512, num_layers=3, pretrain=False)
>>> optimizer = jt.optim.SGD(net.parameters(), lr=0.001, momentum=0.9)
# feat1/feat2/e_feat1/e_feat2 may be outputs by other neural networks
>>> X = pygm.cie(featl1, feat2, A1, A2, e_feat1, e_feat2, n1, n2, network=net)
>>> loss = pygm.utils.permutation_loss(X, X_gt)
>>> optimizer.backward(loss)
>>> optimizer.step()

```

**Note:** If you find this model useful in your research, please cite:

```

@inproceedings{YuICLR20,
  title={Learning deep graph matching with channel-independent embedding and
↳Hungarian attention},
  author={Yu, Tianshu and Wang, Runzhong and Yan, Junchi and Li, Baoxin},
  booktitle={International Conference on Learning Representations},
  year={2020}
}

```

## pygmtools.neural\_solvers.ipca\_gm

```

pygmtools.neural_solvers.ipca_gm(featl1, feat2, A1, A2, n1=None, n2=None, in_channel=1024,
hidden_channel=2048, out_channel=2048, num_layers=2, cross_iter=3,
sk_max_iter=20, sk_tau=0.05, network=None, return_network=False,
pretrain='voc', backend=None)

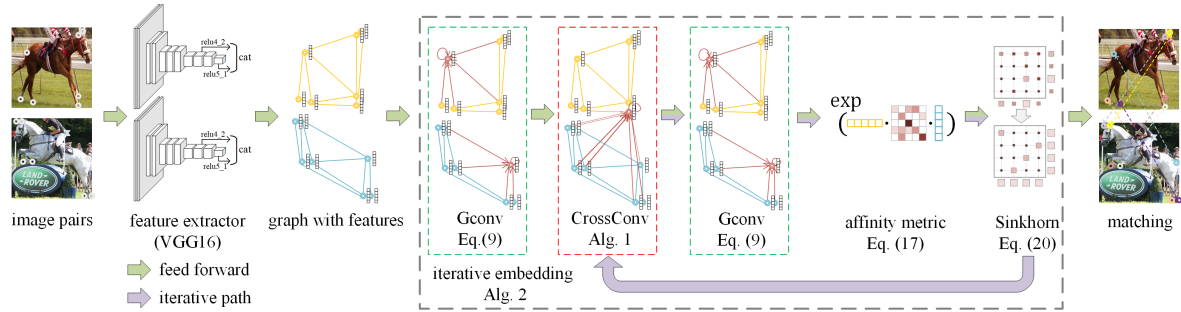
```

The **IPCA-GM** (Iterative Permutation loss and Cross-graph Affinity Graph Matching) neural network model for processing two individual graphs (KB-QAP). The graph matching module is composed of several intra-graph embedding layers, a cross-graph embedding layer, and a Sinkhorn matching layer. The weight matrix of the cross-graph embedding layer is updated iteratively. Only the second last layer has a cross-graph update layer. IPCA-GM is the extended version of PCA-GM (see [pca\\_gm\(\)](#)). The difference is that the cross-graph weight in PCA-GM is computed in one shot, and in IPCA-GM it is updated iteratively.

See the following pipeline for an example, with application to visual graph matching (layers in gray box are



implemented by pygmtools):



See the following paper for more technical details: “Wang et al. Combinatorial Learning of Robust Deep Graph Matching: an Embedding based Approach. TPAMI 2020.”

### Parameters

- **feat1** – ( $b \times n_1 \times d$ ) input feature of graph1
- **feat2** – ( $b \times n_2 \times d$ ) input feature of graph2
- **A1** – ( $b \times n_1 \times n_1$ ) input adjacency matrix of graph1
- **A2** – ( $b \times n_2 \times n_2$ ) input adjacency matrix of graph2
- **n1** – ( $b$ ) number of nodes in graph1. Optional if all equal to  $n_1$
- **n2** – ( $b$ ) number of nodes in graph2. Optional if all equal to  $n_2$
- **in\_channel** – (default: 1024) Channel size of the input layer. It must match the feature dimension ( $d$ ) of **feat1**, **feat2**. Ignored if the network object is given (ignored if **network!** =None)
- **hidden\_channel** – (default: 2048) Channel size of hidden layers. Ignored if the network object is given (ignored if **network!** =None)
- **out\_channel** – (default: 2048) Channel size of the output layer. Ignored if the network object is given (ignored if **network!** =None)
- **num\_layers** – (default: 2) Number of graph embedding layers. Must be  $\geq 2$ . Ignored if the network object is given (ignored if **network!** =None)
- **cross\_iter** – (default: 3) Number of iterations for the cross-graph embedding layer.
- **sk\_max\_iter** – (default: 20) Max number of iterations of Sinkhorn. See `sinkhorn()` for more details about this argument.
- **sk\_tau** – (default: 0.05) The temperature parameter of Sinkhorn. See `sinkhorn()` for more details about this argument.
- **network** – (default: None) The network object. If None, a new network object will be created, and load the model weights specified in **pretrain** argument.
- **return\_network** – (default: False) Return the network object (saving model construction time if calling the model multiple times).
- **pretrain** – (default: ‘voc’) If **network**==None, the pretrained model weights to be loaded. Available pretrained weights: **voc** (on Pascal VOC Keypoint dataset), **willow** (on Willow Object Class dataset), or **False** (no pretraining).
- **backend** – (default: `pygmtools.BACKEND` variable) the backend for computation.

**Returns**

if `return_network==False`,  $(b \times n_1 \times n_2)$  the doubly-stochastic matching matrix

if `return_network==True`,  $(b \times n_1 \times n_2)$  the doubly-stochastic matching matrix, the network object

---

**Note:** You may need a proxy to load the pretrained weights if Google drive is not accessible in your country/region.

---



---

**Note:** This function also supports non-batched input, by ignoring all batch dimensions in the input tensors.

---

**PyTorch Example**

```
>>> import torch
>>> import pygmtools as pygm
>>> pygm.BACKEND = 'pytorch'
>>> _ = torch.manual_seed(1)

# Generate a batch of isomorphic graphs
>>> batch_size = 10
>>> X_gt = torch.zeros(batch_size, 4, 4)
>>> X_gt[:, torch.arange(0, 4, dtype=torch.int64), torch.randperm(4)] = 1
>>> A1 = 1. * (torch.rand(batch_size, 4, 4) > 0.5)
>>> torch.diagonal(A1, dim1=1, dim2=2)[:,:] = 0 # discard self-loop edges
>>> A2 = torch.bmm(torch.bmm(X_gt.transpose(1, 2), A1), X_gt)
>>> feat1 = torch.rand(batch_size, 4, 1024) - 0.5
>>> feat2 = torch.bmm(X_gt.transpose(1, 2), feat1)
>>> n1 = n2 = torch.tensor([4] * batch_size)

# Match by IPCA-GM (load pretrained model)
>>> X, net = pygm.ipca_gm(feat1, feat2, A1, A2, n1, n2, return_network=True)
Downloading to ~/.cache/pygmtools/ipca_gm_voc_pytorch.pt...
>>> (pygm.hungarian(X) * X_gt).sum() / X_gt.sum() # accuracy
tensor(1.)

# Pass the net object to avoid rebuilding the model again
>>> X = pygm.ipca_gm(feat1, feat2, A1, A2, n1, n2, network=net)

# You may also load other pretrained weights
>>> X, net = pygm.ipca_gm(feat1, feat2, A1, A2, n1, n2, return_network=True,
↳ pretrain='willow')
Downloading to ~/.cache/pygmtools/ipca_gm_willow_pytorch.pt...

# You may configure your own model and integrate the model into a deep learning
↳ pipeline. For example:
>>> net = pygm.utils.get_network(pygm.ipca_gm, in_channel=1024, hidden_channel=2048,
↳ out_channel=512, num_layers=3, cross_iter=10, pretrain=False)
>>> optimizer = torch.optim.SGD(net.parameters(), lr=0.001, momentum=0.9)
# feat1/feat2 may be outputs by other neural networks
```

(continues on next page)

(continued from previous page)

```

>>> X = pygm.ipca_gm(featl1, feat2, A1, A2, n1, n2, network=net)
>>> loss = pygm.utils.permutation_loss(X, X_gt)
>>> loss.backward()
>>> optimizer.step()

```

### Jittor Example

```

>>> import jittor as jt
>>> import pygmtools as pygm
>>> pygm.BACKEND = 'jittor'
>>> _ = jt.seed(1)

# Generate a batch of isomorphic graphs
>>> batch_size = 10
>>> X_gt = jt.zeros((batch_size, 4, 4))
>>> X_gt[:, jt.arange(0, 4, dtype=jt.int64), jt.randperm(4)] = 1
>>> A1 = 1. * (jt.rand(batch_size, 4, 4) > 0.5)
>>> for i in range(batch_size):
>>>     for j in range(4):
>>>         A1.data[i][j][j] = 0 # discard self-loop edges
>>> A2 = jt.bmm(jt.bmm(X_gt.transpose(1, 2), A1), X_gt)
>>> feat1 = jt.rand(batch_size, 4, 1024) - 0.5
>>> feat2 = jt.bmm(X_gt.transpose(1, 2), feat1)
>>> n1 = n2 = jt.Var([4] * batch_size)

# Match by IPCA-GM (load pretrained model)
>>> X, net = pygm.ipca_gm(featl1, feat2, A1, A2, n1, n2, return_network=True)
Downloading to ~/.cache/pygmtools/ipca_gm_voc_jittor.pt...
>>> (pygm.hungarian(X) * X_gt).sum() / X_gt.sum() # accuracy
jt.Var([1.], dtype=float32)

# Pass the net object to avoid rebuilding the model again
>>> X = pygm.ipca_gm(featl1, feat2, A1, A2, n1, n2, network=net)

# You may also load other pretrained weights
>>> X, net = pygm.ipca_gm(featl1, feat2, A1, A2, n1, n2, return_network=True,
↳ pretrain='willow')
Downloading to ~/.cache/pygmtools/ipca_gm_willow_jittor.pt...

# You may configure your own model and integrate the model into a deep learning
↳ pipeline. For example:
>>> net = pygm.utils.get_network(pygm.ipca_gm, in_channel=1024, hidden_channel=2048,
↳ out_channel=512, num_layers=3, cross_iter=10, pretrain=False)
>>> optimizer = jt.optim.SGD(net.parameters(), lr=0.001, momentum=0.9)
# feat1/feat2 may be outputs by other neural networks
>>> X = pygm.ipca_gm(featl1, feat2, A1, A2, n1, n2, network=net)
>>> loss = pygm.utils.permutation_loss(X, X_gt)
>>> optimizer.backward(loss)
>>> optimizer.step()

```

**Note:** If you find this model useful in your research, please cite:

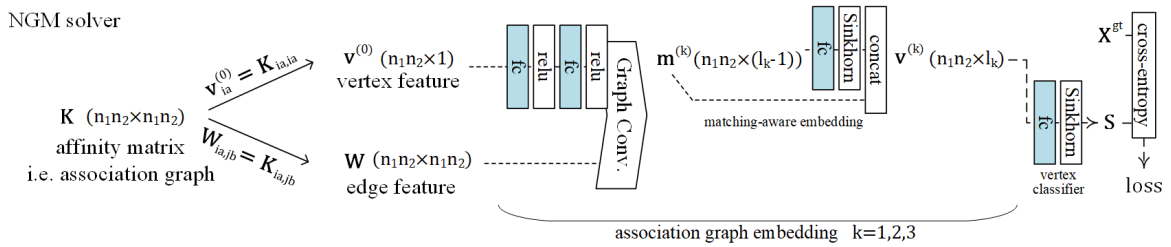
```
@article{WangPAMI20,
  author = {Wang, Runzhong and Yan, Junchi and Yang, Xiaokang},
  title = {Combinatorial Learning of Robust Deep Graph Matching: an Embedding based_
  Approach},
  journal = {IEEE Transactions on Pattern Analysis and Machine Intelligence},
  year = {2020}
}
```

## pygmtools.neural\_solvers.ngm

`pygmtools.neural_solvers.ngm(K, n1=None, n2=None, n1max=None, n2max=None, x0=None, gnn_channels=(16, 16, 16), sk_emb=1, sk_max_iter=20, sk_tau=0.05, network=None, return_network=False, pretrain='voc', backend=None)`

The **NGM** (Neural Graph Matching) model for processing the affinity matrix (the most general form of Lawler's QAP). The math form of graph matching (Lawler's QAP) is equivalent to a vertex classification problem on the **association graph**, which is an equivalent formulation based on the affinity matrix  $\mathbf{K}$ . The graph matching module is composed of several graph convolution layers, Sinkhorn embedding layers and finally a Sinkhorn layer to output a doubly-stochastic matrix.

See the following pipeline for an example:



See the following paper for more technical details: “Wang et al. Neural Graph Matching Network: Learning Lawler’s Quadratic Assignment Problem With Extension to Hypergraph and Multiple-Graph Matching. TPAMI 2022.”

### Parameters

- $\mathbf{K}$  – ( $b \times n_1 n_2 \times n_1 n_2$ ) the input affinity matrix,  $b$ : batch size.
- $n_1$  – ( $b$ ) number of nodes in graph1 (optional if  $n_1max$  is given, and all  $n_1=n_1max$ ).
- $n_2$  – ( $b$ ) number of nodes in graph2 (optional if  $n_2max$  is given, and all  $n_2=n_2max$ ).
- $n_1max$  – ( $b$ ) max number of nodes in graph1 (optional if  $n_1$  is given, and  $n_1max=\max(n_1)$ ).
- $n_2max$  – ( $b$ ) max number of nodes in graph2 (optional if  $n_2$  is given, and  $n_2max=\max(n_2)$ ).
- $\mathbf{x}_0$  – ( $b \times n_1 \times n_2$ ) an initial matching solution to warm-start the vertex embedding. If not given, the vertex embedding is initialized as a vector of all 1s.
- `gnn_channels` – (default: (16, 16, 16)) A list/tuple of channel sizes of the GNN. Ignored if the network object is given (ignored if `network!=None`).
- `sk_emb` – (default: 1) Number of Sinkhorn embedding channels. Sinkhorn embedding is designed to encode the matching constraints inside GNN layers. How it works: a Sinkhorn

embedding channel accepts the vertex feature from the current layer and computes a doubly-stochastic matrix, which is then concatenated to the vertex feature. Ignored if the network object is given (ignored if `network!=None`)

- **sk\_max\_iter** – (default: 20) Max number of iterations of Sinkhorn. See `sinkhorn()` for more details about this argument.
- **sk\_tau** – (default: 0.05) The temperature parameter of Sinkhorn. See `sinkhorn()` for more details about this argument.
- **network** – (default: None) The network object. If None, a new network object will be created, and load the model weights specified in `pretrain` argument.
- **return\_network** – (default: False) Return the network object (saving model construction time if calling the model multiple times).
- **pretrain** – (default: 'voc') If `network==None`, the pretrained model weights to be loaded. Available pretrained weights: `voc` (on Pascal VOC Keypoint dataset), `willow` (on Willow Object Class dataset), or `False` (no pretraining).
- **backend** – (default: `pygmtools.BACKEND` variable) the backend for computation.

#### Returns

if `return_network==False`,  $(b \times n_1 \times n_2)$  the doubly-stochastic matching matrix

if `return_network==True`,  $(b \times n_1 \times n_2)$  the doubly-stochastic matching matrix, the network object

---

**Note:** You may need a proxy to load the pretrained weights if Google drive is not accessible in your country/region.

---



---

**Note:** This function also supports non-batched input, by ignoring all batch dimensions in the input tensors.

---

#### PyTorch Example

```
>>> import torch
>>> import pygmtools as pygm
>>> pygm.BACKEND = 'pytorch'
>>> _ = torch.manual_seed(1)

# Generate a batch of isomorphic graphs
>>> batch_size = 10
>>> X_gt = torch.zeros(batch_size, 4, 4)
>>> X_gt[:, torch.arange(0, 4, dtype=torch.int64), torch.randperm(4)] = 1
>>> A1 = torch.rand(batch_size, 4, 4)
>>> A2 = torch.bmm(torch.bmm(X_gt.transpose(1, 2), A1), X_gt)
>>> n1 = n2 = torch.tensor([4] * batch_size)

# Build affinity matrix
>>> conn1, edge1, ne1 = pygm.utils.dense_to_sparse(A1)
>>> conn2, edge2, ne2 = pygm.utils.dense_to_sparse(A2)
>>> import functools
>>> gaussian_aff = functools.partial(pygm.utils.gaussian_aff_fn, sigma=1.) # set_
```

(continues on next page)

(continued from previous page)

```

↪affinity function
>>> K = pygm.utils.build_aff_mat(None, edge1, conn1, None, edge2, conn2, n1, None,
↪n2, None, edge_aff_fn=gaussian_aff)

# Solve by NGM
>>> X, net = pygm.ngm(K, n1, n2, return_network=True)
Downloading to ~/.cache/pygmtools/ngm_voc_pytorch.pt...
>>> (pygm.hungarian(X) * X_gt).sum() / X_gt.sum() # accuracy
tensor(1.)

# Pass the net object to avoid rebuilding the model again
>>> X = pygm.ngm(K, n1, n2, network=net)

# You may also load other pretrained weights
>>> X, net = pygm.ngm(K, n1, n2, return_network=True, pretrain='willow')
Downloading to ~/.cache/pygmtools/ngm_willow_pytorch.pt...

# You may configure your own model and integrate the model into a deep learning
↪pipeline. For example:
>>> net = pygm.utils.get_network(pygm.ngm, gnn_channels=(32, 64, 128, 64, 32), sk_
↪emb=8, pretrain=False)
>>> optimizer = torch.optim.SGD(net.parameters(), lr=0.001, momentum=0.9)
# K may be outputs by other neural networks (constructed K from node/edge features
↪by pygm.utils.build_aff_mat)
>>> X = pygm.ngm(K, n1, n2, network=net)
>>> loss = pygm.utils.permutation_loss(X, X_gt)
>>> loss.backward()
>>> optimizer.step()

```

## Jittor Example

```

>>> import jittor as jt
>>> import pygmtools as pygm
>>> pygm.BACKEND = 'jittor'
>>> _ = jt.seed(1)

# Generate a batch of isomorphic graphs
>>> batch_size = 10
>>> X_gt = jt.zeros((batch_size, 4, 4))
>>> X_gt[:, jt.arange(0, 4, dtype=jt.int64), jt.randperm(4)] = 1
>>> A1 = jt.rand(batch_size, 4, 4)
>>> A2 = jt.bmm(jt.bmm(X_gt.transpose(1, 2), A1), X_gt)
>>> n1 = n2 = jt.Var([4] * batch_size)

# Build affinity matrix
>>> conn1, edge1, ne1 = pygm.utils.dense_to_sparse(A1)
>>> conn2, edge2, ne2 = pygm.utils.dense_to_sparse(A2)
import functools
>>> gaussian_aff = functools.partial(pygm.utils.gaussian_aff_fn, sigma=1.) # set_
↪affinity function

```

(continues on next page)

(continued from previous page)

```

>>> K = pygm.utils.build_aff_mat(None, edge1, conn1, None, edge2, conn2, n1, None,
↳n2, None, edge_aff_fn=gaussian_aff)

# Solve by NGM
>>> X, net = pygm.ngm(K, n1, n2, return_network=True)
# Downloading to ~/.cache/pygmtools/ngm_voc_jittor.pt...
>>> (pygm.hungarian(X) * X_gt).sum() / X_gt.sum() # accuracy
jt.Var([1.], dtype=float32)

# Pass the net object to avoid rebuilding the model again
>>> X = pygm.ngm(K, n1, n2, network=net)

# You may also load other pretrained weights
>>> X, net = pygm.ngm(K, n1, n2, return_network=True, pretrain='willow')
# Downloading to ~/.cache/pygmtools/ngm_willow_jittor.pt...

# You may configure your own model and integrate the model into a deep learning
↳pipeline. For example:
>>> net = pygm.utils.get_network(pygm.ngm, gnn_channels=(32, 64, 128, 64, 32), sk_
↳emb=8, pretrain=False)
>>> optimizer = jt.optim.SGD(net.parameters(), lr=0.001, momentum=0.9)
# K may be outputs by other neural networks (constructed K from node/edge features
↳by pygm.utils.build_aff_mat)
>>> X = pygm.ngm(K, n1, n2, network=net)
>>> loss = pygm.utils.permutation_loss(X, X_gt)
>>> optimizer.backward(loss)
>>> optimizer.step()

```

**Note:** If you find this model useful in your research, please cite:

```

@ARTICLE{WangPAMI22,
  author={Wang, Runzhong and Yan, Junchi and Yang, Xiaokang},
  journal={IEEE Transactions on Pattern Analysis and Machine Intelligence},
  title={Neural Graph Matching Network: Learning Lawler's Quadratic Assignment
↳Problem With Extension to Hypergraph and Multiple-Graph Matching},
  year={2022},
  volume={44},
  number={9},
  pages={5261-5279},
  doi={10.1109/TPAMI.2021.3078053}
}

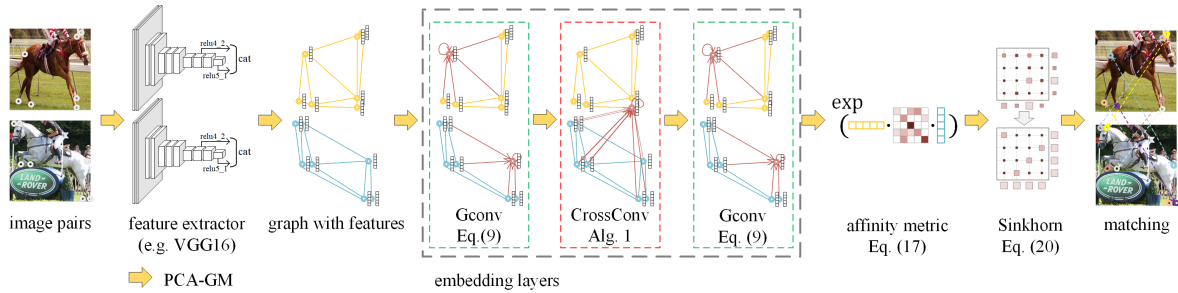
```

## pygmtools.neural\_solvers.pca\_gm

```
pygmtools.neural_solvers.pca_gm(featl1, featl2, A1, A2, n1=None, n2=None, in_channel=1024,
                                hidden_channel=2048, out_channel=2048, num_layers=2,
                                sk_max_iter=20, sk_tau=0.05, network=None, return_network=False,
                                pretrain='voc', backend=None)
```

The **PCA-GM** (Permutation loss and Cross-graph Affinity Graph Matching) neural network model for processing two individual graphs (KB-QAP). The graph matching module is composed of several intra-graph embedding layers, a cross-graph embedding layer, and a Sinkhorn matching layer. Only the second last layer has a cross-graph update layer.

See the following pipeline for an example, with application to visual graph matching (layers in the gray box are implemented by pygmtools):



See the following paper for more technical details: “Wang et al. [Combinatorial Learning of Robust Deep Graph Matching: an Embedding based Approach](#). TPAMI 2020.”

You may be also interested in the extended version IPCA-GM (see [ipca\\_gm\(\)](#)).

## Parameters

- **featl1** –  $(b \times n_1 \times d)$  input feature of graph1
- **featl2** –  $(b \times n_2 \times d)$  input feature of graph2
- **A1** –  $(b \times n_1 \times n_1)$  input adjacency matrix of graph1
- **A2** –  $(b \times n_2 \times n_2)$  input adjacency matrix of graph2
- **n1** –  $(b)$  number of nodes in graph1. Optional if all equal to  $n_1$
- **n2** –  $(b)$  number of nodes in graph2. Optional if all equal to  $n_2$
- **in\_channel** – (default: 1024) Channel size of the input layer. It must match the feature dimension ( $d$ ) of **featl1**, **featl2**. Ignored if the network object is given (ignored if **network!=None**)
- **hidden\_channel** – (default: 2048) Channel size of hidden layers. Ignored if the network object is given (ignored if **network!=None**)
- **out\_channel** – (default: 2048) Channel size of the output layer. Ignored if the network object is given (ignored if **network!=None**)
- **num\_layers** – (default: 2) Number of graph embedding layers. Must be  $\geq 2$ . Ignored if the network object is given (ignored if **network!=None**)
- **sk\_max\_iter** – (default: 20) Max number of iterations of Sinkhorn. See [sinkhorn\(\)](#) for more details about this argument.
- **sk\_tau** – (default: 0.05) The temperature parameter of Sinkhorn. See [sinkhorn\(\)](#) for more details about this argument.



- **network** – (default: None) The network object. If None, a new network object will be created, and load the model weights specified in `pretrain` argument.
- **return\_network** – (default: False) Return the network object (saving model construction time if calling the model multiple times).
- **pretrain** – (default: 'voc') If `network==None`, the pretrained model weights to be loaded. Available pretrained weights: `voc` (on Pascal VOC Keypoint dataset), `willow` (on Willow Object Class dataset), `voc-all` (on Pascal VOC Keypoint dataset, without filtering), or `False` (no pretraining).
- **backend** – (default: `pygmtools.BACKEND` variable) the backend for computation.

### Returns

if `return_network==False`,  $(b \times n_1 \times n_2)$  the doubly-stochastic matching matrix

if `return_network==True`,  $(b \times n_1 \times n_2)$  the doubly-stochastic matching matrix, the network object

---

**Note:** You may need a proxy to load the pretrained weights if Google drive is not accessible in your country/region.

---



---

**Note:** This function also supports non-batched input, by ignoring all batch dimensions in the input tensors.

---

### PyTorch Example

```
>>> import torch
>>> import pygmtools as pygm
>>> pygm.BACKEND = 'pytorch'
>>> _ = torch.manual_seed(1)

# Generate a batch of isomorphic graphs
>>> batch_size = 10
>>> X_gt = torch.zeros(batch_size, 4, 4)
>>> X_gt[:, torch.arange(0, 4, dtype=torch.int64), torch.randperm(4)] = 1
>>> A1 = 1. * (torch.rand(batch_size, 4, 4) > 0.5)
>>> torch.diagonal(A1, dim1=1, dim2=2)[:]= 0 # discard self-loop edges
>>> A2 = torch.bmm(torch.bmm(X_gt.transpose(1, 2), A1), X_gt)
>>> feat1 = torch.rand(batch_size, 4, 1024) - 0.5
>>> feat2 = torch.bmm(X_gt.transpose(1, 2), feat1)
>>> n1 = n2 = torch.tensor([4] * batch_size)

# Match by PCA-GM (load pretrained model)
>>> X, net = pygm.pca_gm(feat1, feat2, A1, A2, n1, n2, return_network=True)
Downloading to ~/.cache/pygmtools/pca_gm_voc_pytorch.pt...
>>> (pygm.hungarian(X) * X_gt).sum() / X_gt.sum() # accuracy
tensor(1.)

# Pass the net object to avoid rebuilding the model again
>>> X = pygm.pca_gm(feat1, feat2, A1, A2, n1, n2, network=net)
```

(continues on next page)

(continued from previous page)

```
# You may also load other pretrained weights
>>> X, net = pygm.pca_gm(featl1, feat2, A1, A2, n1, n2, return_network=True,
↳pretrain='willow')
Downloading to ~/.cache/pygmtools/pca_gm_willow_pytorch.pt...

# You may configure your own model and integrate the model into a deep learning
↳pipeline. For example:
>>> net = pygm.utils.get_network(pygm.pca_gm, in_channel=1024, hidden_channel=2048,
↳out_channel=512, num_layers=3, pretrain=False)
>>> optimizer = torch.optim.SGD(net.parameters(), lr=0.001, momentum=0.9)
# feat1/feat2 may be outputs by other neural networks
>>> X = pygm.pca_gm(featl1, feat2, A1, A2, n1, n2, network=net)
>>> loss = pygm.utils.permutation_loss(X, X_gt)
>>> loss.backward()
>>> optimizer.step()
```

### Jittor Example

```
>>> import jittor as jt
>>> import pygmtools as pygm
>>> pygm.BACKEND = 'jittor'
>>> _ = jt.seed(1)

# Generate a batch of isomorphic graphs
>>> batch_size = 10
>>> X_gt = jt.zeros((batch_size, 4, 4))
>>> X_gt[:, jt.arange(0, 4, dtype=jt.int64), jt.randperm(4)] = 1
>>> A1 = 1. * (jt.rand(batch_size, 4, 4) > 0.5)
>>> for i in range(batch_size):
>>>     for j in range(4):
>>>         A1.data[i][j][j] = 0 # discard self-loop edges
>>> A2 = jt.bmm(jt.bmm(X_gt.transpose(1, 2), A1), X_gt)
>>> feat1 = jt.rand(batch_size, 4, 1024) - 0.5
>>> feat2 = jt.bmm(X_gt.transpose(1, 2), feat1)
>>> n1 = n2 = jt.Var([4] * batch_size)

# Match by PCA-GM (load pretrained model)
>>> X, net = pygm.pca_gm(featl1, feat2, A1, A2, n1, n2, return_network=True)
Downloading to ~/.cache/pygmtools/pca_gm_voc_jittor.pt...

# Pass the net object to avoid rebuilding the model again
>>> X = pygm.pca_gm(featl1, feat2, A1, A2, n1, n2, network=net)

# You may also load other pretrained weights
>>> X, net = pygm.pca_gm(featl1, feat2, A1, A2, n1, n2, return_network=True,
↳pretrain='willow')
Downloading to ~/.cache/pygmtools/pca_gm_willow_jittor.pt...
>>> (pygm.hungarian(X) * X_gt).sum() / X_gt.sum() # accuracy
jt.Var([1.], dtype=float32)
```

(continues on next page)

(continued from previous page)

```
# You may configure your own model and integrate the model into a deep learning
↳ pipeline. For example:
>>> net = pygm.utils.get_network(pygm.pca_gm, in_channel=1024, hidden_channel=2048,
↳ out_channel=512, num_layers=3, pretrain=False)
>>> optimizer = jt.optim.SGD(net.parameters(), lr=0.001, momentum=0.9)
# feat1/feat2 may be outputs by other neural networks
>>> X = pygm.pca_gm(feat1, feat2, A1, A2, n1, n2, network=net)
>>> loss = pygm.utils.permutation_loss(X, X_gt)
>>> optimizer.backward(loss)
>>> optimizer.step()
```

**Note:** If you find this model useful in your research, please cite:

```
@article{WangPAMI20,
  author = {Wang, Runzhong and Yan, Junchi and Yang, Xiaokang},
  title = {Combinatorial Learning of Robust Deep Graph Matching: an Embedding based
↳ Approach},
  journal = {IEEE Transactions on Pattern Analysis and Machine Intelligence},
  year = {2020}
}
```

### 9.4.5 pygmtools.utils

Utility functions: problem formulating, data processing, and beyond.

#### Functions

<i>build_aff_mat</i>	Build affinity matrix for graph matching from input node/edge features.
<i>build_batch</i>	Build a batched tensor from a list of tensors.
<i>compute_affinity_score</i>	Compute the affinity score of graph matching.
<i>dense_to_sparse</i>	Convert a dense connectivity/adjacency matrix to a sparse connectivity/adjacency matrix and an edge weight tensor.
<i>download</i>	Check if content exists.
<i>from_numpy</i>	Convert a numpy ndarray to a tensor.
<i>gaussian_aff_fn</i>	Gaussian kernel affinity function.
<i>generate_isomorphic_graphs</i>	Generate a set of isomorphic graphs, for testing purposes and examples.
<i>get_network</i>	Get the network object of a neural network solver.
<i>inner_prod_aff_fn</i>	Inner product affinity function.
<i>permutation_loss</i>	Binary cross entropy loss between two permutations, also known as "permutation loss".
<i>to_numpy</i>	Convert a tensor to a numpy ndarray.

**pygmtools.utils.build\_aff\_mat**

`pygmtools.utils.build_aff_mat(node_feat1, edge_feat1, connectivity1, node_feat2, edge_feat2, connectivity2, n1=None, ne1=None, n2=None, ne2=None, node_aff_fn=None, edge_aff_fn=None, backend=None)`

Build affinity matrix for graph matching from input node/edge features. The affinity matrix encodes both node-wise and edge-wise affinities and formulates the Quadratic Assignment Problem (QAP), which is the mathematical form of graph matching.

**Parameters**

- **node\_feat1** –  $(b \times n_1 \times f_{node})$  the node feature of graph1
- **edge\_feat1** –  $(b \times ne_1 \times f_{edge})$  the edge feature of graph1
- **connectivity1** –  $(b \times ne_1 \times 2)$  sparse connectivity information of graph 1. `connectivity1[i, j, 0]` is the starting node index of edge j at batch i, and `connectivity1[i, j, 1]` is the ending node index of edge j at batch i
- **node\_feat2** –  $(b \times n_2 \times f_{node})$  the node feature of graph2
- **edge\_feat2** –  $(b \times ne_2 \times f_{edge})$  the edge feature of graph2
- **connectivity2** –  $(b \times ne_2 \times 2)$  sparse connectivity information of graph 2. `connectivity2[i, j, 0]` is the starting node index of edge j at batch i, and `connectivity2[i, j, 1]` is the ending node index of edge j at batch i
- **n1** –  $(b)$  number of nodes in graph1. If not given, it will be inferred based on the shape of `node_feat1` or the values in `connectivity1`
- **ne1** –  $(b)$  number of edges in graph1. If not given, it will be inferred based on the shape of `edge_feat1`
- **n2** –  $(b)$  number of nodes in graph2. If not given, it will be inferred based on the shape of `node_feat2` or the values in `connectivity2`
- **ne2** –  $(b)$  number of edges in graph2. If not given, it will be inferred based on the shape of `edge_feat2`
- **node\_aff\_fn** – (default: `inner_prod_aff_fn`) the node affinity function with the characteristic `node_aff_fn(2D Tensor, 2D Tensor) -> 2D Tensor`, which accepts two node feature tensors and outputs the node-wise affinity tensor. See [inner\\_prod\\_aff\\_fn\(\)](#) as an example.
- **edge\_aff\_fn** – (default: `inner_prod_aff_fn`) the edge affinity function with the characteristic `edge_aff_fn(2D Tensor, 2D Tensor) -> 2D Tensor`, which accepts two edge feature tensors and outputs the edge-wise affinity tensor. See [inner\\_prod\\_aff\\_fn\(\)](#) as an example.
- **backend** – (default: `pygmtools.BACKEND` variable) the backend for computation.

**Returns**

$(b \times n_1 n_2 \times n_1 n_2)$  the affinity matrix

---

**Note:** This function also supports non-batched input, by ignoring all batch dimensions in the input tensors.

---

## Numpy Example

```
>>> import numpy as np
>>> import pygmtools as pygm
>>> pygm.BACKEND = 'numpy'

# Generate a batch of graphs
>>> batch_size = 10
>>> A1 = np.random.rand(batch_size, 4, 4)
>>> A2 = np.random.rand(batch_size, 4, 4)
>>> n1 = n2 = np.repeat([4], batch_size)

# Build affinity matrix by the default inner-product function
>>> conn1, edge1, ne1 = pygm.utils.dense_to_sparse(A1)
>>> conn2, edge2, ne2 = pygm.utils.dense_to_sparse(A2)
>>> K = pygm.utils.build_aff_mat(None, edge1, conn1, None, edge2, conn2, n1, ne1,
↳n2, ne2)

# Build affinity matrix by gaussian kernel
>>> import functools
>>> gaussian_aff = functools.partial(pygm.utils.gaussian_aff_fn, sigma=1.)
>>> K2 = pygm.utils.build_aff_mat(None, edge1, conn1, None, edge2, conn2, n1, ne1,
↳n2, ne2, edge_aff_fn=gaussian_aff)

# Build affinity matrix based on node features
>>> F1 = np.random.rand(batch_size, 4, 10)
>>> F2 = np.random.rand(batch_size, 4, 10)
>>> K3 = pygm.utils.build_aff_mat(F1, edge1, conn1, F2, edge2, conn2, n1, ne1, n2,
↳ne2, edge_aff_fn=gaussian_aff)

# The affinity matrices K, K2, K3 can be further processed by GM solvers
```

## Pytorch Example

```
>>> import torch
>>> import pygmtools as pygm
>>> pygm.BACKEND = 'pytorch'

# Generate a batch of graphs
>>> batch_size = 10
>>> A1 = torch.rand(batch_size, 4, 4)
>>> A2 = torch.rand(batch_size, 4, 4)
>>> n1 = n2 = torch.tensor([4] * batch_size)

# Build affinity matrix by the default inner-product function
>>> conn1, edge1, ne1 = pygm.utils.dense_to_sparse(A1)
>>> conn2, edge2, ne2 = pygm.utils.dense_to_sparse(A2)
>>> K = pygm.utils.build_aff_mat(None, edge1, conn1, None, edge2, conn2, n1, ne1,
↳n2, ne2)

# Build affinity matrix by gaussian kernel
```

(continues on next page)

(continued from previous page)

```

>>> import functools
>>> gaussian_aff = functools.partial(pygm.utils.gaussian_aff_fn, sigma=1.)
>>> K2 = pygm.utils.build_aff_mat(None, edge1, conn1, None, edge2, conn2, n1, ne1,
↳n2, ne2, edge_aff_fn=gaussian_aff)

# Build affinity matrix based on node features
>>> F1 = torch.rand(batch_size, 4, 10)
>>> F2 = torch.rand(batch_size, 4, 10)
>>> K3 = pygm.utils.build_aff_mat(F1, edge1, conn1, F2, edge2, conn2, n1, ne1, n2,
↳ne2, edge_aff_fn=gaussian_aff)

# The affinity matrices K, K2, K3 can be further processed by GM solvers

```

## Paddle Example

::

```

>>> import paddle
>>> import pygmtools as pygm
>>> pygm.BACKEND = 'paddle'

# Generate a batch of graphs >>> batch_size = 10 >>> A1 = paddle.rand((batch_size, 4, 4)) >>> A2 =
paddle.rand((batch_size, 4, 4)) >>> n1 = n2 = paddle.t0_tensor([4] * batch_size)

# Build affinity matrix by the default inner-product function >>> conn1, edge1, ne1 =
pygm.utils.dense_to_sparse(A1) >>> conn2, edge2, ne2 = pygm.utils.dense_to_sparse(A2) >>> K =
pygm.utils.build_aff_mat(None, edge1, conn1, None, edge2, conn2, n1, ne1, n2, ne2)

# Build affinity matrix by gaussian kernel >>> import functools >>> gaussian_aff = func-
tools.partial(pygm.utils.gaussian_aff_fn, sigma=1.) >>> K2 = pygm.utils.build_aff_mat(None, edge1,
conn1, None, edge2, conn2, n1, ne1, n2, ne2, edge_aff_fn=gaussian_aff)

# Build affinity matrix based on node features >>> F1 = paddle.rand((batch_size, 4, 10)) >>> F2 = pad-
dle.rand((batch_size, 4, 10)) >>> K3 = pygm.utils.build_aff_mat(F1, edge1, conn1, F2, edge2, conn2, n1,
ne1, n2, ne2, edge_aff_fn=gaussian_aff)

# The affinity matrices K, K2, K3 can be further processed by GM solvers

```

## pygmtools.utils.build\_batch

`pygmtools.utils.build_batch(input, return_ori_dim=False, backend=None)`

Build a batched tensor from a list of tensors. If the list of tensors are with different sizes of dimensions, it will be padded to the largest dimension.

The batched tensor and the number of original dimensions will be returned.

### Parameters

- **input** – list of input tensors
- **return\_ori\_dim** – (default: False) return the original dimension
- **backend** – (default: `pygmtools.BACKEND` variable) the backend for computation.

### Returns

batched tensor, (if `return_ori_dim=True`) a list of the original dimensions

### Numpy Example

```
>>> import numpy as np
>>> import pygmtools as pygm
>>> pygm.BACKEND = 'numpy'

# batched adjacency matrices
>>> A1 = np.random.rand(4, 4)
>>> A2 = np.random.rand(5, 5)
>>> A3 = np.random.rand(3, 3)
>>> batched_A, ori_shape = pygm.utils.build_batch([A1, A2, A3], return_ori_dim=True)
>>> batched_A.shape
(3, 5, 5)
>>> ori_shape
([4, 5, 3], [4, 5, 3])

# batched node features (feature dimension=10)
>>> F1 = np.random.rand(4, 10)
>>> F2 = np.random.rand(5, 10)
>>> F3 = np.random.rand(3, 10)
>>> batched_F = pygm.utils.build_batch([F1, F2, F3])
>>> batched_F.shape
(3, 5, 10)
```

### Pytorch Example

```
>>> import torch
>>> import pygmtools as pygm
>>> pygm.BACKEND = 'pytorch'

# batched adjacency matrices
>>> A1 = torch.rand(4, 4)
>>> A2 = torch.rand(5, 5)
>>> A3 = torch.rand(3, 3)
>>> batched_A, ori_shape = pygm.utils.build_batch([A1, A2, A3], return_ori_dim=True)
>>> batched_A.shape
torch.Size([3, 5, 5])
>>> ori_shape
(tensor([4, 5, 3]), tensor([4, 5, 3]))

# batched node features (feature dimension=10)
>>> F1 = torch.rand(4, 10)
>>> F2 = torch.rand(5, 10)
>>> F3 = torch.rand(3, 10)
>>> batched_F = pygm.utils.build_batch([F1, F2, F3])
>>> batched_F.shape
torch.Size([3, 5, 10])
```

### Paddle Example

```
>>> import paddle
>>> import pygmtools as pygm
>>> pygm.BACKEND = 'paddle'

# batched adjacency matrices
>>> A1 = paddle.rand((4, 4))
>>> A2 = paddle.rand((5, 5))
>>> A3 = paddle.rand((3, 3))
>>> batched_A, ori_shape = pygm.utils.build_batch([A1, A2, A3], return_ori_dim=True)
>>> batched_A.shape
[3, 5, 5]
>>> ori_shape
(Tensor(shape=[3], dtype=int64, place=Place(cpu), stop_gradient=True, [4, 5, 3]),
 Tensor(shape=[3], dtype=int64, place=Place(cpu), stop_gradient=True, [4, 5, 3]))

# batched node features (feature dimension=10)
>>> F1 = paddle.rand((4, 10))
>>> F2 = paddle.rand((5, 10))
>>> F3 = paddle.rand((3, 10))
>>> batched_F = pygm.utils.build_batch([F1, F2, F3])
>>> batched_F.shape
[3, 5, 10]
```

### pygmtools.utils.compute\_affinity\_score

`pygmtools.utils.compute_affinity_score(X, K, backend=None)`

Compute the affinity score of graph matching. It is the objective score of the corresponding Quadratic Assignment Problem.

$$\text{vec}(\mathbf{X})^\top \mathbf{K} \text{vec}(\mathbf{X})$$

here `vec` means column-wise vectorization.

#### Parameters

- $\mathbf{X}$  – ( $b \times n_1 \times n_2$ ) the permutation matrix that represents the matching result
- $\mathbf{K}$  – ( $b \times n_1 n_2 \times n_1 n_2$ ) the affinity matrix
- **backend** – (default: `pygmtools.BACKEND` variable) the backend for computation.

#### Returns

(*b*) the objective score

---

**Note:** This function also supports non-batched input if the batch dimension of  $\mathbf{X}$ ,  $\mathbf{K}$  is ignored.

---



## Pytorch Example

```
>>> import pygmtools as pygm
>>> import torch
>>> pygm.BACKEND = 'pytorch'

# Generate a graph matching problem
>>> X_gt = torch.zeros(4, 4)
>>> X_gt[torch.arange(0, 4, dtype=torch.int64), torch.randperm(4)] = 1
>>> A1 = torch.rand(4, 4)
>>> A2 = torch.mm(torch.mm(X_gt.transpose(0,1), A1), X_gt)
>>> conn1, edge1 = pygm.utils.dense_to_sparse(A1)
>>> conn2, edge2 = pygm.utils.dense_to_sparse(A2)
>>> import functools
>>> gaussian_aff = functools.partial(pygm.utils.gaussian_aff_fn, sigma=1.)
>>> K = pygm.utils.build_aff_mat(None, edge1, conn1, None, edge2, conn2, None, None,
→ None, None, edge_aff_fn=gaussian_aff)

# Compute the objective score of ground truth matching
>>> pygm.utils.compute_affinity_score(X_gt, K)
tensor(16.)
```

## pygmtools.utils.dense\_to\_sparse

`pygmtools.utils.dense_to_sparse(dense_adj, backend=None)`

Convert a dense connectivity/adjacency matrix to a sparse connectivity/adjacency matrix and an edge weight tensor.

### Parameters

- **dense\_adj** – ( $b \times n \times n$ ) the dense adjacency matrix. This function also supports non-batched input where the batch dimension  $b$  is ignored
- **backend** – (default: `pygmtools.BACKEND` variable) the backend for computation.

### Returns

if batched input: ( $b \times ne \times 2$ ) sparse connectivity matrix, ( $b \times ne \times 1$ ) edge weight tensor, ( $b$ ) number of edges

if non-batched input: ( $ne \times 2$ ) sparse connectivity matrix, ( $ne \times 1$ ) edge weight tensor,

## Numpy Example

```
>>> import numpy as np
>>> import pygmtools as pygm
>>> pygm.BACKEND = 'numpy'
>>> np.random.seed(0)

>>> batch_size = 10
>>> A = np.random.rand(batch_size, 4, 4)
>>> A[:, np.arange(4), np.arange(4)] = 0 # remove the diagonal elements
>>> A.shape
```

(continues on next page)

(continued from previous page)

```

(10, 4, 4)

>>> conn, edge, ne = pygm.utils.dense_to_sparse(A)
>>> conn.shape # connectivity: (batch x num_edge x 2)
(10, 12, 2)

>>> edge.shape # edge feature (batch x num_edge x feature_dim)
(10, 12, 1)

>>> ne
[12, 12, 12, 12, 12, 12, 12, 12, 12, 12]

```

### Pytorch Example

```

>>> import torch
>>> import pygmtools as pygm
>>> pygm.BACKEND = 'pytorch'
>>> _ = torch.manual_seed(0)

>>> batch_size = 10
>>> A = torch.rand(batch_size, 4, 4)
>>> torch.diagonal(A, dim1=1, dim2=2)[:]= 0 # remove the diagonal elements
>>> A.shape
torch.Size([10, 4, 4])

>>> conn, edge, ne = pygm.utils.dense_to_sparse(A)
>>> conn.shape # connectivity: (batch x num_edge x 2)
torch.Size([10, 12, 2])

>>> edge.shape # edge feature (batch x num_edge x feature_dim)
torch.Size([10, 12, 1])

>>> ne
tensor([12, 12, 12, 12, 12, 12, 12, 12, 12, 12])

```

### Paddle Example

```

>>> import paddle
>>> import pygmtools as pygm
>>> pygm.BACKEND = 'paddle'
>>> paddle.seed(0)

>>> batch_size = 10
>>> A = paddle.rand((batch_size, 4, 4))
>>> paddle.diagonal(A, axis1=1, axis2=2)[:]= 0 # remove the diagonal elements
>>> A.shape
[10, 4, 4]

>>> conn, edge, ne = pygm.utils.dense_to_sparse(A)

```

(continues on next page)

(continued from previous page)

```
>>> conn.shape # connectivity: (batch x num_edge x 2)
torch.Size([10, 16, 2])

>>> edge.shape # edge feature (batch x num_edge x feature_dim)
torch.Size([10, 16, 1])

>>> ne
Tensor(shape=[10], dtype=int64, place=Place(cpu), stop_gradient=True,
        [16, 16, 16, 16, 16, 16, 16, 16, 16, 16])
```

## pygmtools.utils.download

`pygmtools.utils.download(filename, url, md5=None, retries=5)`

Check if content exists. If not, download the content to `<user cache path>/pygmtools/<filename>`. `<user cache path>` depends on your system. For example, on Debian, it should be `$HOME/.cache`.

### Parameters

- **filename** – the destination file name
- **url** – the url
- **md5** – (optional) the md5sum to verify the content. It should match the result of md5sum file on Linux.
- **retries** – (default: 5) max number of retries

### Returns

the full path to the file: `<user cache path>/pygmtools/<filename>`

## pygmtools.utils.from\_numpy

`pygmtools.utils.from_numpy(input, device=None, backend=None)`

Convert a numpy ndarray to a tensor. This is the helper function to convert tensors across different backends via numpy.

### Parameters

- **input** – input ndarray/*MultiMatchingResult*
- **device** – (default: None) the target device
- **backend** – (default: `pygmtools.BACKEND` variable) the backend for computation.

### Returns

tensor for the backend

### pygmtools.utils.gaussian\_aff\_fn

`pygmtools.utils.gaussian_aff_fn(feats1, feats2, sigma=1.0, backend=None)`

Gaussian kernel affinity function. The affinity is defined as

$$\exp\left(-\frac{(\mathbf{f}_1 - \mathbf{f}_2)^2}{\sigma}\right)$$

#### Parameters

- **feats1** –  $(b \times n_1 \times f)$  the feature vectors  $\mathbf{f}_1$
- **feats2** –  $(b \times n_2 \times f)$  the feature vectors  $\mathbf{f}_2$
- **sigma** – (default: 1) the parameter  $\sigma$  in Gaussian kernel
- **backend** – (default: `pygmtools.BACKEND` variable) the backend for computation.

#### Returns

$(b \times n_1 \times n_2)$  element-wise Gaussian affinity matrix

### pygmtools.utils.generate\_isomorphic\_graphs

`pygmtools.utils.generate_isomorphic_graphs(node_num, graph_num=2, node_feat_dim=0, backend=None)`

Generate a set of isomorphic graphs, for testing purposes and examples.

#### Parameters

- **node\_num** – number of nodes in each graph
- **graph\_num** – (default: 2) number of graphs
- **node\_feat\_dim** – (default: 0) number of node feature dimensions
- **backend** – (default: `pygmtools.BACKEND` variable) the backend for computation.

#### Returns

if `graph_num==2`, this function returns  $(m \times n \times n)$  the adjacency matrix, and  $(n \times n)$  the permutation matrix;

else, this function returns  $(m \times n \times n)$  the adjacency matrix, and  $(m \times m \times n \times n)$  the multi-matching permutation matrix

### pygmtools.utils.get\_network

`pygmtools.utils.get_network(nn_solver_func, **params)`

Get the network object of a neural network solver.

#### Parameters

- **nn\_solver\_func** – the neural network solver function, for example `pygm.pca_gm`
- **params** – keyword parameters to define the neural network

#### Returns

the network object

## Pytorch Example

```
>>> import pygmtools as pygm
>>> import torch
>>> pygm.BACKEND = 'pytorch'
>>> pygm.utils.get_network(pygm.pca_gm, pretrain='willow')
PCA_GM_Net(
  (gnn_layer_0): Siamese_Gconv(
    (gconv): Gconv(
      (a_fc): Linear(in_features=1024, out_features=2048, bias=True)
      (u_fc): Linear(in_features=1024, out_features=2048, bias=True)
    )
  )
  (cross_graph_0): Linear(in_features=4096, out_features=2048, bias=True)
  (affinity_0): WeightedInnerProdAffinity()
  (affinity_1): WeightedInnerProdAffinity()
  (gnn_layer_1): Siamese_Gconv(
    (gconv): Gconv(
      (a_fc): Linear(in_features=2048, out_features=2048, bias=True)
      (u_fc): Linear(in_features=2048, out_features=2048, bias=True)
    )
  )
)

# the neural network can be integrated into a deep learning pipeline
>>> net = pygm.utils.get_network(pygm.pca_gm, in_channel=1024, hidden_channel=2048,
↳ out_channel=512, num_layers=3, pretrain=False)
>>> optimizer = torch.optim.SGD(net.parameters(), lr=0.01, momentum=0.9)
```

## pygmtools.utils.inner\_prod\_aff\_fn

`pygmtools.utils.inner_prod_aff_fn(feat1, feat2, backend=None)`

Inner product affinity function. The affinity is defined as

$$\mathbf{f}_1^\top \cdot \mathbf{f}_2$$

### Parameters

- **feat1** – ( $b \times n_1 \times f$ ) the feature vectors  $\mathbf{f}_1$
- **feat2** – ( $b \times n_2 \times f$ ) the feature vectors  $\mathbf{f}_2$
- **backend** – (default: `pygmtools.BACKEND` variable) the backend for computation.

### Returns

( $b \times n_1 \times n_2$ ) element-wise inner product affinity matrix

### pygmtools.utils.permutation\_loss

`pygmtools.utils.permutation_loss(pred_dsmat, gt_perm, n1=None, n2=None, backend=None)`

Binary cross entropy loss between two permutations, also known as “permutation loss”. Proposed by “Wang et al. Learning Combinatorial Embedding Networks for Deep Graph Matching. ICCV 2019.”

$$L_{perm} = - \sum_{i \in \mathcal{V}_1, j \in \mathcal{V}_2} (\mathbf{X}_{i,j}^{gt} \log \mathbf{S}_{i,j} + (1 - \mathbf{X}_{i,j}^{gt}) \log(1 - \mathbf{S}_{i,j}))$$

where  $\mathcal{V}_1, \mathcal{V}_2$  are vertex sets for two graphs.

#### Parameters

- **pred\_dsmat** – ( $b \times n_1 \times n_2$ ) predicted doubly-stochastic matrix ( $\mathbf{S}$ )
- **gt\_perm** – ( $b \times n_1 \times n_2$ ) ground truth permutation matrix ( $\mathbf{X}^{gt}$ )
- **n1** – (optional) ( $b$ ) number of exact pairs in the first graph.
- **n2** – (optional) ( $b$ ) number of exact pairs in the second graph.
- **backend** – (default: `pygmtools.BACKEND` variable) the backend for computation.

#### Returns

- (1) averaged permutation loss

---

**Note:** We support batched instances with different number of nodes, therefore **n1** and **n2** are required if you want to specify the exact number of nodes of each instance in the batch.

---

---

**Note:** For batched input, this loss function computes the averaged loss among all instances in the batch. This function also supports non-batched input if the batch dimension ( $b$ ) is ignored.

---

### pygmtools.utils.to\_numpy

`pygmtools.utils.to_numpy(input, backend=None)`

Convert a tensor to a numpy ndarray. This is the helper function to convert tensors across different backends via numpy.

#### Parameters

- **input** – input tensor/*MultiMatchingResult*
- **backend** – (default: `pygmtools.BACKEND` variable) the backend for computation.

#### Returns

- numpy ndarray

## Classes

---

<i>MultiMatchingResult</i>	A memory-efficient class for multi-graph matching results.
----------------------------	--

---

### MultiMatchingResult

**class** pygmtools.utils.**MultiMatchingResult**(*cycle\_consistent=False, backend=None*)

A memory-efficient class for multi-graph matching results. For non-cycle consistent results, the dense storage for  $m$  graphs with  $n$  nodes requires a size of  $(m \times m \times n \times n)$ , and this implementation requires  $((m - 1) \times m \times n \times n/2)$ . For cycle consistent result, this implementation requires only  $(m \times n \times n)$ .

#### Numpy Example

```
>>> import numpy as np
>>> import pygmtools as pygm
>>> np.random.seed(0)

>>> X = pygm.utils.MultiMatchingResult(backend='numpy')
>>> X[0, 1] = np.zeros((4, 4))
>>> X[0, 1][np.arange(0, 4, dtype=np.int64), np.random.permutation(4)] = 1
>>> X
MultiMatchingResult:
{'0,1': array([[0., 0., 1., 0.],
               [0., 0., 0., 1.],
               [0., 1., 0., 0.],
               [1., 0., 0., 0.]])}
>>> X[1, 0]
array([[0., 0., 0., 1.],
       [0., 0., 1., 0.],
       [1., 0., 0., 0.],
       [0., 1., 0., 0.]])
```

**static from\_numpy**(*data, device=None, new\_backend=None*)

Convert a numpy-backend MultiMatchingResult data to another backend.

#### Parameters

- **data** – the numpy-backend data
- **device** – (default: None) the target device
- **new\_backend** – (default: pygmtools.BACKEND variable) the target backend

#### Returns

a new MultiMatchingResult instance for new\_backend on device

**from\_numpy\_**(*device=None, new\_backend=None*)

In-place operation for [from\\_numpy\(\)](#).

**static to\_numpy**(*data*)

Convert an any-type MultiMatchingResult to numpy backend.

**Parameters**

**data** – the any-type data

**Returns**

a new MultiMatchingResult instance for numpy

**to\_numpy\_()**

In-place operation for [to\\_numpy\(\)](#).

## 9.4.6 pygmtools.benchmark

The Benchmark module with a unified data interface to evaluate graph matching methods.

If you are interested in the performance and the deep learning framework, please refer to our [ThinkMatch project](#).

### Classes

---

*Benchmark*

The *Benchmark* module provides a unified data interface and an evaluating platform for different datasets.

---

### Benchmark

```
class pygmtools.benchmark.Benchmark(name, sets, obj_resize=(256, 256), problem='2GM',
                                     filter='intersection', **args)
```

The *Benchmark* module provides a unified data interface and an evaluating platform for different datasets.

**Parameters**

- **name** – str, dataset name, currently support 'PascalVOC', 'WillowObject', 'IMC\_PT\_SparseGM', 'CUB2011', 'SPair71k'
- **sets** – str, problem set, 'train' for training set and 'test' for test set
- **obj\_resize** – tuple, (default: (256, 256)) resized object size
- **problem** – str, (default: '2GM') problem type, '2GM' for 2-graph matching and 'MGM' for multi-graph matching
- **filter** – str, (default: 'intersection') filter of nodes, 'intersection' refers to retaining only common nodes; 'inclusion' is only for 2GM and refers to filtering only one graph to make its nodes a subset of the other graph, and 'unfiltered' refers to retaining all nodes in all graphs
- **args** – keyword settings for specific dataset

**compute\_img\_num(classes)**

Compute number of images in specified classes.

**Parameters**

**classes** – list of dataset classes

**Returns**

list of numbers of images in each class



**compute\_length**(*cls=None, num=2*)

Compute the length of image combinations in specified class.

**Parameters**

- **cls** – int or str, class of expected data. None for all classes
- **num** – int, number of images in each image ID list; for example, 2 for two-graph matching problem

**Returns**

length of combinations

**eval**(*prediction, classes, verbose=False*)

Evaluate test results and compute matching accuracy and coverage.

**Parameters**

- **prediction** – list, prediction result, like `[{'ids': (id1, id2), 'cls': cls, 'permmat': np.array or scipy.sparse}, ...]`
- **classes** – list of evaluated classes
- **verbose** – bool, whether to print the result

**Returns**

evaluation result in each class and their averages, including p, r, f1 and their standard deviation and coverage

**eval\_cls**(*prediction, cls, verbose=False*)

Evaluate test results and compute matching accuracy and coverage on one specified class.

**Parameters**

- **prediction** – list, prediction result on one class, like `[{'ids': (id1, id2), 'cls': cls, 'permmat': np.array or scipy.sparse}, ...]`
- **cls** – str, evaluated class
- **verbose** – bool, whether to print the result

**Returns**

evaluation result on the specified class, including p, r, f1 and their standard deviation and coverage

**get\_data**(*ids, test=False, shuffle=True*)

Fetch a data pair or pairs of data by image ID for training or test.

**Parameters**

- **ids** – list of image ID, usually in `train.json` or `test.json`
- **test** – bool, whether the fetched data is used for test; if true, this function will not return ground truth
- **shuffle** – bool, whether to shuffle the order of keypoints

**Returns**

**data\_list**: list of data, like `[{'img': np.array, 'kpts': coordinates of kpts}, ...]`

**perm\_mat\_dict**: ground truth, like `{(0,1):scipy.sparse, (0,2):scipy.sparse, ...}`, (0,1) refers to data pair (`ids[0]`, `ids[1]`)

**ids**: list of image ID

**get\_id\_combination**(cls=None, num=2)

Get the combination of images and length of combinations in specified class.

**Parameters**

- **cls** – int or str, class of expected data. None for all classes
- **num** – int, number of images in each image ID list; for example, 2 for 2GM

**Returns**

**id\_combination\_list**: list of combinations of image ids

**length**: length of combinations

**rand\_get\_data**(cls=None, num=2, test=False, shuffle=True)

Randomly fetch data for training or test. Implemented by calling `get_data` function.

**Parameters**

- **cls** – int or str, class of expected data. None for random class
- **num** – int, number of images; for example, 2 for 2GM
- **test** – bool, whether the fetched data is used for test; if true, this function will not return ground truth
- **shuffle** – bool, whether to shuffle the order of keypoints

**Returns**

**data\_list**: list of data, like `[{'img': np.array, 'kpts': coordinates of kpts}, ...]`

**perm\_mat\_dict**: ground truth, like `{(0,1):scipy.sparse, (0,2):scipy.sparse, ...}`, (0,1) refers to data pair (ids[0],ids[1])

**ids**: list of image ID

**rm\_gt\_cache**(last\_epoch=False)

Remove ground truth cache.

**Parameters**

**last\_epoch** – Boolean variable, whether this epoch is last epoch; if true, the directory of cache will also be removed.

## 9.4.7 pygmtools.dataset

The implementations of data loading and data processing.

### Classes

<i>CUB2011</i>	Download and preprocess <b>CUB2011</b> dataset.
<i>IMC_PT_SparseGM</i>	Download and preprocess <b>IMC_PT_SparseGM</b> dataset.
<i>PascalVOC</i>	Download and preprocess <b>PascalVOC Keypoint</b> dataset.
<i>SPair71k</i>	Download and preprocess <b>SPair71k</b> dataset.
<i>WillowObject</i>	Download and preprocess <b>Willow Object Class</b> dataset.

## CUB2011

**class** pygmtools.dataset.CUB2011(*sets*, *obj\_resize*, *\*\*ds\_dict*)

Download and preprocess CUB2011 dataset.

### Parameters

- **sets** – str, problem set, 'train' for training set and 'test' for testing set
- **obj\_resize** – tuple, resized image size
- **ds\_dict** – settings of dataset, containing at most 2 params(keys) for CUB2011:
  - **ROOT\_DIR**: str, directory of data
  - **CLS\_SPLIT**: str, 'ori' (original split), 'sup' (super class) or 'all' (all birds as one class)

**download**(*url=None*)

Automatically download CUB2011 dataset.

### Parameters

**url** – str, web url of CUB2011

**process**()

Process the dataset and generate data-(size, size).json for preprocessed dataset, train.json for training set, and test.json for testing set.

## IMC\_PT\_SparseGM

**class** pygmtools.dataset.IMC\_PT\_SparseGM(*sets*, *obj\_resize*, *\*\*ds\_dict*)

Download and preprocess IMC\_PT\_SparseGM dataset.

### Parameters

- **sets** – str, problem set, 'train' for training set and 'test' for testing set
- **obj\_resize** – tuple, resized image size
- **ds\_dict** – settings of dataset, containing at most 4 params(keys) for IMC\_PT\_SparseGM:
  - **ROOT\_DIR\_IMG**: str, directory of images
  - **ROOT\_DIR\_NPZ**: str, directory of annotations
  - **CLASSES**: dict, classes of training and test data, keys: 'train' for training and 'test' for test
  - **MAX\_KPT\_NUM**: int, maximum kpt\_num in an image

**download**(*url=None*)

Automatically download IMC\_PT\_SparseGM dataset.

### Parameters

**url** – str, web url of IMC\_PT\_SparseGM

**process**()

Process the dataset and generate data-(size, size).json for preprocessed dataset, train.json for training set, and test.json for testing set.

## PascalVOC

**class** pygmtools.dataset.**PascalVOC**(*sets, obj\_resize, \*\*ds\_dict*)

Download and preprocess **PascalVOC Keypoint** dataset.

### Parameters

- **sets** – str, problem set, 'train' for training set and 'test' for testing set
- **obj\_resize** – tuple, resized image size
- **ds\_dict** – settings of dataset, containing at most 5 params(keys) for PascalVOC:
  - **KPT\_ANNO\_DIR**: str, directory of keypoint annotations
  - **ROOT\_DIR**: str, directory of data
  - **SET\_SPLIT**: str, set split path
  - **CLASSES**: list, data classes
  - **CACHE\_PATH**: str, directory of data cache

**download**(*url=None, name=None*)

Automatically download PascalVOC dataset.

### Parameters

- **url** – str, web url of PascalVOC and PascalVOC annotation
- **name** – str, "PascalVOC" to download PascalVOC and "PascalVOC\_anno" to download PascalVOC annotation

**process**()

Process the dataset and generate `data-(size, size).json` for preprocessed dataset, `train.json` for training set, and `test.json` for testing set.

## SPair71k

**class** pygmtools.dataset.**SPair71k**(*sets, obj\_resize, problem='2GM', \*\*ds\_dict*)

Download and preprocess **SPair71k** dataset.

### Parameters

- **sets** – str, problem set, 'train' for training set and 'test' for testing set
- **obj\_resize** – tuple, resized image size
- **problem** – str, problem type, only '2GM' is supported in SPair71k
- **ds\_dict** – settings of dataset, containing at most 5 params(keys) for SPair71k:
  - **ROOT\_DIR**: str, directory of data
  - **TRAIN\_DIFF\_PARAMS**: list of images that should be dumped in train set
  - **EVAL\_DIFF\_PARAMS**: list of images that should be dumped in testing set
  - **COMB\_CLS**: bool, whether to combine images in different classes
  - **SIZE**: str, 'large' for SPair71k-large and 'small' for SPair71k-small

**download**(*url=None*)

Automatically download SPair71k dataset.

**Parameters**

**url** – str, web url of SPair71k

**process**()

Process the dataset and generate `data-(size, size).json` for preprocessed dataset, `train.json` for training set, and `test.json` for testing set.

## WillowObject

**class** pygmtools.dataset.**WillowObject**(*sets, obj\_resize, \*\*ds\_dict*)

Download and preprocess **Willow Object Class** dataset.

**Parameters**

- **sets** – str, problem set, 'train' for training set and 'test' for testing set
- **obj\_resize** – tuple, resized image size
- **ds\_dict** – settings of dataset, containing at most 6 params(keys) for WillowObject:
  - **ROOT\_DIR**: str, directory of data
  - **CLASSES**: list, data classes
  - **TRAIN\_NUM**: int, number of images for train in each class
  - **SPLIT\_OFFSET**: int, offset when split train and testing set
  - **TRAIN\_SAME\_AS\_TEST**: bool, whether to use same images for training and test
  - **RAND\_OUTLIER**: int, number of added outliers in one image

**download**(*url=None*)

Automatically download WillowObject dataset.

**Parameters**

**url** – str, web url of WillowObject

**process**()

Process the dataset and generate `data-(size, size).json` for preprocessed dataset, `train.json` for training set, and `test.json` for testing set.

**Warning:** By default the API functions and modules run on `numpy` backend. You could set the default backend by setting `pygm.BACKEND`. If you enable other backends than `numpy`, the corresponding package should be installed. See [the installation guide](#) for details.

## 9.5 Examples Gallery

Below is the gallery of pygmtools examples (categorized by the backend).

**Warning:** The examples are under construction. Will be updated very soon.

### 9.5.1 PyTorch Backend Examples

#### Introduction: Matching Isomorphic Graphs

This example is an introduction to pygmtools which shows how to match isomorphic graphs. Isomorphic graphs means graphs whose structures are identical, but the node correspondence is unknown.

```
# Author: Runzhong Wang <runzhong.wang@sjtu.edu.cn>
#
# License: Mulan PSL v2 License
```

**Note:** The following solvers support QAP formulation, and are included in this example:

- `rrwm()` (classic solver)
- `ipfp()` (classic solver)
- `sm()` (classic solver)
- `ngm()` (neural network solver)

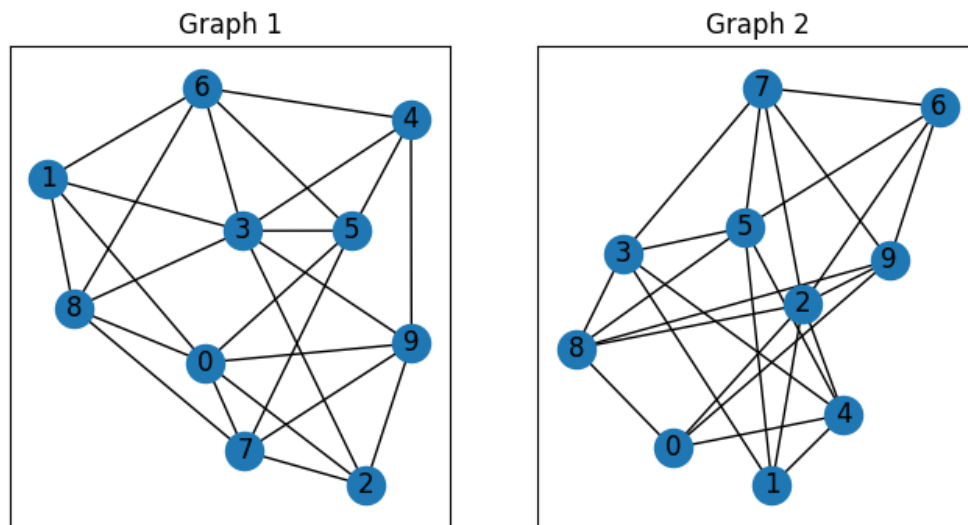
```
import torch # pytorch backend
import pygmtools as pygm
import matplotlib.pyplot as plt # for plotting
from matplotlib.patches import ConnectionPatch # for plotting matching result
import networkx as nx # for plotting graphs
pygm.BACKEND = 'pytorch' # set default backend for pygmtools
_ = torch.manual_seed(1) # fix random seed
```

#### Generate two isomorphic graphs

```
num_nodes = 10
X_gt = torch.zeros(num_nodes, num_nodes)
X_gt[torch.arange(0, num_nodes, dtype=torch.int64), torch.randperm(num_nodes)] = 1
A1 = torch.rand(num_nodes, num_nodes)
A1 = (A1 + A1.t() > 1.) * (A1 + A1.t()) / 2
torch.diagonal(A1)[:] = 0
A2 = torch.mm(torch.mm(X_gt.t(), A1), X_gt)
n1 = torch.tensor([num_nodes])
n2 = torch.tensor([num_nodes])
```

## Visualize the graphs

```
plt.figure(figsize=(8, 4))
G1 = nx.from_numpy_array(A1.numpy())
G2 = nx.from_numpy_array(A2.numpy())
pos1 = nx.spring_layout(G1)
pos2 = nx.spring_layout(G2)
plt.subplot(1, 2, 1)
plt.title('Graph 1')
nx.draw_networkx(G1, pos=pos1)
plt.subplot(1, 2, 2)
plt.title('Graph 2')
nx.draw_networkx(G2, pos=pos2)
```



These two graphs look dissimilar because they are not aligned. We then align these two graphs by graph matching.

## Build affinity matrix

To match isomorphic graphs by graph matching, we follow the formulation of Quadratic Assignment Problem (QAP):

$$\begin{aligned} & \max_{\mathbf{X}} \text{vec}(\mathbf{X})^\top \mathbf{K} \text{vec}(\mathbf{X}) \\ & s.t. \quad \mathbf{X} \in \{0, 1\}^{n_1 \times n_2}, \mathbf{X}\mathbf{1} = \mathbf{1}, \mathbf{X}^\top \mathbf{1} \leq \mathbf{1} \end{aligned}$$

where the first step is to build the affinity matrix ( $\mathbf{K}$ )

```
conn1, edge1 = pygm.utils.dense_to_sparse(A1)
conn2, edge2 = pygm.utils.dense_to_sparse(A2)
import functools
gaussian_aff = functools.partial(pygm.utils.gaussian_aff_fn, sigma=.1) # set affinity_
↪ function
K = pygm.utils.build_aff_mat(None, edge1, conn1, None, edge2, conn2, n1, None, n2, None, ↪
↪ edge_aff_fn=gaussian_aff)
```

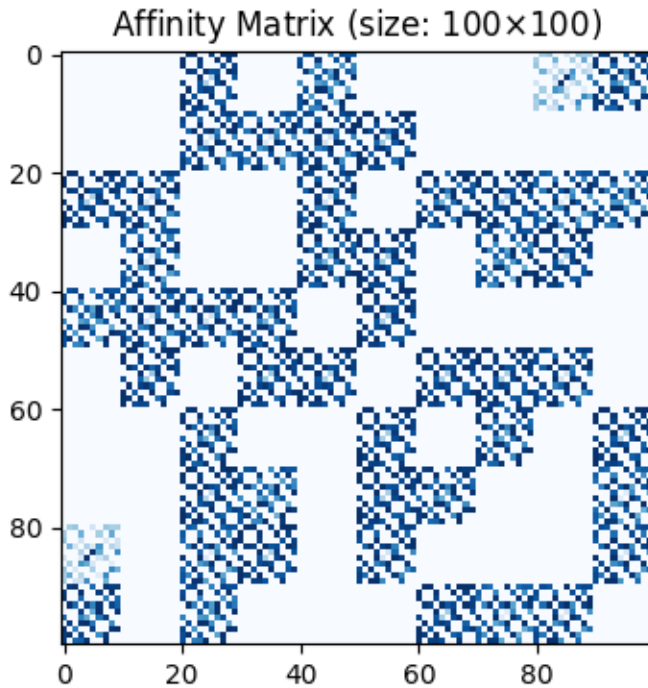
Visualization of the affinity matrix. For graph matching problem with  $N$  nodes, the affinity matrix has  $N^2 \times N^2$  elements because there are  $N^2$  edges in each graph.

---

**Note:** The diagonal elements of the affinity matrix is empty because there is no node features in this example.

---

```
plt.figure(figsize=(4, 4))
plt.title(f'Affinity Matrix (size: {K.shape[0]}x{K.shape[1]})')
plt.imshow(K.numpy(), cmap='Blues')
```



```
<matplotlib.image.AxesImage object at 0x7efe935af710>
```

### Solve graph matching problem by RRWM solver

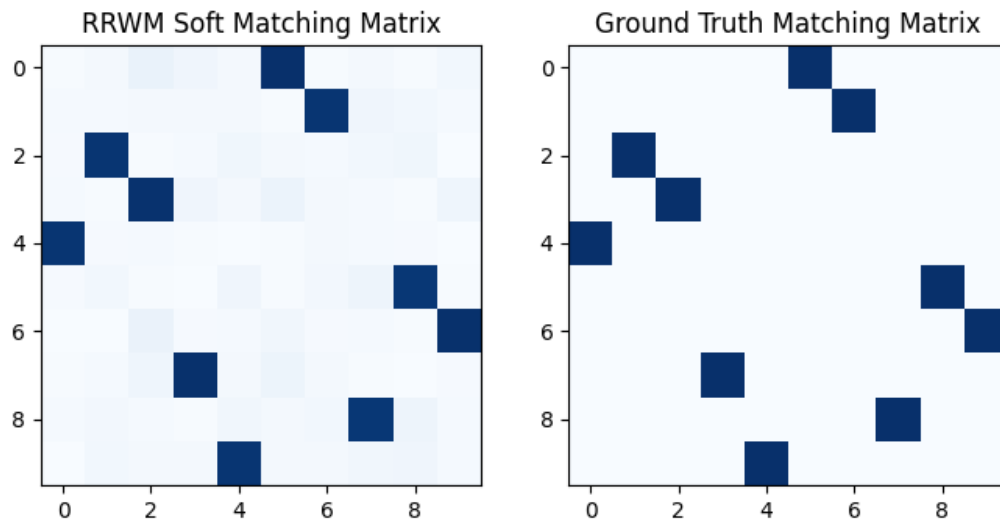
See `rrwm()` for the API reference.

```
X = pygm.rrwm(K, n1, n2)
```

The output of RRWM is a soft matching matrix. Visualization:

```
plt.figure(figsize=(8, 4))
plt.subplot(1, 2, 1)
plt.title('RRWM Soft Matching Matrix')
plt.imshow(X.numpy(), cmap='Blues')
plt.subplot(1, 2, 2)
plt.title('Ground Truth Matching Matrix')
plt.imshow(X_gt.numpy(), cmap='Blues')
```





```
<matplotlib.image.AxesImage object at 0x7efe934020d0>
```

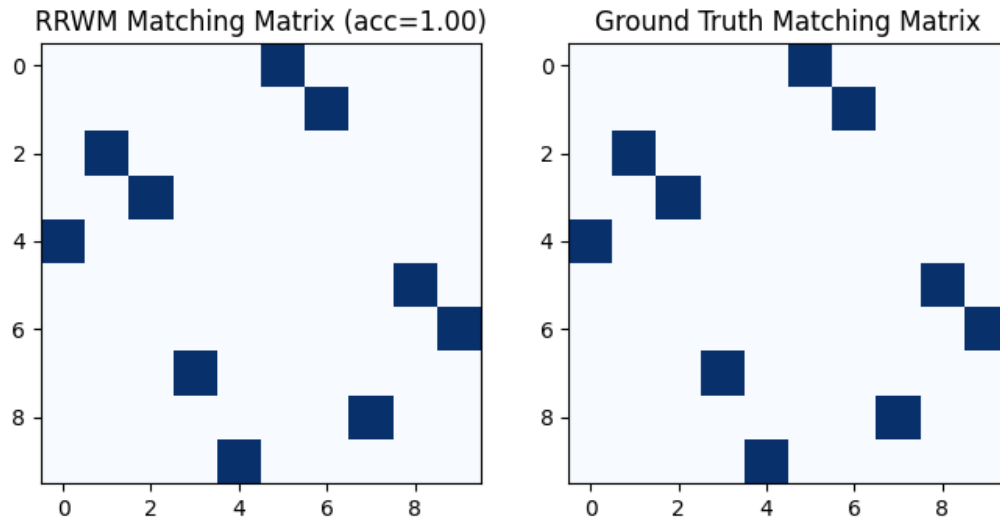
### Get the discrete matching matrix

Hungarian algorithm is then adopted to reach a discrete matching matrix

```
X = pygm.hungarian(X)
```

Visualization of the discrete matching matrix:

```
plt.figure(figsize=(8, 4))
plt.subplot(1, 2, 1)
plt.title(f'RRWM Matching Matrix (acc={(X * X_gt).sum() / X_gt.sum():.2f})')
plt.imshow(X.numpy(), cmap='Blues')
plt.subplot(1, 2, 2)
plt.title('Ground Truth Matching Matrix')
plt.imshow(X_gt.numpy(), cmap='Blues')
```

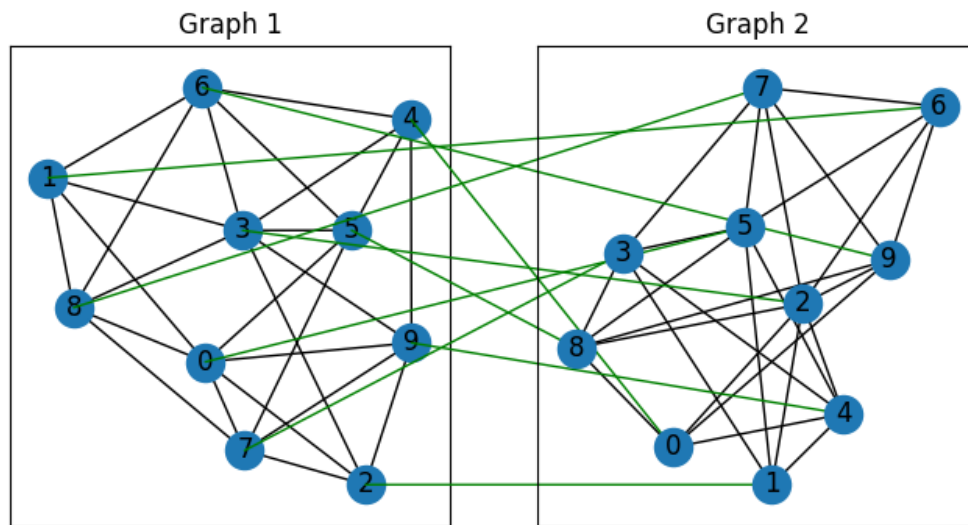


```
<matplotlib.image.AxesImage object at 0x7efe932e0650>
```

### Align the original graphs

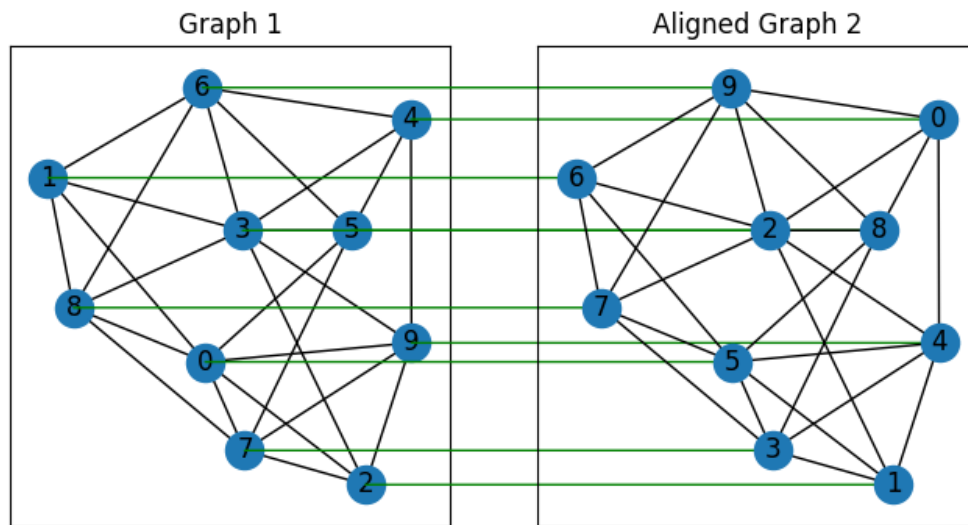
Draw the matching (green lines for correct matching, red lines for wrong matching):

```
plt.figure(figsize=(8, 4))
ax1 = plt.subplot(1, 2, 1)
plt.title('Graph 1')
nx.draw_networkx(G1, pos=pos1)
ax2 = plt.subplot(1, 2, 2)
plt.title('Graph 2')
nx.draw_networkx(G2, pos=pos2)
for i in range(num_nodes):
    j = torch.argmax(X[i]).item()
    con = ConnectionPatch(xyA=pos1[i], xyB=pos2[j], coordsA="data", coordsB="data",
                          axesA=ax1, axesB=ax2, color="green" if X_gt[i, j] else "red")
    plt.gca().add_artist(con)
```



Align the nodes:

```
align_A2 = torch.mm(torch.mm(X, A2), X.t())
plt.figure(figsize=(8, 4))
ax1 = plt.subplot(1, 2, 1)
plt.title('Graph 1')
nx.draw_networkx(G1, pos=pos1)
ax2 = plt.subplot(1, 2, 2)
plt.title('Aligned Graph 2')
align_pos2 = {}
for i in range(num_nodes):
    j = torch.argmax(X[i]).item()
    align_pos2[j] = pos1[i]
    con = ConnectionPatch(xyA=pos1[i], xyB=align_pos2[j], coordsA="data", coordsB="data",
                        axesA=ax1, axesB=ax2, color="green" if X_gt[i, j] else "red")
    plt.gca().add_artist(con)
nx.draw_networkx(G2, pos=align_pos2)
```



Other solvers are also available

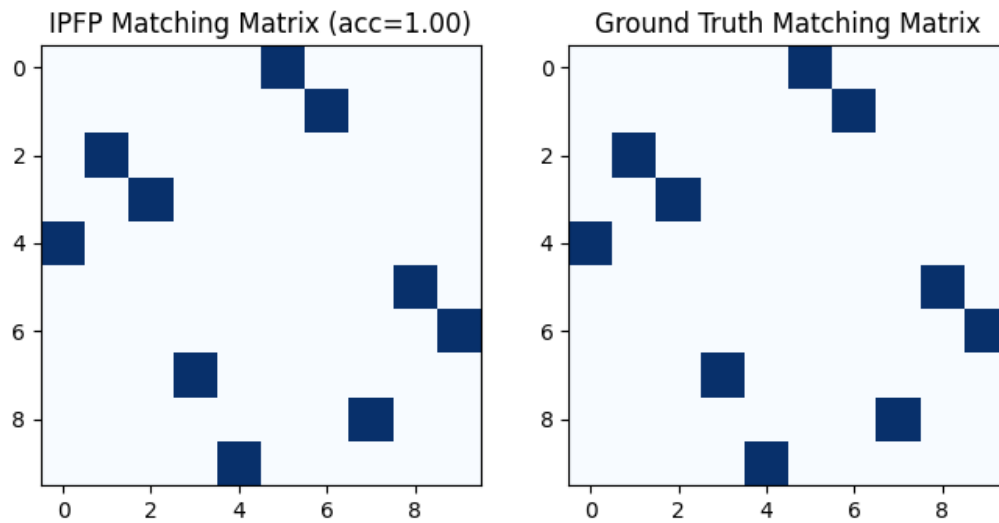
### Classic IPFP solver

See [`ipfp\(\)`](#) for the API reference.

```
X = pygm.ipfp(K, n1, n2)
```

Visualization of IPFP matching result:

```
plt.figure(figsize=(8, 4))
plt.subplot(1, 2, 1)
plt.title(f'IPFP Matching Matrix (acc={X * X_gt.sum() / X_gt.sum():.2f})')
plt.imshow(X.numpy(), cmap='Blues')
plt.subplot(1, 2, 2)
plt.title('Ground Truth Matching Matrix')
plt.imshow(X_gt.numpy(), cmap='Blues')
```



```
<matplotlib.image.AxesImage object at 0x7efe931fa1d0>
```

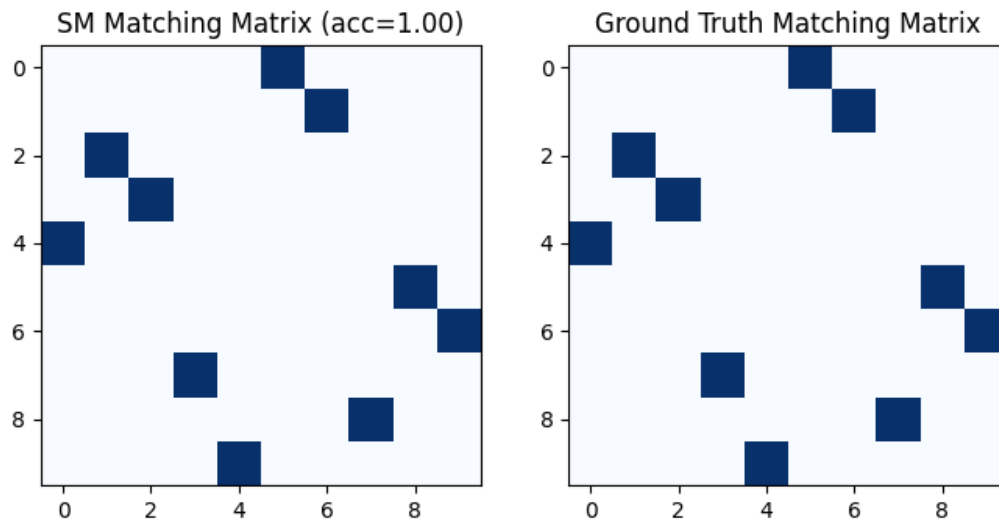
### Classic SM solver

See `sm()` for the API reference.

```
X = pygm.sm(K, n1, n2)
X = pygm.hungarian(X)
```

Visualization of SM matching result:

```
plt.figure(figsize=(8, 4))
plt.subplot(1, 2, 1)
plt.title(f'SM Matching Matrix (acc={X * X_gt.sum() / X_gt.sum():.2f})')
plt.imshow(X.numpy(), cmap='Blues')
plt.subplot(1, 2, 2)
plt.title('Ground Truth Matching Matrix')
plt.imshow(X_gt.numpy(), cmap='Blues')
```



```
<matplotlib.image.AxesImage object at 0x7efe93504f10>
```

## NGM neural network solver

See [ngm\(\)](#) for the API reference.

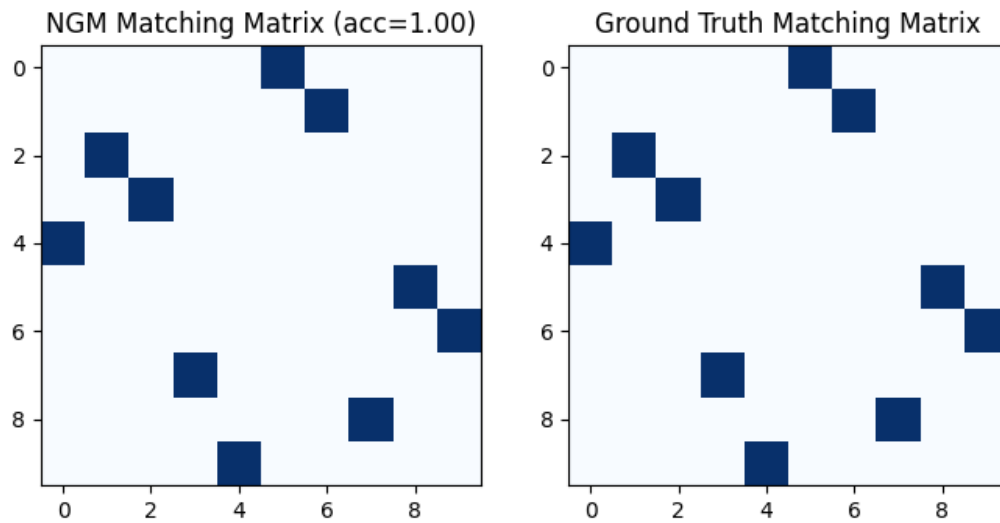
```
with torch.set_grad_enabled(False):
    X = pygm.ngm(K, n1, n2, pretrain='voc')
    X = pygm.hungarian(X)
```

Downloading to /home/docs/.cache/pygmtools/ngm\_voc\_pytorch.pt...

```
0%|          | 0/23119 [00:00<?, ?it/s]
100%|#####| 22.6k/22.6k [00:00<00:00, 1.62MB/s]
```

Visualization of NGM matching result:

```
plt.figure(figsize=(8, 4))
plt.subplot(1, 2, 1)
plt.title(f'NGM Matching Matrix (acc={X * X_gt).sum() / X_gt.sum():.2f})')
plt.imshow(X.numpy(), cmap='Blues')
plt.subplot(1, 2, 2)
plt.title('Ground Truth Matching Matrix')
plt.imshow(X_gt.numpy(), cmap='Blues')
```



```
<matplotlib.image.AxesImage object at 0x7efe9d4de250>
```

Total running time of the script: ( 0 minutes 3.455 seconds)

### Seeded Graph Matching

Seeded graph matching means some partial of the matching result is already known, and the known matching results are called “seeds”. In this example, we show how to exploit such prior with pygmtools.

```
# Author: Runzhong Wang <runzhong.wang@sjtu.edu.cn>
#
# License: Mulan PSL v2 License
```

**Note:** How to perform seeded graph matching is still an open research problem. In this example, we show a simple yet effective approach that works with pygmtools.

**Note:** The following solvers are included in this example:

- `rrwm()` (classic solver)
- `ipfp()` (classic solver)
- `sm()` (classic solver)
- `ngm()` (neural network solver)

```
import torch # pytorch backend
import pygmtools as pygm
import matplotlib.pyplot as plt # for plotting
from matplotlib.patches import ConnectionPatch # for plotting matching result
import networkx as nx # for plotting graphs
```

(continues on next page)

(continued from previous page)

```
pygm.BACKEND = 'pytorch' # set default backend for pygmtools
_ = torch.manual_seed(1) # fix random seed
```

### Generate two isomorphic graphs (with seeds)

In this example, we assume the first three nodes are already aligned. Firstly, we generate the seed matching matrix:

```
num_nodes = 10
num_seeds = 3
seed_mat = torch.zeros(num_nodes, num_nodes)
seed_mat[:num_seeds, :num_seeds] = torch.eye(num_seeds)
```

Then we generate the isomorphic graphs:

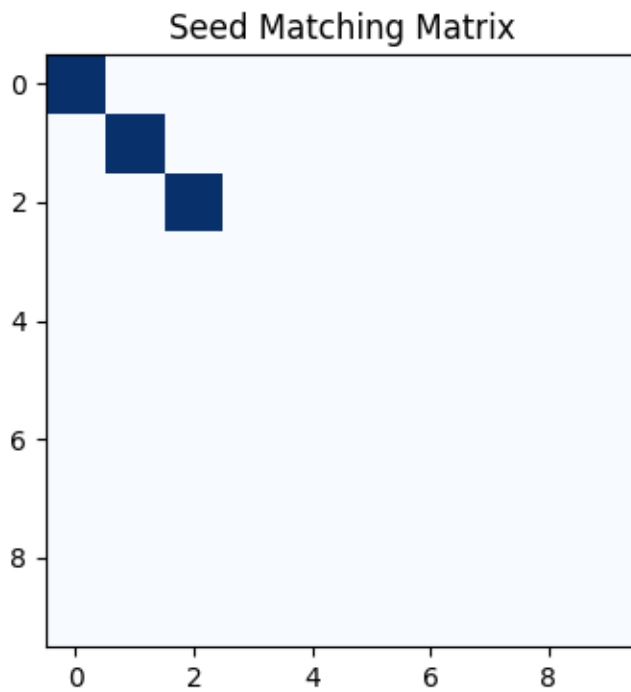
```
X_gt = seed_mat.clone()
X_gt[num_seeds:, num_seeds:][torch.arange(0, num_nodes-num_seeds, dtype=torch.int64),
↪ torch.randperm(num_nodes-num_seeds)] = 1
A1 = torch.rand(num_nodes, num_nodes)
A1 = (A1 + A1.t() > 1.) * (A1 + A1.t()) / 2
torch.diagonal(A1)[:] = 0
A2 = torch.mm(torch.mm(X_gt.t(), A1), X_gt)
n1 = torch.tensor([num_nodes])
n2 = torch.tensor([num_nodes])
```

### Visualize the graphs and seeds

The seed matching matrix:

```
plt.figure(figsize=(4, 4))
plt.title('Seed Matching Matrix')
plt.imshow(seed_mat.numpy(), cmap='Blues')
```

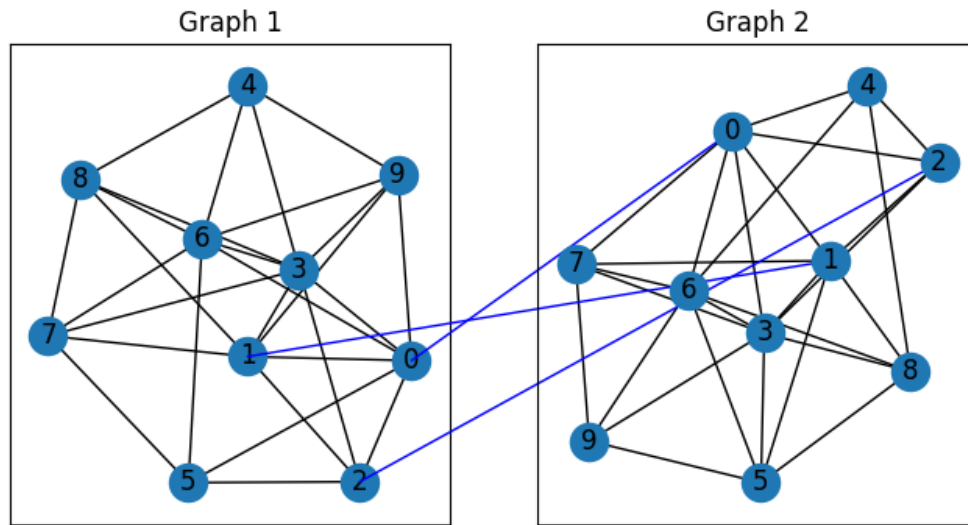




```
<matplotlib.image.AxesImage object at 0x7efe935ad890>
```

The blue lines denote the matching seeds.

```
plt.figure(figsize=(8, 4))
G1 = nx.from_numpy_array(A1.numpy())
G2 = nx.from_numpy_array(A2.numpy())
pos1 = nx.spring_layout(G1)
pos2 = nx.spring_layout(G2)
ax1 = plt.subplot(1, 2, 1)
plt.title('Graph 1')
nx.draw_networkx(G1, pos=pos1)
ax2 = plt.subplot(1, 2, 2)
plt.title('Graph 2')
nx.draw_networkx(G2, pos=pos2)
for i in range(num_seeds):
    j = torch.argmax(seed_mat[i]).item()
    con = ConnectionPatch(xyA=pos1[i], xyB=pos2[j], coordsA="data", coordsB="data",
                          axesA=ax1, axesB=ax2, color="blue")
    plt.gca().add_artist(con)
```



Now these two graphs look dissimilar because they are not aligned. We then align these two graphs by graph matching.

### Build affinity matrix with seed prior

We follow the formulation of Quadratic Assignment Problem (QAP):

$$\begin{aligned} \max_{\mathbf{X}} \quad & \text{vec}(\mathbf{X})^\top \mathbf{K} \text{vec}(\mathbf{X}) \\ \text{s.t.} \quad & \mathbf{X} \in \{0, 1\}^{n_1 \times n_2}, \mathbf{X}\mathbf{1} = \mathbf{1}, \mathbf{X}^\top \mathbf{1} \leq \mathbf{1} \end{aligned}$$

where the first step is to build the affinity matrix ( $\mathbf{K}$ ). We firstly build a “standard” affinity matrix:

```
conn1, edge1 = pygm.utils.dense_to_sparse(A1)
conn2, edge2 = pygm.utils.dense_to_sparse(A2)
import functools
gaussian_aff = functools.partial(pygm.utils.gaussian_aff_fn, sigma=.1) # set affinity_
↪function
K = pygm.utils.build_aff_mat(None, edge1, conn1, None, edge2, conn2, n1, None, n2, None,
↪edge_aff_fn=gaussian_aff)
```

The next step is to add the seed matching information as priors to the affinity matrix. The matching priors are treated as node affinities and the corresponding node affinity is added by 10 if there is an matching prior.

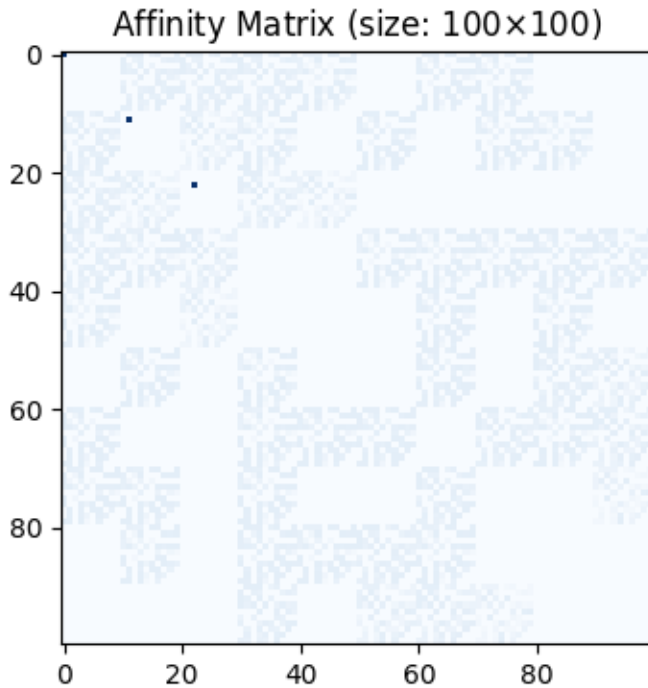
**Note:** The node affinity matrix is transposed because in the graph matching formulation followed by pygmtools,  $\text{vec}(\mathbf{X})$  means column vectorization. The node affinity should also be column- vectorized.

```
torch.diagonal(K)[:]. += seed_mat.t().reshape(-1) * 10
```

Visualization of the affinity matrix.

**Note:** In this example, the diagonal elements reflect the matching prior.

```
plt.figure(figsize=(4, 4))
plt.title(f'Affinity Matrix (size: {K.shape[0]}$\times${K.shape[1]})')
plt.imshow(K.numpy(), cmap='Blues')
```



```
<matplotlib.image.AxesImage object at 0x7efe93115d10>
```

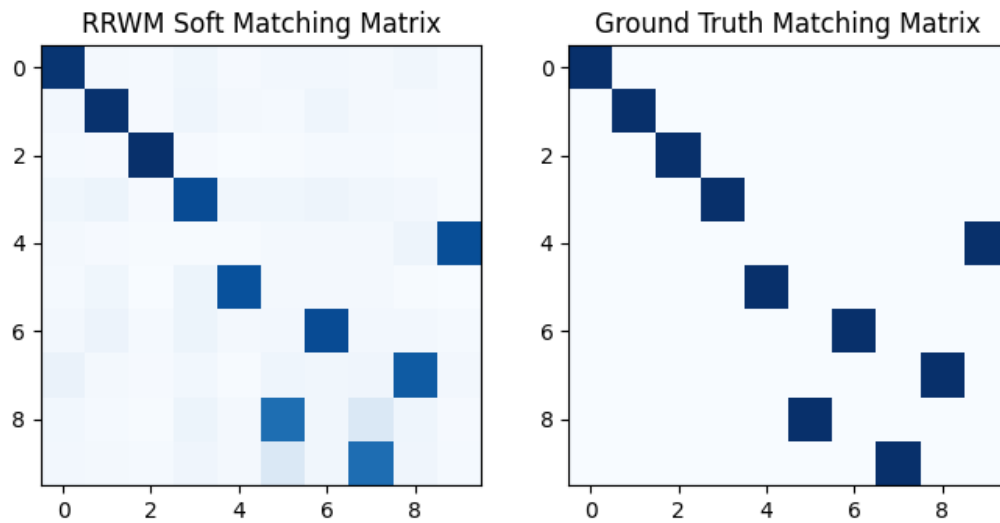
### Solve graph matching problem by RRWM solver

See [rrwm\(\)](#) for the API reference.

```
X = pygm.rrwm(K, n1, n2)
```

The output of RRWM is a soft matching matrix. The matching prior is well-preserved:

```
plt.figure(figsize=(8, 4))
plt.subplot(1, 2, 1)
plt.title('RRWM Soft Matching Matrix')
plt.imshow(X.numpy(), cmap='Blues')
plt.subplot(1, 2, 2)
plt.title('Ground Truth Matching Matrix')
plt.imshow(X_gt.numpy(), cmap='Blues')
```



```
<matplotlib.image.AxesImage object at 0x7efe9341d4d0>
```

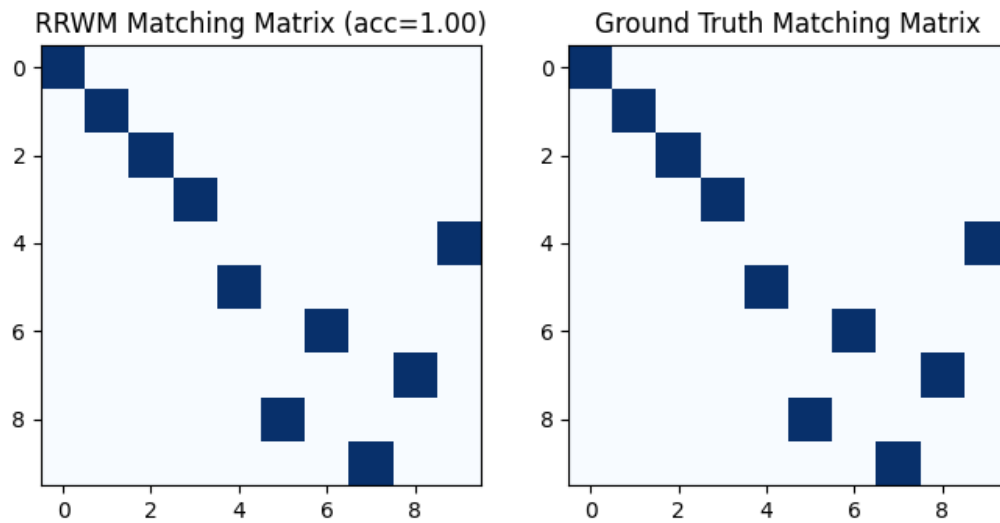
### Get the discrete matching matrix

Hungarian algorithm is then adopted to reach a discrete matching matrix

```
X = pygm.hungarian(X)
```

Visualization of the discrete matching matrix:

```
plt.figure(figsize=(8, 4))
plt.subplot(1, 2, 1)
plt.title(f'RRWM Matching Matrix (acc={(X * X_gt).sum() / X_gt.sum():.2f})')
plt.imshow(X.numpy(), cmap='Blues')
plt.subplot(1, 2, 2)
plt.title('Ground Truth Matching Matrix')
plt.imshow(X_gt.numpy(), cmap='Blues')
```

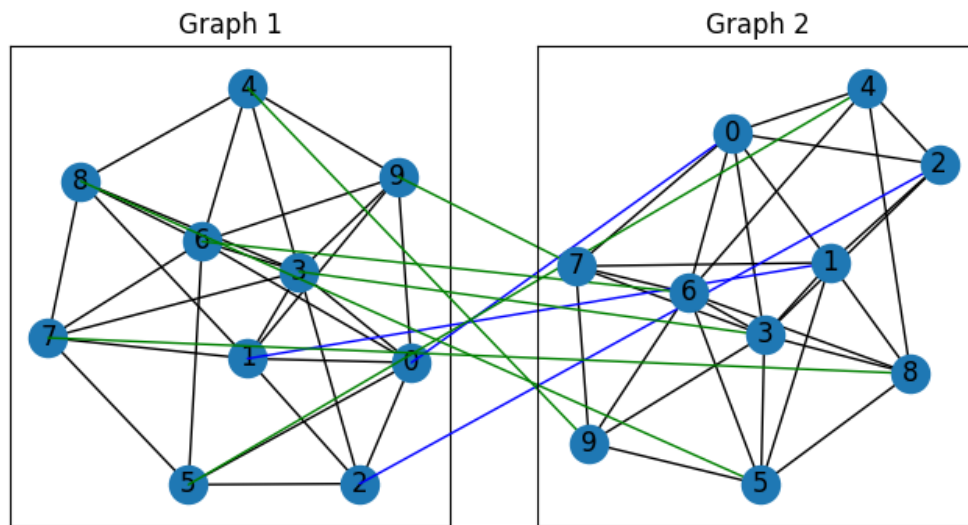


```
<matplotlib.image.AxesImage object at 0x7efe93449710>
```

### Align the original graphs

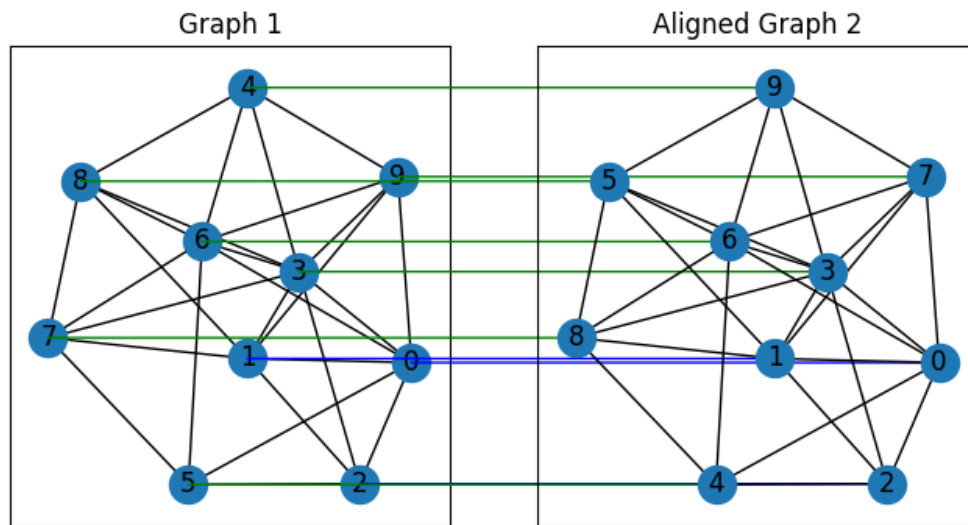
Draw the matching (green lines for correct matching, red lines for wrong matching, blue lines for seed matching):

```
plt.figure(figsize=(8, 4))
ax1 = plt.subplot(1, 2, 1)
plt.title('Graph 1')
nx.draw_networkx(G1, pos=pos1)
ax2 = plt.subplot(1, 2, 2)
plt.title('Graph 2')
nx.draw_networkx(G2, pos=pos2)
for i in range(num_nodes):
    j = torch.argmax(X[i]).item()
    if seed_mat[i, j]:
        line_color = "blue"
    elif X_gt[i, j]:
        line_color = "green"
    else:
        line_color = "red"
    con = ConnectionPatch(xyA=pos1[i], xyB=pos2[j], coordsA="data", coordsB="data",
                        axesA=ax1, axesB=ax2, color=line_color)
    plt.gca().add_artist(con)
```



Align the nodes:

```
align_A2 = torch.mm(torch.mm(X, A2), X.t())
plt.figure(figsize=(8, 4))
ax1 = plt.subplot(1, 2, 1)
plt.title('Graph 1')
nx.draw_networkx(G1, pos=pos1)
ax2 = plt.subplot(1, 2, 2)
plt.title('Aligned Graph 2')
align_pos2 = {}
for i in range(num_nodes):
    j = torch.argmax(X[i]).item()
    align_pos2[j] = pos1[i]
    if seed_mat[i, j]:
        line_color = "blue"
    elif X_gt[i, j]:
        line_color = "green"
    else:
        line_color = "red"
    con = ConnectionPatch(xyA=pos1[i], xyB=align_pos2[j], coordsA="data", coordsB="data",
                        axesA=ax1, axesB=ax2, color=line_color)
    plt.gca().add_artist(con)
nx.draw_networkx(G2, pos=align_pos2)
```



### Other solvers are also available

Only the affinity matrix is modified to encode matching priors, thus other graph matching solvers are also available to handle this seeded graph matching setting.

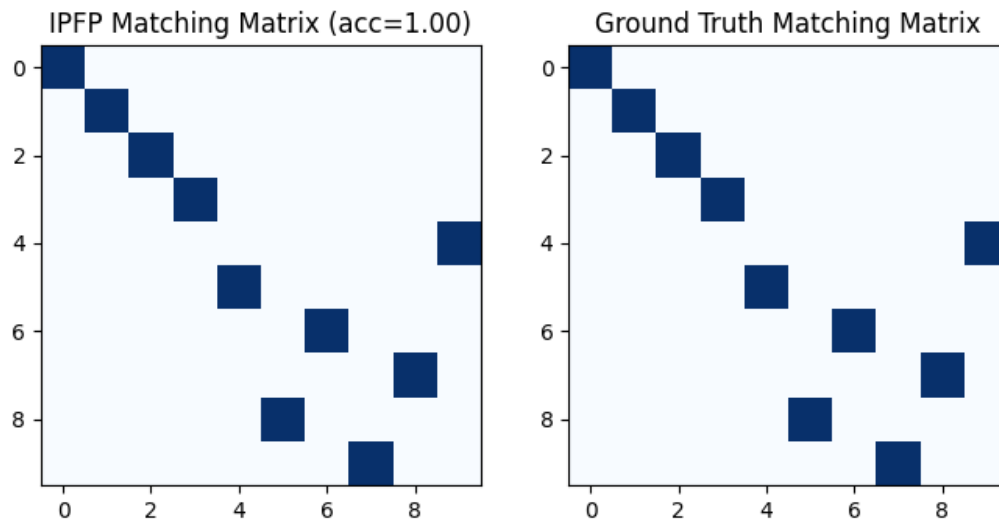
### Classic IPFP solver

See [`ipfp\(\)`](#) for the API reference.

```
X = pygm.ipfp(K, n1, n2)
```

Visualization of IPFP matching result:

```
plt.figure(figsize=(8, 4))
plt.subplot(1, 2, 1)
plt.title(f'IPFP Matching Matrix (acc={X * X_gt.sum() / X_gt.sum():.2f})')
plt.imshow(X.numpy(), cmap='Blues')
plt.subplot(1, 2, 2)
plt.title('Ground Truth Matching Matrix')
plt.imshow(X_gt.numpy(), cmap='Blues')
```



```
<matplotlib.image.AxesImage object at 0x7efe91ca1350>
```

### Classic SM solver

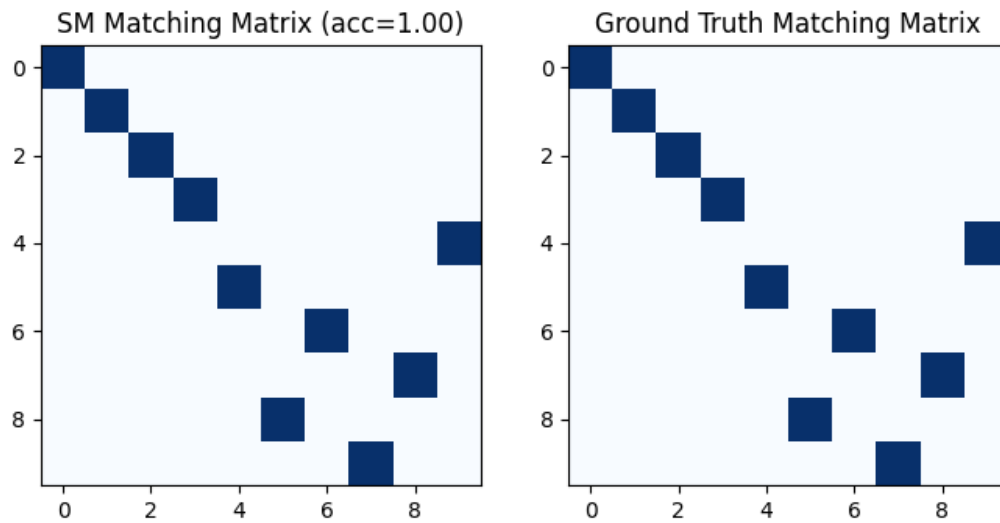
See [sm\(\)](#) for the API reference.

```
X = pygm.sm(K, n1, n2)
X = pygm.hungarian(X)
```

Visualization of SM matching result:

```
plt.figure(figsize=(8, 4))
plt.subplot(1, 2, 1)
plt.title(f'SM Matching Matrix (acc={X * X_gt.sum() / X_gt.sum():.2f})')
plt.imshow(X.numpy(), cmap='Blues')
plt.subplot(1, 2, 2)
plt.title('Ground Truth Matching Matrix')
plt.imshow(X_gt.numpy(), cmap='Blues')
```





```
<matplotlib.image.AxesImage object at 0x7efe93241ed0>
```

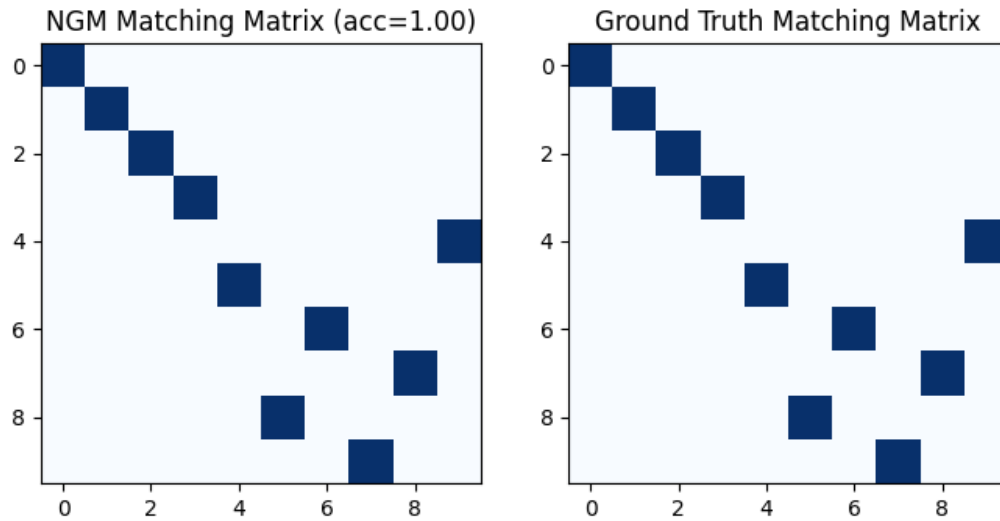
### NGM neural network solver

See [ngm\(\)](#) for the API reference.

```
with torch.set_grad_enabled(False):
    X = pygm.ngm(K, n1, n2, pretrain='voc')
    X = pygm.hungarian(X)
```

Visualization of NGM matching result:

```
plt.figure(figsize=(8, 4))
plt.subplot(1, 2, 1)
plt.title(f'NGM Matching Matrix (acc={(X * X_gt).sum() / X_gt.sum():.2f})')
plt.imshow(X.numpy(), cmap='Blues')
plt.subplot(1, 2, 2)
plt.title('Ground Truth Matching Matrix')
plt.imshow(X_gt.numpy(), cmap='Blues')
```



```
<matplotlib.image.AxesImage object at 0x7efe931bdfd0>
```

**Total running time of the script:** ( 0 minutes 1.651 seconds)

### Discovering Subgraphs

This example shows how to match a smaller graph to a subset of a larger graph.

```
# Author: Runzhong Wang <runzhong.wang@sjtu.edu.cn>
#
# License: Mulan PSL v2 License
```

---

**Note:** The following solvers are included in this example:

- `rrwm()` (classic solver)
- `ipfp()` (classic solver)
- `sm()` (classic solver)
- `ngm()` (neural network solver)

---

```
import torch # pytorch backend
import pygmtools as pygm
import matplotlib.pyplot as plt # for plotting
from matplotlib.patches import ConnectionPatch # for plotting matching result
import networkx as nx # for plotting graphs
pygm.BACKEND = 'pytorch' # set default backend for pygmtools
_ = torch.manual_seed(1) # fix random seed
```

## Generate the larger graph

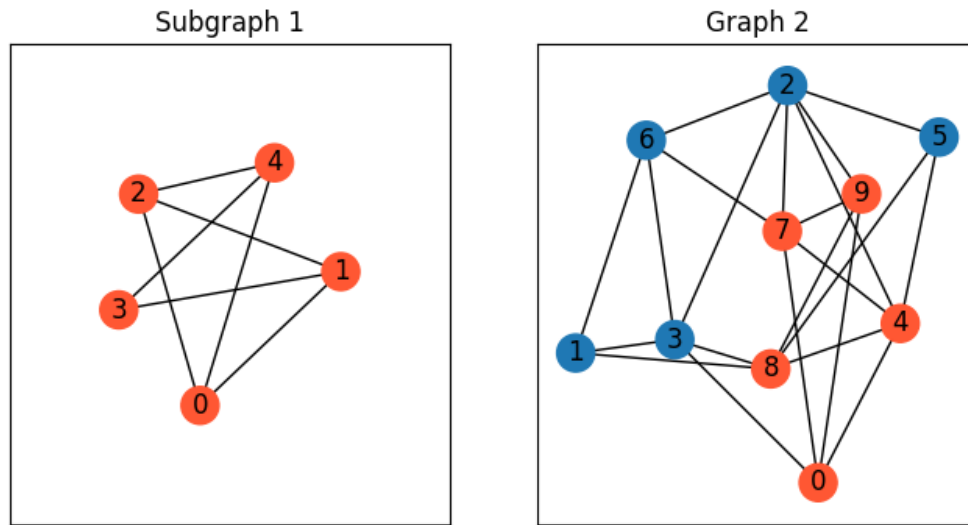
```
num_nodes2 = 10
A2 = torch.rand(num_nodes2, num_nodes2)
A2 = (A2 + A2.t() > 1.) * (A2 + A2.t()) / 2
torch.diagonal(A2)[:] = 0
n2 = torch.tensor([num_nodes2])
```

## Generate the smaller graph

```
num_nodes1 = 5
G2 = nx.from_numpy_array(A2.numpy())
pos2 = nx.spring_layout(G2)
pos2_t = torch.tensor([pos2[_] for _ in range(num_nodes2)])
selected = [0] # build G1 as a cluster in visualization
unselected = list(range(1, num_nodes2))
while len(selected) < num_nodes1:
    dist = torch.sum(torch.sum(torch.abs(pos2_t[selected].unsqueeze(1) - pos2_
↪t[unselected].unsqueeze(0)), dim=-1), dim=0)
    select_id = unselected[torch.argmin(dist).item()] # find the closest node from_
↪unselected
    selected.append(select_id)
    unselected.remove(select_id)
selected.sort()
A1 = A2[selected, :][:, selected]
X_gt = torch.eye(num_nodes2)[selected, :]
n1 = torch.tensor([num_nodes1])
```

## Visualize the graphs

```
G1 = nx.from_numpy_array(A1.numpy())
pos1 = {_: pos2[selected[_]] for _ in range(num_nodes1)}
color1 = ['#FF5733' for _ in range(num_nodes1)]
color2 = ['#FF5733' if _ in selected else '#1f78b4' for _ in range(num_nodes2)]
plt.figure(figsize=(8, 4))
plt.subplot(1, 2, 1)
plt.title('Subgraph 1')
plt.gca().margins(0.4)
nx.draw_networkx(G1, pos=pos1, node_color=color1)
plt.subplot(1, 2, 2)
plt.title('Graph 2')
nx.draw_networkx(G2, pos=pos2, node_color=color2)
```



We then show how to automatically discover the matching by graph matching.

### Build affinity matrix

To match the larger graph and the smaller graph, we follow the formulation of Quadratic Assignment Problem (QAP):

$$\begin{aligned} \max_{\mathbf{X}} \quad & \text{vec}(\mathbf{X})^\top \mathbf{K} \text{vec}(\mathbf{X}) \\ \text{s.t.} \quad & \mathbf{X} \in \{0, 1\}^{n_1 \times n_2}, \mathbf{X}\mathbf{1} = \mathbf{1}, \mathbf{X}^\top \mathbf{1} \leq \mathbf{1} \end{aligned}$$

where the first step is to build the affinity matrix ( $\mathbf{K}$ )

```
conn1, edge1 = pygm.utils.dense_to_sparse(A1)
conn2, edge2 = pygm.utils.dense_to_sparse(A2)
import functools
gaussian_aff = functools.partial(pygm.utils.gaussian_aff_fn, sigma=.001) # set affinity_
↪function
K = pygm.utils.build_aff_mat(None, edge1, conn1, None, edge2, conn2, n1, None, n2, None,
↪edge_aff_fn=gaussian_aff)
```

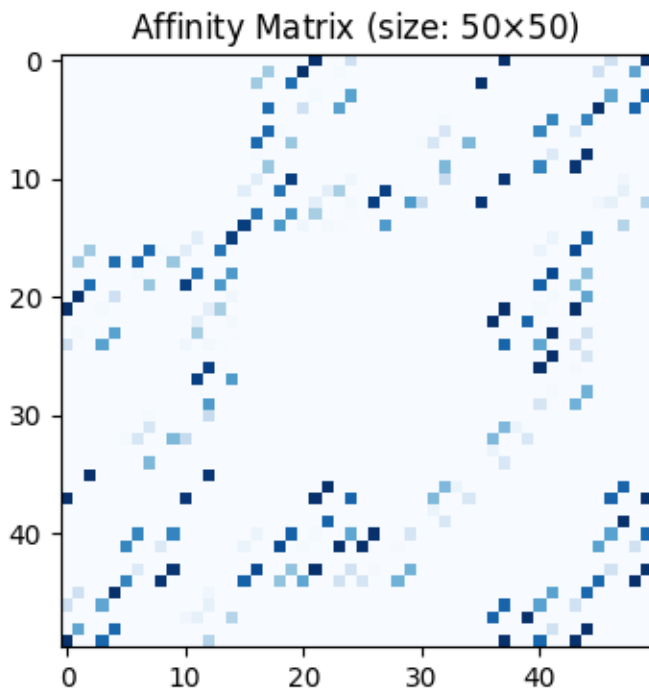
Visualization of the affinity matrix. For graph matching problem with  $N_1$  and  $N_2$  nodes, the affinity matrix has  $N_1 N_2 \times N_1 N_2$  elements because there are  $N_1^2$  and  $N_2^2$  edges in each graph, respectively.

---

**Note:** The diagonal elements of the affinity matrix is empty because there is no node features in this example.

---

```
plt.figure(figsize=(4, 4))
plt.title(f'Affinity Matrix (size: {K.shape[0]}x{K.shape[1]})')
plt.imshow(K.numpy(), cmap='Blues')
```



```
<matplotlib.image.AxesImage object at 0x7efe91d88610>
```

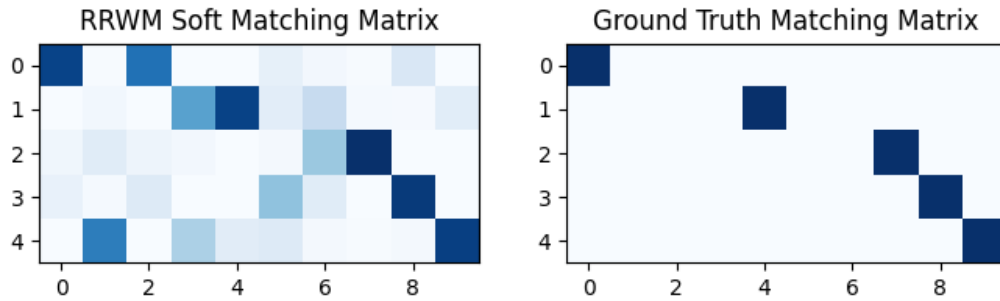
### Solve graph matching problem by RRWM solver

See [rrwm\(\)](#) for the API reference.

```
X = pygm.rrwm(K, n1, n2)
```

The output of RRWM is a soft matching matrix. Visualization:

```
plt.figure(figsize=(8, 4))
plt.subplot(1, 2, 1)
plt.title('RRWM Soft Matching Matrix')
plt.imshow(X.numpy(), cmap='Blues')
plt.subplot(1, 2, 2)
plt.title('Ground Truth Matching Matrix')
plt.imshow(X_gt.numpy(), cmap='Blues')
```



```
<matplotlib.image.AxesImage object at 0x7efeebf28f90>
```

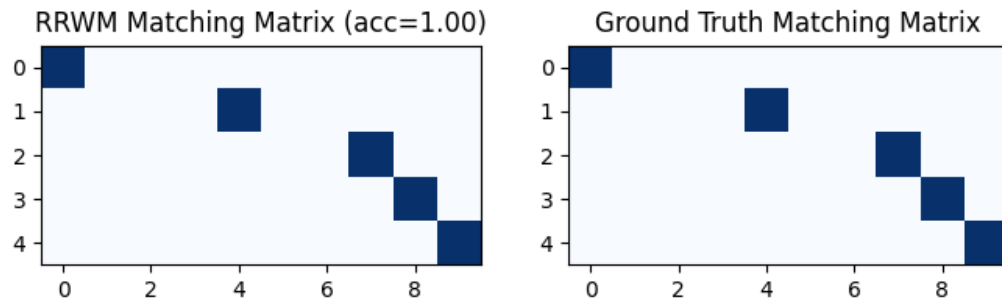
### Get the discrete matching matrix

Hungarian algorithm is then adopted to reach a discrete matching matrix

```
X = pygm.hungarian(X)
```

Visualization of the discrete matching matrix:

```
plt.figure(figsize=(8, 4))
plt.subplot(1, 2, 1)
plt.title(f'RRWM Matching Matrix (acc={(X * X_gt).sum() / X_gt.sum():.2f})')
plt.imshow(X.numpy(), cmap='Blues')
plt.subplot(1, 2, 2)
plt.title('Ground Truth Matching Matrix')
plt.imshow(X_gt.numpy(), cmap='Blues')
```

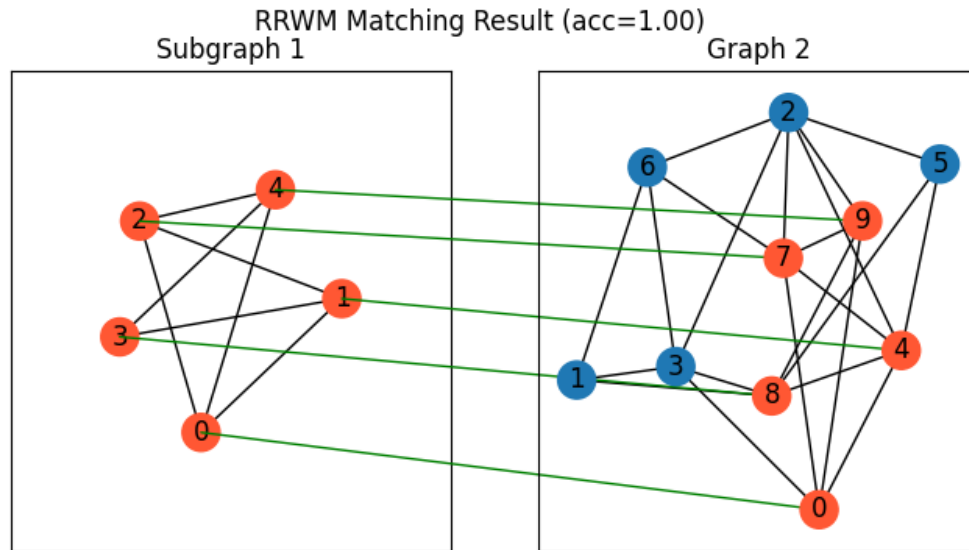


```
<matplotlib.image.AxesImage object at 0x7efe93431090>
```

### Match the subgraph

Draw the matching:

```
plt.figure(figsize=(8, 4))
plt.suptitle(f'RRWM Matching Result (acc={X * X_gt.sum() / X_gt.sum():.2f})')
ax1 = plt.subplot(1, 2, 1)
plt.title('Subgraph 1')
plt.gca().margins(0.4)
nx.draw_networkx(G1, pos=pos1, node_color=color1)
ax2 = plt.subplot(1, 2, 2)
plt.title('Graph 2')
nx.draw_networkx(G2, pos=pos2, node_color=color2)
for i in range(num_nodes1):
    j = torch.argmax(X[i]).item()
    con = ConnectionPatch(xyA=pos1[i], xyB=pos2[j], coordsA="data", coordsB="data",
                          axesA=ax1, axesB=ax2, color="green" if X_gt[i,j] == 1 else "red")
    plt.gca().add_artist(con)
```



Other solvers are also available

### Classic IPFP solver

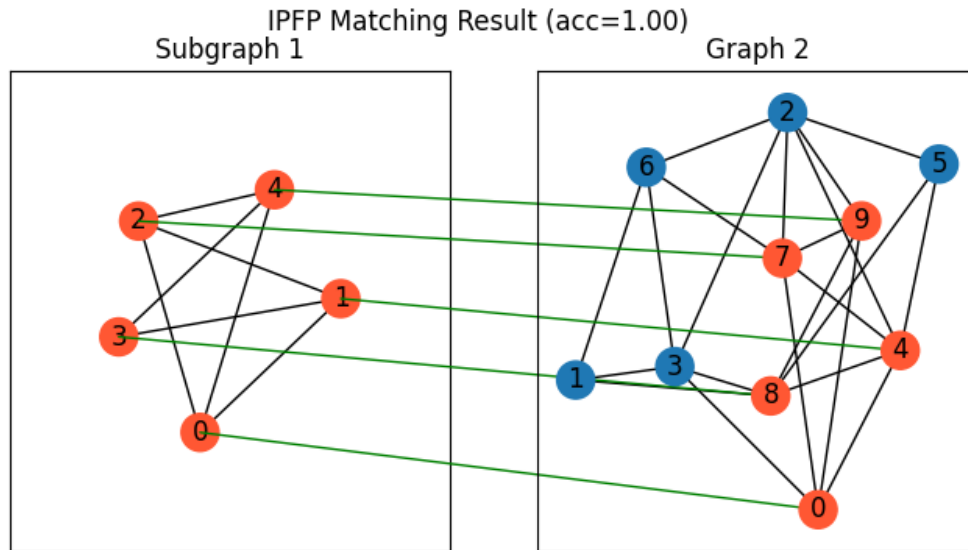
See `ipfp()` for the API reference.

```
X = pygm.ipfp(K, n1, n2)
```

Visualization of IPFP matching result:

```
plt.figure(figsize=(8, 4))
plt.suptitle(f'IPFP Matching Result (acc={X * X_gt.sum() / X_gt.sum():.2f})')
ax1 = plt.subplot(1, 2, 1)
plt.title('Subgraph 1')
plt.gca().margins(0.4)
nx.draw_networkx(G1, pos=pos1, node_color=color1)
ax2 = plt.subplot(1, 2, 2)
plt.title('Graph 2')
nx.draw_networkx(G2, pos=pos2, node_color=color2)
for i in range(num_nodes1):
    j = torch.argmax(X[i]).item()
    con = ConnectionPatch(xyA=pos1[i], xyB=pos2[j], coordsA="data", coordsB="data",
                        axesA=ax1, axesB=ax2, color="green" if X_gt[i,j] == 1 else "red",
                        →)
    plt.gca().add_artist(con)
```





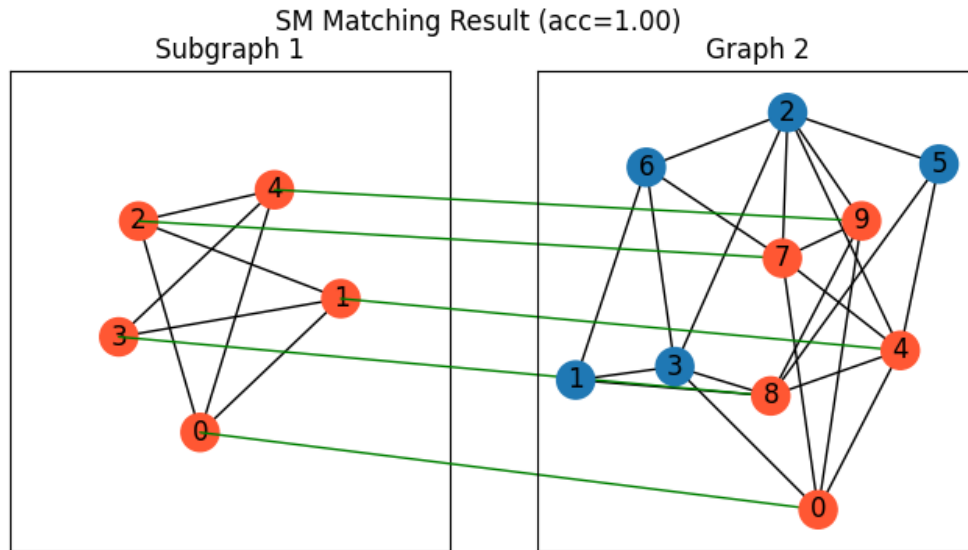
### Classic SM solver

See `sm()` for the API reference.

```
X = pygm.sm(K, n1, n2)
X = pygm.hungarian(X)
```

Visualization of SM matching result:

```
plt.figure(figsize=(8, 4))
plt.suptitle(f'SM Matching Result (acc={X * X_gt.sum() / X_gt.sum():.2f})')
ax1 = plt.subplot(1, 2, 1)
plt.title('Subgraph 1')
plt.gca().margins(0.4)
nx.draw_networkx(G1, pos=pos1, node_color=color1)
ax2 = plt.subplot(1, 2, 2)
plt.title('Graph 2')
nx.draw_networkx(G2, pos=pos2, node_color=color2)
for i in range(num_nodes1):
    j = torch.argmax(X[i]).item()
    con = ConnectionPatch(xyA=pos1[i], xyB=pos2[j], coordsA="data", coordsB="data",
                        axesA=ax1, axesB=ax2, color="green" if X_gt[i,j] == 1 else "red",
                        →)
    plt.gca().add_artist(con)
```



### NGM neural network solver

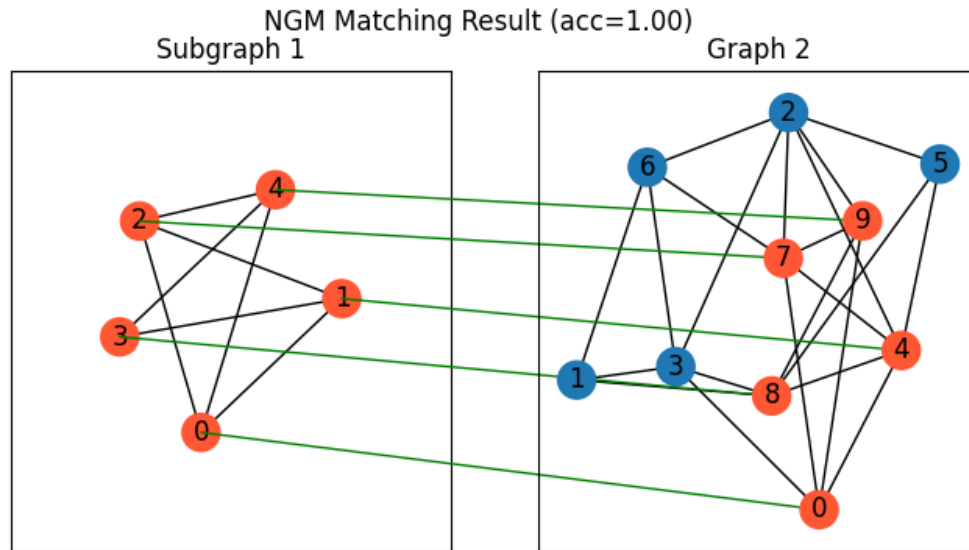
See `ngm()` for the API reference.

**Note:** The NGM solvers are pretrained on a different problem setting, so their performance may seem inferior. To improve their performance, you may change the way of building affinity matrices, or try finetuning NGM on the new problem.

```
with torch.set_grad_enabled(False):
    X = pygm.ngm(K, n1, n2, pretrain='voc')
    X = pygm.hungarian(X)
```

Visualization of NGM matching result:

```
plt.figure(figsize=(8, 4))
plt.suptitle(f'NGM Matching Result (acc={X * X_gt).sum() / X_gt.sum().sum():.2f}')
ax1 = plt.subplot(1, 2, 1)
plt.title('Subgraph 1')
plt.gca().margins(0.4)
nx.draw_networkx(G1, pos=pos1, node_color=color1)
ax2 = plt.subplot(1, 2, 2)
plt.title('Graph 2')
nx.draw_networkx(G2, pos=pos2, node_color=color2)
for i in range(num_nodes1):
    j = torch.argmax(X[i]).item()
    con = ConnectionPatch(xyA=pos1[i], xyB=pos2[j], coordsA="data", coordsB="data",
                          axesA=ax1, axesB=ax2, color="green" if X_gt[i,j] == 1 else "red")
    plt.gca().add_artist(con)
```



Total running time of the script: ( 0 minutes 1.396 seconds)

### Matching Image Keypoints by QAP Solvers

This example shows how to match image keypoints by graph matching solvers provided by pygmtools. These solvers follow the Quadratic Assignment Problem formulation and can generally work out-of-box. The matched images can be further processed for other downstream tasks.

```
# Author: Runzhong Wang <runzhong.wang@sjtu.edu.cn>
#
# License: Mulan PSL v2 License
```

**Note:** The following solvers support QAP formulation, and are included in this example:

- `rrwm()` (classic solver)
- `ipfp()` (classic solver)
- `sm()` (classic solver)
- `ngm()` (neural network solver)

```
import torch # pytorch backend
import torchvision # CV models
import pygmtools as pygm
import matplotlib.pyplot as plt # for plotting
from matplotlib.patches import ConnectionPatch # for plotting matching result
import scipy.io as sio # for loading .mat file
import scipy.spatial as spa # for Delaunay triangulation
from sklearn.decomposition import PCA as PCAdimReduc
import itertools
import numpy as np
```

(continues on next page)

(continued from previous page)

```
from PIL import Image
pygm.BACKEND = 'pytorch' # set default backend for pygmtools
```

## Load the images

Images are from the Willow Object Class dataset (this dataset also available with the Benchmark of pygmtools, see [WillowObject](#)).

The images are resized to 256x256.

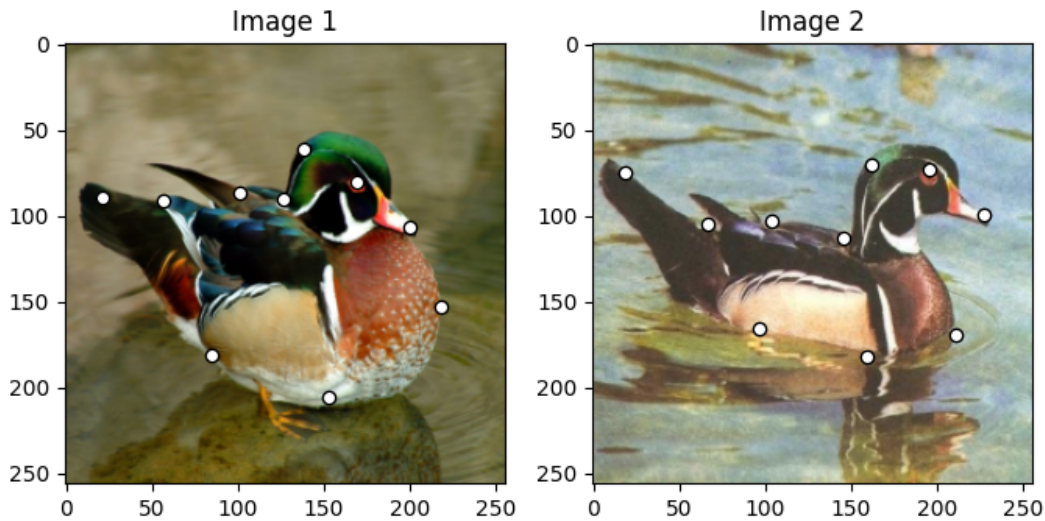
```
obj_resize = (256, 256)
img1 = Image.open('../data/willow_duck_0001.png')
img2 = Image.open('../data/willow_duck_0002.png')
kpts1 = torch.tensor(sio.loadmat('../data/willow_duck_0001.mat')['pts_coord'])
kpts2 = torch.tensor(sio.loadmat('../data/willow_duck_0002.mat')['pts_coord'])
kpts1[0] = kpts1[0] * obj_resize[0] / img1.size[0]
kpts1[1] = kpts1[1] * obj_resize[1] / img1.size[1]
kpts2[0] = kpts2[0] * obj_resize[0] / img2.size[0]
kpts2[1] = kpts2[1] * obj_resize[1] / img2.size[1]
img1 = img1.resize(obj_resize, resample=Image.BILINEAR)
img2 = img2.resize(obj_resize, resample=Image.BILINEAR)
```

```
/home/docs/checkouts/readthedocs.org/user_builds/pygmtools/checkouts/0.3.0/examples/
↳pytorch/plot_image_matching.py:59: DeprecationWarning: BILINEAR is deprecated and will
↳be removed in Pillow 10 (2023-07-01). Use Resampling.BILINEAR instead.
    img1 = img1.resize(obj_resize, resample=Image.BILINEAR)
/home/docs/checkouts/readthedocs.org/user_builds/pygmtools/checkouts/0.3.0/examples/
↳pytorch/plot_image_matching.py:60: DeprecationWarning: BILINEAR is deprecated and will
↳be removed in Pillow 10 (2023-07-01). Use Resampling.BILINEAR instead.
    img2 = img2.resize(obj_resize, resample=Image.BILINEAR)
```

Visualize the images and keypoints

```
def plot_image_with_graph(img, kpt, A=None):
    plt.imshow(img)
    plt.scatter(kpt[0], kpt[1], c='w', edgecolors='k')
    if A is not None:
        for idx in torch.nonzero(A, as_tuple=False):
            plt.plot((kpt[0, idx[0]], kpt[0, idx[1]]), (kpt[1, idx[0]], kpt[1, idx[1]]),
↳'k-')

plt.figure(figsize=(8, 4))
plt.subplot(1, 2, 1)
plt.title('Image 1')
plot_image_with_graph(img1, kpts1)
plt.subplot(1, 2, 2)
plt.title('Image 2')
plot_image_with_graph(img2, kpts2)
```



## Build the graphs

Graph structures are built based on the geometric structure of the keypoint set. In this example, we refer to [Delaunay triangulation](#).

```
def delaunay_triangulation(kpt):
    d = spa.Delaunay(kpt.numpy().transpose())
    A = torch.zeros(len(kpt[0]), len(kpt[0]))
    for simplex in d.simplices:
        for pair in itertools.permutations(simplex, 2):
            A[pair] = 1
    return A
```

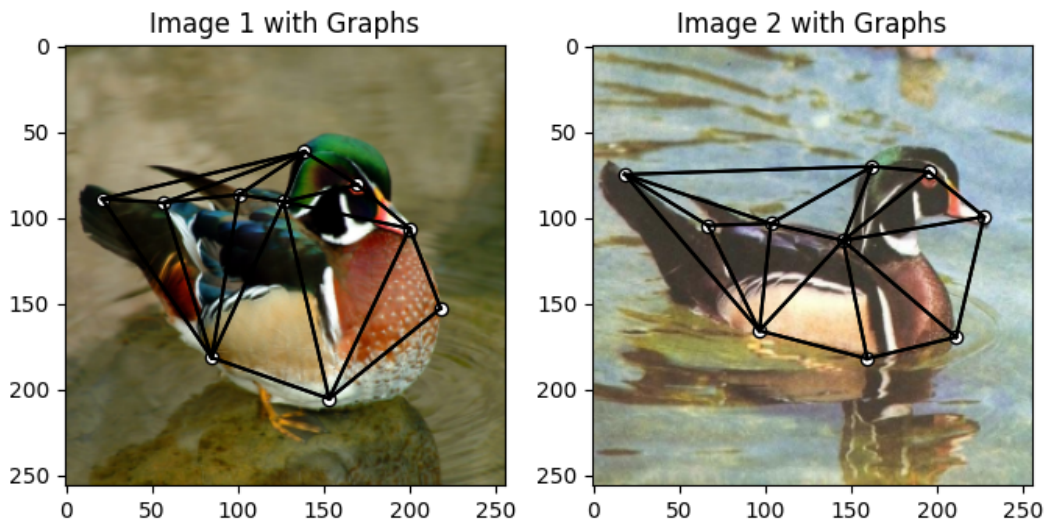
```
A1 = delaunay_triangulation(kpts1)
A2 = delaunay_triangulation(kpts2)
```

We encode the length of edges as edge features

```
A1 = ((kpts1.unsqueeze(1) - kpts1.unsqueeze(2)) ** 2).sum(dim=0) * A1
A1 = (A1 / A1.max()).to(dtype=torch.float32)
A2 = ((kpts2.unsqueeze(1) - kpts2.unsqueeze(2)) ** 2).sum(dim=0) * A2
A2 = (A2 / A2.max()).to(dtype=torch.float32)
```

Visualize the graphs

```
plt.figure(figsize=(8, 4))
plt.subplot(1, 2, 1)
plt.title('Image 1 with Graphs')
plot_image_with_graph(img1, kpts1, A1)
plt.subplot(1, 2, 2)
plt.title('Image 2 with Graphs')
plot_image_with_graph(img2, kpts2, A2)
```



### Extract node features

Let's adopt the VGG16 CNN model to extract node features.

```
vgg16_cnn = torchvision.models.vgg16_bn(True)
torch_img1 = torch.from_numpy(np.array(img1, dtype=np.float32) / 256).permute(2, 0, 1).
↳unsqueeze(0) # shape: BxCxHxW
torch_img2 = torch.from_numpy(np.array(img2, dtype=np.float32) / 256).permute(2, 0, 1).
↳unsqueeze(0) # shape: BxCxHxW
with torch.set_grad_enabled(False):
    feat1 = vgg16_cnn.features(torch_img1)
    feat2 = vgg16_cnn.features(torch_img2)
```

Downloading: "[https://download.pytorch.org/models/vgg16\\_bn-6c64b313.pth](https://download.pytorch.org/models/vgg16_bn-6c64b313.pth)" to /home/docs/.  
↳cache/torch/hub/checkpoints/vgg16\_bn-6c64b313.pth

```
0%|          | 0.00/528M [00:00<?, ?B/s]
0%|          | 840k/528M [00:00<01:04, 8.53MB/s]
1%|1         | 7.30M/528M [00:00<00:12, 43.3MB/s]
3%|2         | 14.3M/528M [00:00<00:09, 57.2MB/s]
4%|4         | 21.4M/528M [00:00<00:08, 63.9MB/s]
5%|5         | 28.6M/528M [00:00<00:07, 67.8MB/s]
7%|6         | 35.7M/528M [00:00<00:07, 70.1MB/s]
8%|8         | 42.9M/528M [00:00<00:07, 71.7MB/s]
9%|9         | 50.1M/528M [00:00<00:06, 72.6MB/s]
11%|#        | 57.2M/528M [00:00<00:06, 73.2MB/s]
12%|#2       | 64.4M/528M [00:01<00:06, 73.9MB/s]
14%|#3       | 71.8M/528M [00:01<00:06, 74.9MB/s]
15%|#5       | 79.2M/528M [00:01<00:06, 75.9MB/s]
16%|#6       | 86.6M/528M [00:01<00:06, 76.2MB/s]
18%|#7       | 94.0M/528M [00:01<00:05, 76.5MB/s]
```

(continues on next page)

(continued from previous page)

19% #9		101M/528M	[00:01<00:05, 76.9MB/s]
21% ##		109M/528M	[00:01<00:05, 77.2MB/s]
22% ##2		116M/528M	[00:01<00:05, 77.1MB/s]
23% ##3		124M/528M	[00:01<00:05, 77.4MB/s]
25% ##4		131M/528M	[00:01<00:05, 77.6MB/s]
26% ##6		139M/528M	[00:02<00:05, 77.5MB/s]
28% ##7		146M/528M	[00:02<00:05, 77.7MB/s]
29% ##9		154M/528M	[00:02<00:04, 78.5MB/s]
31% ###		161M/528M	[00:02<00:04, 79.0MB/s]
32% ###2		169M/528M	[00:02<00:04, 79.7MB/s]
33% ###3		177M/528M	[00:02<00:04, 79.8MB/s]
35% ###4		184M/528M	[00:02<00:04, 80.0MB/s]
36% ###6		192M/528M	[00:02<00:04, 80.0MB/s]
38% ###7		200M/528M	[00:02<00:04, 80.1MB/s]
39% ###9		208M/528M	[00:02<00:04, 80.8MB/s]
41% ####		216M/528M	[00:03<00:04, 81.0MB/s]
42% ####2		223M/528M	[00:03<00:03, 80.7MB/s]
44% ####3		231M/528M	[00:03<00:03, 79.3MB/s]
45% ####5		239M/528M	[00:03<00:03, 79.7MB/s]
47% ####6		246M/528M	[00:03<00:03, 80.1MB/s]
48% ####8		254M/528M	[00:03<00:03, 80.7MB/s]
50% ####9		262M/528M	[00:03<00:03, 81.5MB/s]
51% #####1		270M/528M	[00:03<00:03, 82.6MB/s]
53% #####2		278M/528M	[00:03<00:03, 82.9MB/s]
54% #####4		286M/528M	[00:03<00:03, 83.0MB/s]
56% #####5		294M/528M	[00:04<00:02, 83.0MB/s]
57% #####7		302M/528M	[00:04<00:02, 83.1MB/s]
59% #####8		310M/528M	[00:04<00:02, 83.4MB/s]
60% #####		318M/528M	[00:04<00:02, 84.0MB/s]
62% #####1		327M/528M	[00:04<00:02, 84.2MB/s]
63% #####3		335M/528M	[00:04<00:02, 84.1MB/s]
65% #####4		343M/528M	[00:04<00:02, 84.5MB/s]
66% #####6		351M/528M	[00:04<00:02, 84.9MB/s]
68% #####8		359M/528M	[00:04<00:02, 85.4MB/s]
70% #####9		368M/528M	[00:04<00:01, 85.9MB/s]
71% #####1		376M/528M	[00:05<00:01, 86.5MB/s]
73% #####2		384M/528M	[00:05<00:01, 86.6MB/s]
74% #####4		393M/528M	[00:05<00:01, 86.6MB/s]
76% #####5		401M/528M	[00:05<00:01, 86.5MB/s]
78% #####7		409M/528M	[00:05<00:01, 86.8MB/s]
79% #####9		417M/528M	[00:05<00:01, 86.8MB/s]
81% #####		426M/528M	[00:05<00:01, 86.9MB/s]
82% #####2		434M/528M	[00:05<00:01, 87.4MB/s]
84% #####3		443M/528M	[00:05<00:01, 88.1MB/s]
86% #####5		451M/528M	[00:05<00:00, 88.4MB/s]
87% #####7		460M/528M	[00:06<00:00, 88.8MB/s]
89% #####8		469M/528M	[00:06<00:00, 89.3MB/s]
90% #####		477M/528M	[00:06<00:00, 89.4MB/s]
92% #####2		486M/528M	[00:06<00:00, 89.8MB/s]
94% #####3		495M/528M	[00:06<00:00, 90.1MB/s]
95% #####5		503M/528M	[00:06<00:00, 89.9MB/s]
97% #####6		512M/528M	[00:06<00:00, 89.9MB/s]

(continues on next page)

(continued from previous page)

```
99%|#####8| 520M/528M [00:06<00:00, 89.8MB/s]
100%|#####| 528M/528M [00:06<00:00, 81.2MB/s]
```

Normalize the features

```
num_features = feat1.shape[1]
def l2norm(node_feat):
    return torch.nn.functional.local_response_norm(
        node_feat, node_feat.shape[1] * 2, alpha=node_feat.shape[1] * 2, beta=0.5, k=0)

feat1 = l2norm(feat1)
feat2 = l2norm(feat2)
```

Up-sample the features to the original image size

```
feat1_upsample = torch.nn.functional.interpolate(feat1, obj_resize, mode='bilinear')
feat2_upsample = torch.nn.functional.interpolate(feat2, obj_resize, mode='bilinear')
```

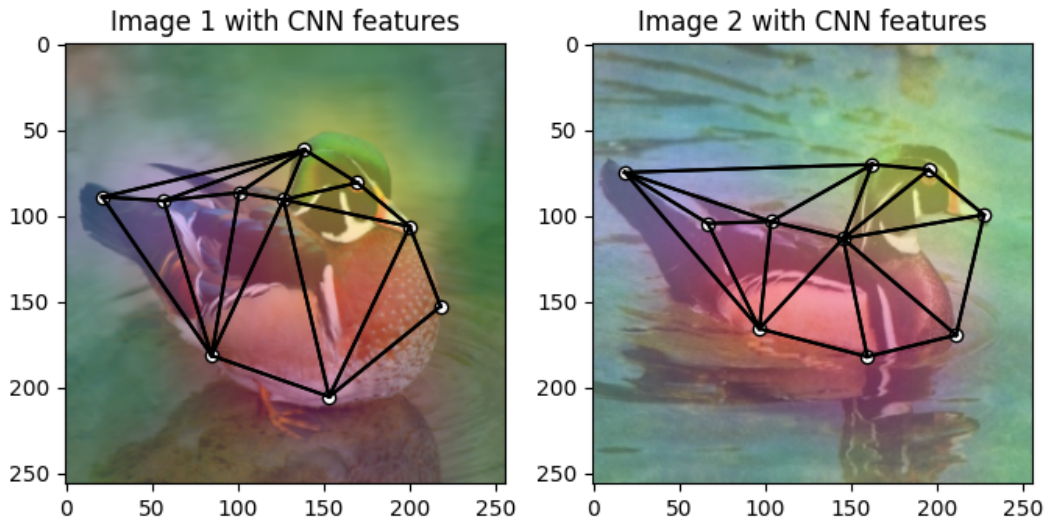
```
/home/docs/checkouts/readthedocs.org/user_builds/pygmtools/envs/0.3.0/lib/python3.7/site-
packages/torch/nn/functional.py:3121: UserWarning: Default upsampling behavior when
mode=bilinear is changed to align_corners=False since 0.4.0. Please specify align_
corners=True if the old behavior is desired. See the documentation of nn.Upsample for
details.
"See the documentation of nn.Upsample for details.".format(mode))
```

Visualize the extracted CNN feature (dimensionality reduction via principle component analysis)

```
pca_dim_reduc = PCAdimReduc(n_components=3, whiten=True)
feat_dim_reduc = pca_dim_reduc.fit_transform(
    np.concatenate((
        feat1_upsample.permute(0, 2, 3, 1).reshape(-1, num_features).numpy(),
        feat2_upsample.permute(0, 2, 3, 1).reshape(-1, num_features).numpy()
    ), axis=0)
)
feat_dim_reduc = feat_dim_reduc / np.max(np.abs(feat_dim_reduc), axis=0, keepdims=True) /
    2 + 0.5
feat1_dim_reduc = feat_dim_reduc[:obj_resize[0] * obj_resize[1], :]
feat2_dim_reduc = feat_dim_reduc[obj_resize[0] * obj_resize[1]:, :]

plt.figure(figsize=(8, 4))
plt.subplot(1, 2, 1)
plt.title('Image 1 with CNN features')
plot_image_with_graph(img1, kpts1, A1)
plt.imshow(feat1_dim_reduc.reshape(obj_resize[0], obj_resize[1], 3), alpha=0.5)
plt.subplot(1, 2, 2)
plt.title('Image 2 with CNN features')
plot_image_with_graph(img2, kpts2, A2)
plt.imshow(feat2_dim_reduc.reshape(obj_resize[0], obj_resize[1], 3), alpha=0.5)
```





```
<matplotlib.image.AxesImage object at 0x7efe8ca25e50>
```

Extract node features by nearest interpolation

```
rounded_kpts1 = torch.round(kpts1).to(dtype=torch.long)
rounded_kpts2 = torch.round(kpts2).to(dtype=torch.long)
node1 = feat1_upsample[0, :, rounded_kpts1[0], rounded_kpts1[1]].t() # shape: NxC
node2 = feat2_upsample[0, :, rounded_kpts2[0], rounded_kpts2[1]].t() # shape: NxC
```

## Build affinity matrix

We follow the formulation of Quadratic Assignment Problem (QAP):

$$\begin{aligned} \max_{\mathbf{X}} \quad & \text{vec}(\mathbf{X})^\top \mathbf{K} \text{vec}(\mathbf{X}) \\ \text{s.t.} \quad & \mathbf{X} \in \{0, 1\}^{n_1 \times n_2}, \mathbf{X}\mathbf{1} = \mathbf{1}, \mathbf{X}^\top \mathbf{1} \leq \mathbf{1} \end{aligned}$$

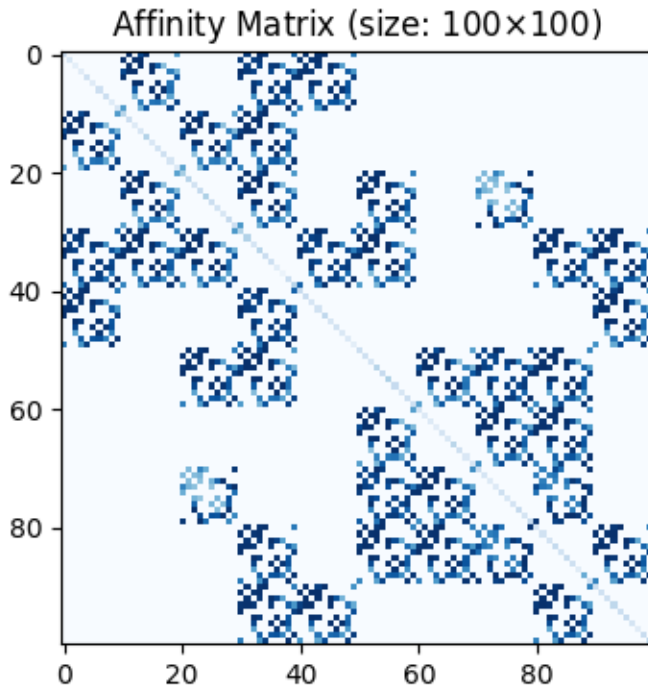
where the first step is to build the affinity matrix ( $\mathbf{K}$ )

```
conn1, edge1 = pygm.utils.dense_to_sparse(A1)
conn2, edge2 = pygm.utils.dense_to_sparse(A2)
import functools
gaussian_aff = functools.partial(pygm.utils.gaussian_aff_fn, sigma=1) # set affinity_
↪ function
K = pygm.utils.build_aff_mat(node1, edge1, conn1, node2, edge2, conn2, edge_aff_
↪ fn=gaussian_aff)
```

Visualization of the affinity matrix. For graph matching problem with  $N$  nodes, the affinity matrix has  $N^2 \times N^2$  elements because there are  $N^2$  edges in each graph.

**Note:** The diagonal elements are node affinities, the off-diagonal elements are edge features.

```
plt.figure(figsize=(4, 4))
plt.title(f'Affinity Matrix (size: {K.shape[0]}\\times{K.shape[1]})')
plt.imshow(K.numpy(), cmap='Blues')
```



```
<matplotlib.image.AxesImage object at 0x7efe6b8bf5d0>
```

### Solve graph matching problem by RRWM solver

See [rrwm\(\)](#) for the API reference.

```
X = pygm.rrwm(K, kpts1.shape[1], kpts2.shape[1])
```

The output of RRWM is a soft matching matrix. Hungarian algorithm is then adopted to reach a discrete matching matrix

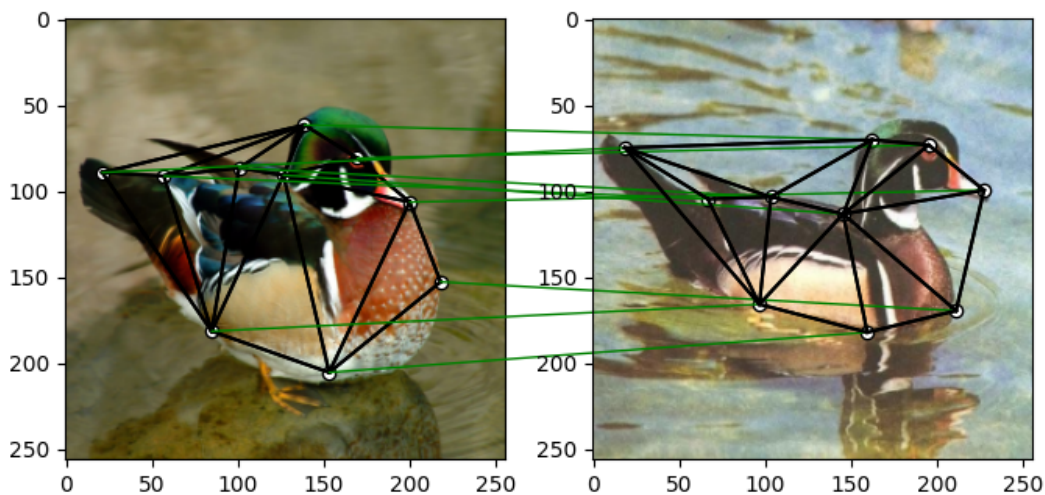
```
X = pygm.hungarian(X)
```

## Plot the matching

The correct matchings are marked by green, and wrong matchings are marked by red. In this example, the nodes are ordered by their ground truth classes (i.e. the ground truth matching matrix is a diagonal matrix).

```
plt.figure(figsize=(8, 4))
plt.suptitle('Image Matching Result by RRWM')
ax1 = plt.subplot(1, 2, 1)
plot_image_with_graph(img1, kpts1, A1)
ax2 = plt.subplot(1, 2, 2)
plot_image_with_graph(img2, kpts2, A2)
for i in range(X.shape[0]):
    j = torch.argmax(X[i]).item()
    con = ConnectionPatch(xyA=kpts1[:, i], xyB=kpts2[:, j], coordsA="data", coordsB="data",
        ↪,
                        axesA=ax1, axesB=ax2, color="red" if i != j else "green")
    plt.gca().add_artist(con)
```

Image Matching Result by RRWM



## Solve by other solvers

We could also do a quick benchmarking of other solvers on this specific problem.

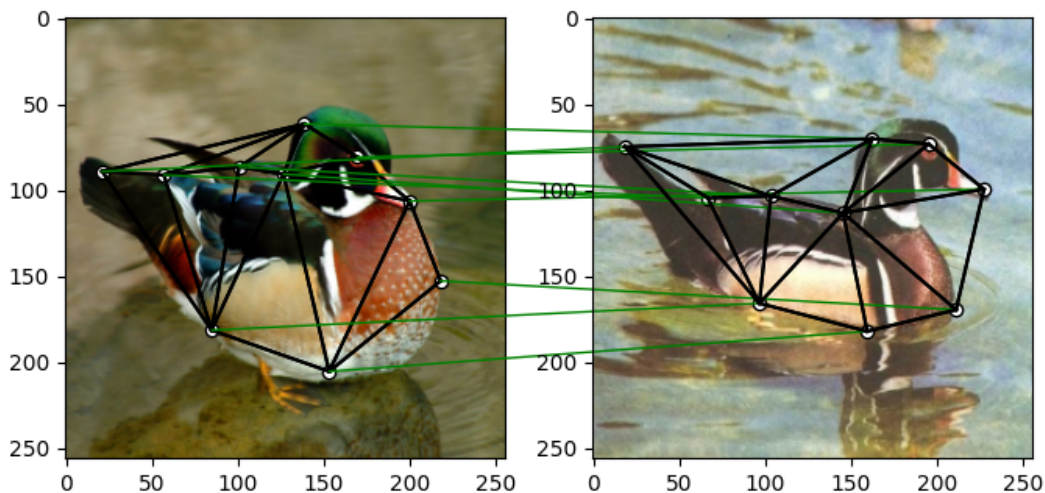
## IPFP solver

See `ipfp()` for the API reference.

```
X = pygm.ipfp(K, kpts1.shape[1], kpts2.shape[1])

plt.figure(figsize=(8, 4))
plt.suptitle('Image Matching Result by IPFP')
ax1 = plt.subplot(1, 2, 1)
plot_image_with_graph(img1, kpts1, A1)
ax2 = plt.subplot(1, 2, 2)
plot_image_with_graph(img2, kpts2, A2)
for i in range(X.shape[0]):
    j = torch.argmax(X[i]).item()
    con = ConnectionPatch(xyA=kpts1[:, i], xyB=kpts2[:, j], coordsA="data", coordsB="data",
        ↪,
                           axesA=ax1, axesB=ax2, color="red" if i != j else "green")
    plt.gca().add_artist(con)
```

Image Matching Result by IPFP



## SM solver

See `sm()` for the API reference.

```
X = pygm.sm(K, kpts1.shape[1], kpts2.shape[1])
X = pygm.hungarian(X)

plt.figure(figsize=(8, 4))
plt.suptitle('Image Matching Result by SM')
ax1 = plt.subplot(1, 2, 1)
plot_image_with_graph(img1, kpts1, A1)
ax2 = plt.subplot(1, 2, 2)
plot_image_with_graph(img2, kpts2, A2)
```

(continues on next page)

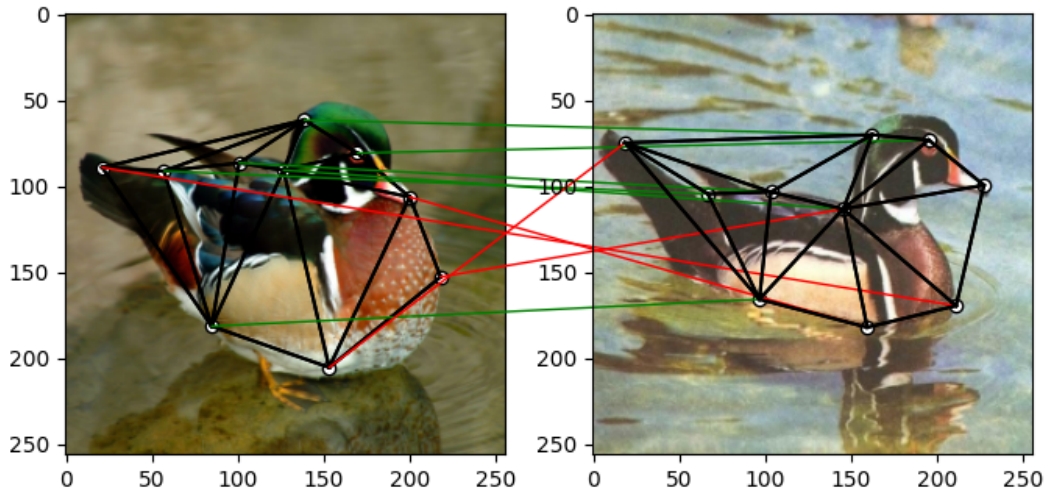
(continued from previous page)

```

for i in range(X.shape[0]):
    j = torch.argmax(X[i]).item()
    con = ConnectionPatch(xyA=kpts1[:, i], xyB=kpts2[:, j], coordsA="data", coordsB="data
    ↪",
                        axesA=ax1, axesB=ax2, color="red" if i != j else "green")
    plt.gca().add_artist(con)

```

Image Matching Result by SM



## NGM solver

See [ngm\(\)](#) for the API reference.

**Note:** The NGM solvers are pretrained on a different problem setting, so their performance may seem inferior. To improve their performance, you may change the way of building affinity matrices, or try finetuning NGM on the new problem.

The NGM solver pretrained on Willow dataset:

```

X = pygm.ngm(K, kpts1.shape[1], kpts2.shape[1], pretrain='willow')
X = pygm.hungarian(X)

plt.figure(figsize=(8, 4))
plt.suptitle('Image Matching Result by NGM (willow pretrain)')
ax1 = plt.subplot(1, 2, 1)
plot_image_with_graph(img1, kpts1, A1)
ax2 = plt.subplot(1, 2, 2)
plot_image_with_graph(img2, kpts2, A2)
for i in range(X.shape[0]):
    j = torch.argmax(X[i]).item()
    con = ConnectionPatch(xyA=kpts1[:, i], xyB=kpts2[:, j], coordsA="data", coordsB="data

```

(continues on next page)



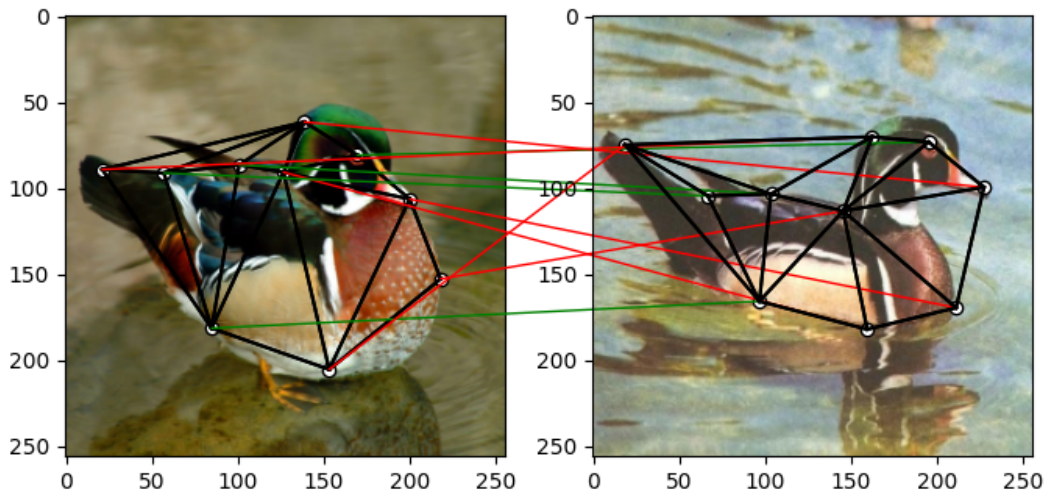
(continued from previous page)

```

→",
                                axesA=ax1, axesB=ax2, color="red" if i != j else "green")
plt.gca().add_artist(con)

```

Image Matching Result by NGM (willow pretrain)



Downloading to /home/docs/.cache/pygmtools/ngm\_willow\_pytorch.pt...

```

0%|          | 0/23119 [00:00<?, ?it/s]
100%|#####| 22.6k/22.6k [00:00<00:00, 1.43MB/s]

```

The NGM solver pretrained on VOC dataset:

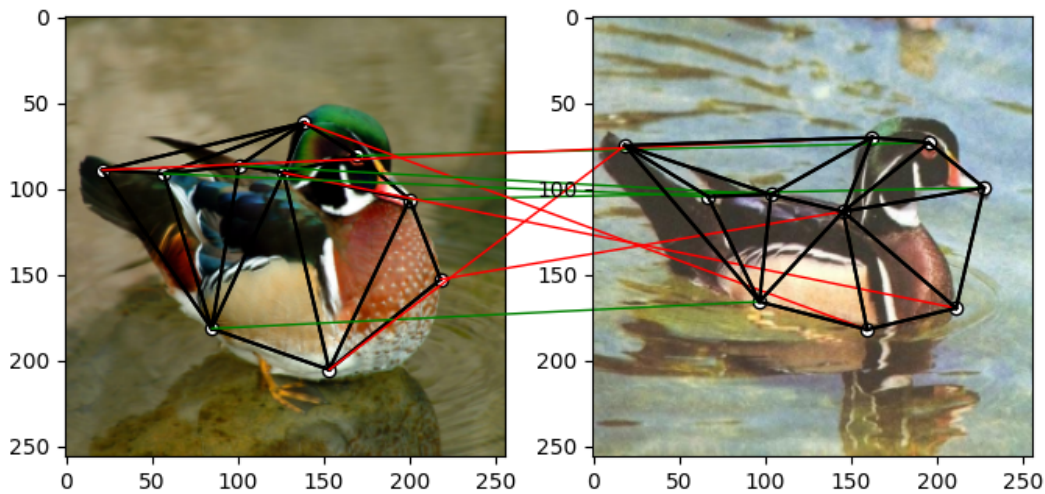
```

X = pygm.ngm(K, kpts1.shape[1], kpts2.shape[1], pretrain='voc')
X = pygm.hungarian(X)

plt.figure(figsize=(8, 4))
plt.suptitle('Image Matching Result by NGM (voc pretrain)')
ax1 = plt.subplot(1, 2, 1)
plot_image_with_graph(img1, kpts1, A1)
ax2 = plt.subplot(1, 2, 2)
plot_image_with_graph(img2, kpts2, A2)
for i in range(X.shape[0]):
    j = torch.argmax(X[i]).item()
    con = ConnectionPatch(xyA=kpts1[:, i], xyB=kpts2[:, j], coordsA="data", coordsB="data
→",
                                axesA=ax1, axesB=ax2, color="red" if i != j else "green")
plt.gca().add_artist(con)

```

Image Matching Result by NGM (voc pretrain)



Total running time of the script: ( 0 minutes 17.204 seconds)

### Matching Image Keypoints by Graph Matching Neural Networks

This example shows how to match image keypoints by neural network-based graph matching solvers. These graph matching solvers are designed to match two individual graphs. The matched images can be further passed to tackle downstream tasks.

```
# Author: Runzhong Wang <runzhong.wang@sjtu.edu.cn>
#
# License: Mulan PSL v2 License
```

**Note:** The following solvers are based on matching two individual graphs, and are included in this example:

- `pca_gm()` (neural network solver)
- `ipca_gm()` (neural network solver)
- `cie()` (neural network solver)

```
import torch # pytorch backend
import torchvision # CV models
import pygmtools as pygm
import matplotlib.pyplot as plt # for plotting
from matplotlib.patches import ConnectionPatch # for plotting matching result
import scipy.io as sio # for loading .mat file
import scipy.spatial as spa # for Delaunay triangulation
from sklearn.decomposition import PCA as PCAdimReduc
import itertools
import numpy as np
from PIL import Image
pygm.BACKEND = 'pytorch' # set default backend for pygmtools
```

## Predicting Matching by Graph Matching Neural Networks

In this section we show how to do predictions (inference) by graph matching neural networks. Let's take PCA-GM (`pca_gm()`) as an example.

### Load the images

Images are from the Willow Object Class dataset (this dataset also available with the Benchmark of pygmtools, see [WillowObject](#)).

The images are resized to 256x256.

```
obj_resize = (256, 256)
img1 = Image.open('../data/willow_duck_0001.png')
img2 = Image.open('../data/willow_duck_0002.png')
kpts1 = torch.tensor(sio.loadmat('../data/willow_duck_0001.mat')['pts_coord'])
kpts2 = torch.tensor(sio.loadmat('../data/willow_duck_0002.mat')['pts_coord'])
kpts1[0] = kpts1[0] * obj_resize[0] / img1.size[0]
kpts1[1] = kpts1[1] * obj_resize[1] / img1.size[1]
kpts2[0] = kpts2[0] * obj_resize[0] / img2.size[0]
kpts2[1] = kpts2[1] * obj_resize[1] / img2.size[1]
img1 = img1.resize(obj_resize, resample=Image.BILINEAR)
img2 = img2.resize(obj_resize, resample=Image.BILINEAR)
torch_img1 = torch.from_numpy(np.array(img1, dtype=np.float32) / 256).permute(2, 0, 1).
↳unsqueeze(0) # shape: BxCxHxW
torch_img2 = torch.from_numpy(np.array(img2, dtype=np.float32) / 256).permute(2, 0, 1).
↳unsqueeze(0) # shape: BxCxHxW
```

```
/home/docs/checkouts/readthedocs.org/user_builds/pygmtools/checkouts/0.3.0/examples/
↳pytorch/plot_deep_image_matching.py:62: DeprecationWarning: BILINEAR is deprecated and
↳will be removed in Pillow 10 (2023-07-01). Use Resampling.BILINEAR instead.
    img1 = img1.resize(obj_resize, resample=Image.BILINEAR)
/home/docs/checkouts/readthedocs.org/user_builds/pygmtools/checkouts/0.3.0/examples/
↳pytorch/plot_deep_image_matching.py:63: DeprecationWarning: BILINEAR is deprecated and
↳will be removed in Pillow 10 (2023-07-01). Use Resampling.BILINEAR instead.
    img2 = img2.resize(obj_resize, resample=Image.BILINEAR)
```

Visualize the images and keypoints

```
def plot_image_with_graph(img, kpt, A=None):
    plt.imshow(img)
    plt.scatter(kpt[0], kpt[1], c='w', edgecolors='k')
    if A is not None:
        for idx in torch.nonzero(A, as_tuple=False):
            plt.plot((kpt[0, idx[0]], kpt[0, idx[1]]), (kpt[1, idx[0]], kpt[1, idx[1]]),
↳'k-')

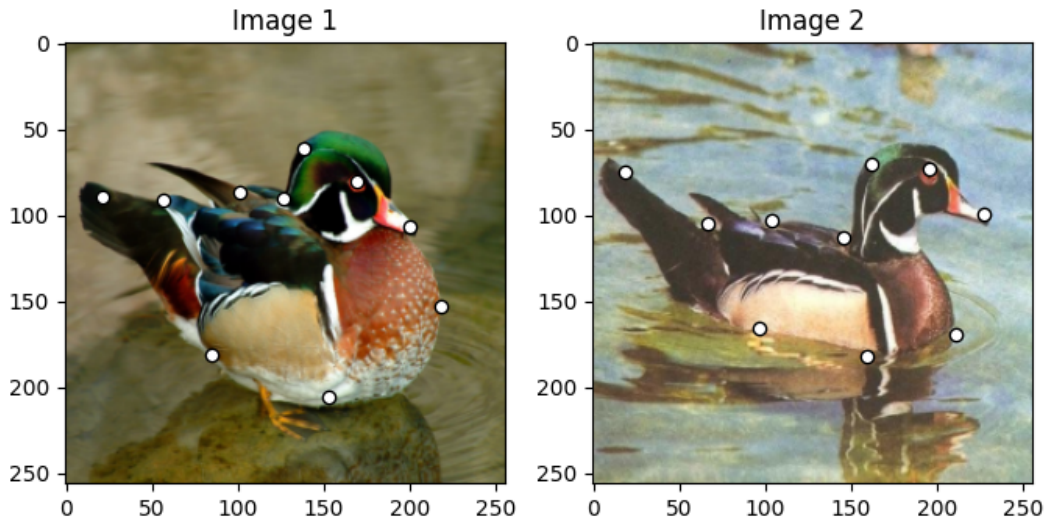
plt.figure(figsize=(8, 4))
plt.subplot(1, 2, 1)
plt.title('Image 1')
plot_image_with_graph(img1, kpts1)
plt.subplot(1, 2, 2)
```

(continues on next page)



(continued from previous page)

```
plt.title('Image 2')
plot_image_with_graph(img2, kpts2)
```



### Build the graphs

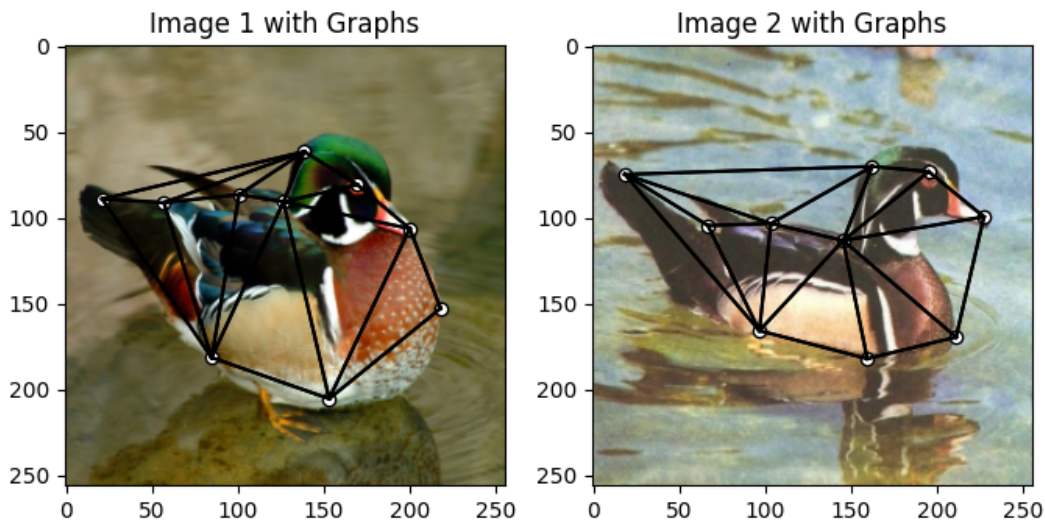
Graph structures are built based on the geometric structure of the keypoint set. In this example, we refer to [Delaunay triangulation](#).

```
def delaunay_triangulation(kpt):
    d = spa.Delaunay(kpt.numpy().transpose())
    A = torch.zeros(len(kpt[0]), len(kpt[0]))
    for simplex in d.simplices:
        for pair in itertools.permutations(simplex, 2):
            A[pair] = 1
    return A
```

```
A1 = delaunay_triangulation(kpts1)
A2 = delaunay_triangulation(kpts2)
```

Visualize the graphs

```
plt.figure(figsize=(8, 4))
plt.subplot(1, 2, 1)
plt.title('Image 1 with Graphs')
plot_image_with_graph(img1, kpts1, A1)
plt.subplot(1, 2, 2)
plt.title('Image 2 with Graphs')
plot_image_with_graph(img2, kpts2, A2)
```



### Extract node features via CNN

Deep graph matching solvers can be fused with CNN feature extractors, to build an end-to-end learning pipeline.

In this example, let's adopt the deep graph solvers based on matching two individual graphs. The image features are based on two intermediate layers from the VGG16 CNN model, following existing deep graph matching papers (such as [pca\\_gm\(\)](#))

Let's firstly fetch and download the VGG16 model:

```
vgg16_cnn = torchvision.models.vgg16_bn(True)
```

List of layers of VGG16:

```
print(vgg16_cnn.features)
```

```
Sequential(
  (0): Conv2d(3, 64, kernel_size=(3, 3), stride=(1, 1), padding=(1, 1))
  (1): BatchNorm2d(64, eps=1e-05, momentum=0.1, affine=True, track_running_stats=True)
  (2): ReLU(inplace=True)
  (3): Conv2d(64, 64, kernel_size=(3, 3), stride=(1, 1), padding=(1, 1))
  (4): BatchNorm2d(64, eps=1e-05, momentum=0.1, affine=True, track_running_stats=True)
  (5): ReLU(inplace=True)
  (6): MaxPool2d(kernel_size=2, stride=2, padding=0, dilation=1, ceil_mode=False)
  (7): Conv2d(64, 128, kernel_size=(3, 3), stride=(1, 1), padding=(1, 1))
  (8): BatchNorm2d(128, eps=1e-05, momentum=0.1, affine=True, track_running_stats=True)
  (9): ReLU(inplace=True)
  (10): Conv2d(128, 128, kernel_size=(3, 3), stride=(1, 1), padding=(1, 1))
  (11): BatchNorm2d(128, eps=1e-05, momentum=0.1, affine=True, track_running_stats=True)
  (12): ReLU(inplace=True)
  (13): MaxPool2d(kernel_size=2, stride=2, padding=0, dilation=1, ceil_mode=False)
  (14): Conv2d(128, 256, kernel_size=(3, 3), stride=(1, 1), padding=(1, 1))
  (15): BatchNorm2d(256, eps=1e-05, momentum=0.1, affine=True, track_running_stats=True)
```

(continues on next page)

(continued from previous page)

```

(16): ReLU(inplace=True)
(17): Conv2d(256, 256, kernel_size=(3, 3), stride=(1, 1), padding=(1, 1))
(18): BatchNorm2d(256, eps=1e-05, momentum=0.1, affine=True, track_running_stats=True)
(19): ReLU(inplace=True)
(20): Conv2d(256, 256, kernel_size=(3, 3), stride=(1, 1), padding=(1, 1))
(21): BatchNorm2d(256, eps=1e-05, momentum=0.1, affine=True, track_running_stats=True)
(22): ReLU(inplace=True)
(23): MaxPool2d(kernel_size=2, stride=2, padding=0, dilation=1, ceil_mode=False)
(24): Conv2d(256, 512, kernel_size=(3, 3), stride=(1, 1), padding=(1, 1))
(25): BatchNorm2d(512, eps=1e-05, momentum=0.1, affine=True, track_running_stats=True)
(26): ReLU(inplace=True)
(27): Conv2d(512, 512, kernel_size=(3, 3), stride=(1, 1), padding=(1, 1))
(28): BatchNorm2d(512, eps=1e-05, momentum=0.1, affine=True, track_running_stats=True)
(29): ReLU(inplace=True)
(30): Conv2d(512, 512, kernel_size=(3, 3), stride=(1, 1), padding=(1, 1))
(31): BatchNorm2d(512, eps=1e-05, momentum=0.1, affine=True, track_running_stats=True)
(32): ReLU(inplace=True)
(33): MaxPool2d(kernel_size=2, stride=2, padding=0, dilation=1, ceil_mode=False)
(34): Conv2d(512, 512, kernel_size=(3, 3), stride=(1, 1), padding=(1, 1))
(35): BatchNorm2d(512, eps=1e-05, momentum=0.1, affine=True, track_running_stats=True)
(36): ReLU(inplace=True)
(37): Conv2d(512, 512, kernel_size=(3, 3), stride=(1, 1), padding=(1, 1))
(38): BatchNorm2d(512, eps=1e-05, momentum=0.1, affine=True, track_running_stats=True)
(39): ReLU(inplace=True)
(40): Conv2d(512, 512, kernel_size=(3, 3), stride=(1, 1), padding=(1, 1))
(41): BatchNorm2d(512, eps=1e-05, momentum=0.1, affine=True, track_running_stats=True)
(42): ReLU(inplace=True)
(43): MaxPool2d(kernel_size=2, stride=2, padding=0, dilation=1, ceil_mode=False)
)

```

Let's define the CNN feature extractor, which outputs the features of layer (30) and layer (37)

```

class CNNNet(torch.nn.Module):
    def __init__(self, vgg16_module):
        super(CNNNet, self).__init__()
        # The naming of the layers follow ThinkMatch convention to load pretrained_
        ↪models.
        self.node_layers = torch.nn.Sequential(*[_ for _ in vgg16_module.features[:31]])
        self.edge_layers = torch.nn.Sequential(*[_ for _ in vgg16_module.
        ↪features[31:38]])

    def forward(self, inp_img):
        feat_local = self.node_layers(inp_img)
        feat_global = self.edge_layers(feat_local)
        return feat_local, feat_global

```

Download pretrained CNN weights (from [ThinkMatch](#)), load the weights and then extract the CNN features

```

cnn = CNNNet(vgg16_cnn)
path = pygm.utils.download('vgg16_pca_voc_pytorch.pt', 'https://drive.google.com/u/0/uc?
        ↪export=download&confirm=Z-AR&id=1JnX3cSPvRYBSrDKVwByzp7CADgVCJCO_')
if torch.cuda.is_available():

```

(continues on next page)

(continued from previous page)

```

map_location = torch.device('cuda:0')
else:
    map_location = torch.device('cpu')
cnn.load_state_dict(torch.load(path, map_location=map_location), strict=False)
with torch.set_grad_enabled(False):
    feat1_local, feat1_global = cnn(torch_img1)
    feat2_local, feat2_global = cnn(torch_img2)

```

Downloading to /home/docs/.cache/pygmtools/vgg16\_pca\_voc\_pytorch.pt...

```

0%|          | 0/166984482 [00:00<?, ?it/s]
1%|          | 1.11M/159M [00:00<00:14, 11.6MB/s]
6%|5        | 9.53M/159M [00:00<00:02, 56.5MB/s]
11%|#1       | 18.3M/159M [00:00<00:02, 72.6MB/s]
17%|#6       | 27.1M/159M [00:00<00:01, 80.0MB/s]
23%|##2      | 36.0M/159M [00:00<00:01, 84.6MB/s]
28%|##8      | 45.0M/159M [00:00<00:01, 88.1MB/s]
34%|###3     | 54.1M/159M [00:00<00:01, 90.3MB/s]
40%|###9     | 63.2M/159M [00:00<00:01, 92.0MB/s]
45%|####5    | 72.3M/159M [00:00<00:00, 92.9MB/s]
51%|####1    | 81.4M/159M [00:01<00:00, 93.5MB/s]
57%|####6    | 90.5M/159M [00:01<00:00, 94.2MB/s]
63%|####2    | 99.7M/159M [00:01<00:00, 94.8MB/s]
68%|####8    | 109M/159M [00:01<00:00, 95.5MB/s]
74%|####4    | 118M/159M [00:01<00:00, 96.3MB/s]
80%|#####   | 128M/159M [00:01<00:00, 97.1MB/s]
86%|#####6  | 137M/159M [00:01<00:00, 97.8MB/s]
92%|#####2  | 147M/159M [00:01<00:00, 98.2MB/s]
98%|#####8  | 156M/159M [00:01<00:00, 98.4MB/s]
100%|#####  | 159M/159M [00:01<00:00, 90.9MB/s]

```

Normalize the features

```

def l2norm(node_feat):
    return torch.nn.functional.local_response_norm(
        node_feat, node_feat.shape[1] * 2, alpha=node_feat.shape[1] * 2, beta=0.5, k=0)

feat1_local = l2norm(feat1_local)
feat1_global = l2norm(feat1_global)
feat2_local = l2norm(feat2_local)
feat2_global = l2norm(feat2_global)

```

Up-sample the features to the original image size and concatenate

```

feat1_local_upsample = torch.nn.functional.interpolate(feat1_local, obj_resize, mode=
    ↪ 'bilinear')
feat1_global_upsample = torch.nn.functional.interpolate(feat1_global, obj_resize, mode=
    ↪ 'bilinear')
feat2_local_upsample = torch.nn.functional.interpolate(feat2_local, obj_resize, mode=
    ↪ 'bilinear')
feat2_global_upsample = torch.nn.functional.interpolate(feat2_global, obj_resize, mode=
    ↪ 'bilinear')

```

(continues on next page)

(continued from previous page)

```

feat1_upsample = torch.cat((feat1_local_upsample, feat1_global_upsample), dim=1)
feat2_upsample = torch.cat((feat2_local_upsample, feat2_global_upsample), dim=1)
num_features = feat1_upsample.shape[1]

```

```

/home/docs/checkouts/readthedocs.org/user_builds/pygmtools/envs/0.3.0/lib/python3.7/site-
↪ packages/torch/nn/functional.py:3121: UserWarning: Default upsampling behavior when
↪ mode=bilinear is changed to align_corners=False since 0.4.0. Please specify align_
↪ corners=True if the old behavior is desired. See the documentation of nn.Upsample for
↪ details.
  "See the documentation of nn.Upsample for details.".format(mode))

```

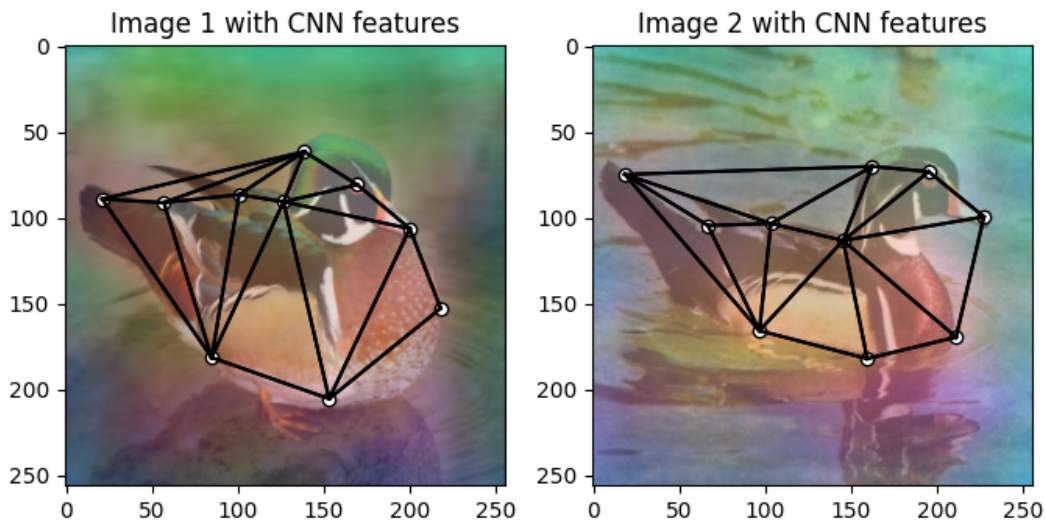
Visualize the extracted CNN feature (dimensionality reduction via principle component analysis)

```

pca_dim_reduc = PCAdimReduc(n_components=3, whiten=True)
feat_dim_reduc = pca_dim_reduc.fit_transform(
    np.concatenate((
        feat1_upsample.permute(0, 2, 3, 1).reshape(-1, num_features).numpy(),
        feat2_upsample.permute(0, 2, 3, 1).reshape(-1, num_features).numpy()
    ), axis=0)
)
feat_dim_reduc = feat_dim_reduc / np.max(np.abs(feat_dim_reduc), axis=0, keepdims=True) /
↪ 2 + 0.5
feat1_dim_reduc = feat_dim_reduc[:obj_resize[0] * obj_resize[1], :]
feat2_dim_reduc = feat_dim_reduc[obj_resize[0] * obj_resize[1]:, :]

plt.figure(figsize=(8, 4))
plt.subplot(1, 2, 1)
plt.title('Image 1 with CNN features')
plot_image_with_graph(img1, kpts1, A1)
plt.imshow(feat1_dim_reduc.reshape(obj_resize[0], obj_resize[1], 3), alpha=0.5)
plt.subplot(1, 2, 2)
plt.title('Image 2 with CNN features')
plot_image_with_graph(img2, kpts2, A2)
plt.imshow(feat2_dim_reduc.reshape(obj_resize[0], obj_resize[1], 3), alpha=0.5)

```



```
<matplotlib.image.AxesImage object at 0x7efe8caba510>
```

Extract node features by nearest interpolation

```
rounded_kpts1 = torch.round(kpts1).to(dtype=torch.long)
rounded_kpts2 = torch.round(kpts2).to(dtype=torch.long)
node1 = feat1_upsample[0, :, rounded_kpts1[0], rounded_kpts1[1]].t() # shape: NxC
node2 = feat2_upsample[0, :, rounded_kpts2[0], rounded_kpts2[1]].t() # shape: NxC
```

## Call PCA-GM matching model

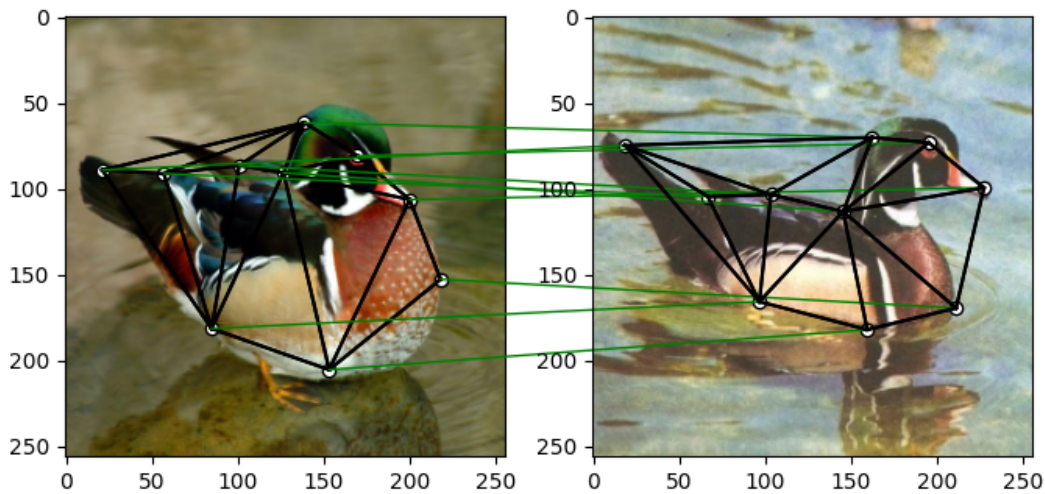
See [pca\\_gm\(\)](#) for the API reference.

```
X = pygm.pca_gm(node1, node2, A1, A2, pretrain='voc')
X = pygm.hungarian(X)

plt.figure(figsize=(8, 4))
plt.suptitle('Image Matching Result by PCA-GM')
ax1 = plt.subplot(1, 2, 1)
plot_image_with_graph(img1, kpts1, A1)
ax2 = plt.subplot(1, 2, 2)
plot_image_with_graph(img2, kpts2, A2)
for i in range(X.shape[0]):
    j = torch.argmax(X[i]).item()
    con = ConnectionPatch(xyA=kpts1[:, i], xyB=kpts2[:, j], coordsA="data", coordsB="data",
        axesA=ax1, axesB=ax2, color="red" if i != j else "green")
    plt.gca().add_artist(con)
```



Image Matching Result by PCA-GM



Downloading to /home/docs/.cache/pygmtools/pca\_gm\_voc\_pytorch.pt...

```

0%|          | 0/117485843 [00:00<?, ?it/s]
1%|          | 800k/112M [00:00<00:14, 8.17MB/s]
7%|7        | 8.28M/112M [00:00<00:02, 49.6MB/s]
15%|#4      | 16.7M/112M [00:00<00:01, 67.1MB/s]
22%|##2     | 25.1M/112M [00:00<00:01, 75.2MB/s]
30%|##9     | 33.4M/112M [00:00<00:01, 79.6MB/s]
37%|###7    | 41.8M/112M [00:00<00:00, 82.3MB/s]
45%|####4   | 50.2M/112M [00:00<00:00, 84.2MB/s]
52%|#####2 | 58.5M/112M [00:00<00:00, 85.3MB/s]
60%|#####9 | 66.9M/112M [00:00<00:00, 86.0MB/s]
67%|#####7 | 75.4M/112M [00:01<00:00, 86.6MB/s]
75%|#####4 | 83.8M/112M [00:01<00:00, 87.0MB/s]
82%|#####2 | 92.2M/112M [00:01<00:00, 87.5MB/s]
90%|#####  | 101M/112M [00:01<00:00, 88.8MB/s]
98%|#####7 | 110M/112M [00:01<00:00, 89.3MB/s]
100%|##### | 112M/112M [00:01<00:00, 82.1MB/s]

```

### Matching images with other neural networks

The above pipeline also works for other deep graph matching networks. Here we give examples of `ipca_gm()` and `cie()`.

## Matching by IPCA-GM model

See `ipca_gm()` for the API reference.

```
path = pygm.utils.download('vgg16_ipca_voc_pytorch.pt', 'https://drive.google.com/u/0/uc?
↳export=download&confirm=Z-AR&id=1TGrbSQRmUkClH3Alz20Cwqjl8r8gf5yI')
cnn.load_state_dict(torch.load(path, map_location=map_location), strict=False)

with torch.set_grad_enabled(False):
    feat1_local, feat1_global = cnn(torch_img1)
    feat2_local, feat2_global = cnn(torch_img2)
```

Downloading to /home/docs/.cache/pygmtools/vgg16\_ipca\_voc\_pytorch.pt...

```
0%|          | 0/166984418 [00:00<?, ?it/s]
1%|          | 1.09M/159M [00:00<00:14, 11.4MB/s]
5%|5        | 8.02M/159M [00:00<00:04, 37.1MB/s]
10%|#       | 16.0M/159M [00:00<00:03, 46.1MB/s]
15%|#5      | 24.0M/159M [00:00<00:02, 51.4MB/s]
20%|##      | 32.0M/159M [00:00<00:02, 54.9MB/s]
25%|##5     | 40.0M/159M [00:00<00:02, 59.9MB/s]
30%|###     | 48.0M/159M [00:00<00:01, 59.7MB/s]
35%|###5    | 56.0M/159M [00:01<00:01, 61.3MB/s]
40%|####    | 64.0M/159M [00:01<00:02, 41.0MB/s]
45%|####5   | 72.0M/159M [00:01<00:02, 34.9MB/s]
51%|#####  | 81.2M/159M [00:01<00:01, 44.4MB/s]
55%|#####5 | 88.2M/159M [00:01<00:01, 49.9MB/s]
61%|#####1 | 97.4M/159M [00:02<00:01, 59.4MB/s]
66%|#####6 | 106M/159M [00:02<00:00, 65.2MB/s]
72%|#####1 | 115M/159M [00:02<00:00, 72.7MB/s]
77%|#####6 | 122M/159M [00:02<00:00, 72.3MB/s]
83%|#####2 | 132M/159M [00:02<00:00, 79.0MB/s]
88%|#####7 | 140M/159M [00:02<00:00, 61.8MB/s]
94%|#####3 | 149M/159M [00:02<00:00, 70.5MB/s]
100%|#####9| 159M/159M [00:02<00:00, 77.6MB/s]
100%|#####| 159M/159M [00:02<00:00, 58.2MB/s]
```

Normalize the features

```
def l2norm(node_feat):
    return torch.nn.functional.local_response_norm(
        node_feat, node_feat.shape[1] * 2, alpha=node_feat.shape[1] * 2, beta=0.5, k=0)

feat1_local = l2norm(feat1_local)
feat1_global = l2norm(feat1_global)
feat2_local = l2norm(feat2_local)
feat2_global = l2norm(feat2_global)
```

Up-sample the features to the original image size and concatenate

```
feat1_local_upsample = torch.nn.functional.interpolate(feat1_local, obj_resize, mode=
↳'bilinear')
feat1_global_upsample = torch.nn.functional.interpolate(feat1_global, obj_resize, mode=
```

(continues on next page)



(continued from previous page)

```

↪ 'bilinear')
feat2_local_upsample = torch.nn.functional.interpolate(feat2_local, obj_resize, mode=
↪ 'bilinear')
feat2_global_upsample = torch.nn.functional.interpolate(feat2_global, obj_resize, mode=
↪ 'bilinear')
feat1_upsample = torch.cat((feat1_local_upsample, feat1_global_upsample), dim=1)
feat2_upsample = torch.cat((feat2_local_upsample, feat2_global_upsample), dim=1)
num_features = feat1_upsample.shape[1]

```

```

/home/docs/checkouts/readthedocs.org/user_builds/pygmtools/envs/0.3.0/lib/python3.7/site-
↪ packages/torch/nn/functional.py:3121: UserWarning: Default upsampling behavior when
↪ mode=bilinear is changed to align_corners=False since 0.4.0. Please specify align_
↪ corners=True if the old behavior is desired. See the documentation of nn.Upsample for
↪ details.
    "See the documentation of nn.Upsample for details.".format(mode))

```

Extract node features by nearest interpolation

```

rounded_kpts1 = torch.round(kpts1).to(dtype=torch.long)
rounded_kpts2 = torch.round(kpts2).to(dtype=torch.long)
node1 = feat1_upsample[0, :, rounded_kpts1[0], rounded_kpts1[1]].t() # shape: NxC
node2 = feat2_upsample[0, :, rounded_kpts2[0], rounded_kpts2[1]].t() # shape: NxC

```

Build edge features as edge lengths

```

kpts1_dis = (kpts1.unsqueeze(0) - kpts1.unsqueeze(1))
kpts1_dis = torch.norm(kpts1_dis, p=2, dim=2).detach()
kpts2_dis = (kpts2.unsqueeze(0) - kpts2.unsqueeze(1))
kpts2_dis = torch.norm(kpts2_dis, p=2, dim=2).detach()

Q1 = torch.exp(-kpts1_dis / obj_resize[0])
Q2 = torch.exp(-kpts2_dis / obj_resize[0])

```

Matching by IPCA-GM model

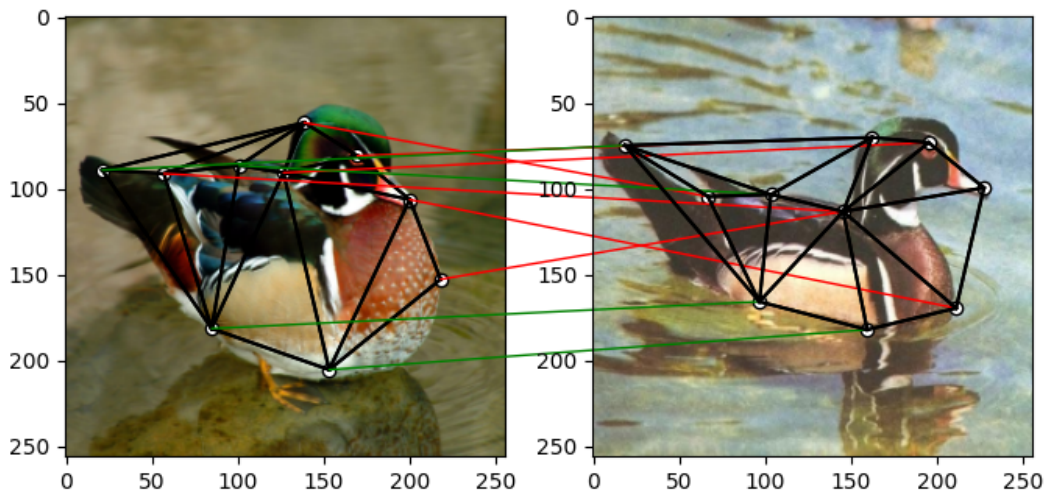
```

X = pygm.ipca_gm(node1, node2, A1, A2, pretrain='voc')
X = pygm.hungarian(X)

plt.figure(figsize=(8, 4))
plt.suptitle('Image Matching Result by IPCA-GM')
ax1 = plt.subplot(1, 2, 1)
plot_image_with_graph(img1, kpts1, A1)
ax2 = plt.subplot(1, 2, 2)
plot_image_with_graph(img2, kpts2, A2)
for i in range(X.shape[0]):
    j = torch.argmax(X[i]).item()
    con = ConnectionPatch(xyA=kpts1[:, i], xyB=kpts2[:, j], coordsA="data", coordsB="data"
↪ ",
                        axesA=ax1, axesB=ax2, color="red" if i != j else "green")
    plt.gca().add_artist(con)

```

Image Matching Result by IPCA-GM



Downloading to /home/docs/.cache/pygmtools/ipca\_gm\_voc\_pytorch.pt...

```

0%|          | 0/100708304 [00:00<?, ?it/s]
1%|1         | 1.06M/96.0M [00:00<00:08, 11.1MB/s]
10%|9        | 9.36M/96.0M [00:00<00:01, 55.4MB/s]
19%|#8       | 18.0M/96.0M [00:00<00:01, 71.4MB/s]
28%|##7      | 26.7M/96.0M [00:00<00:00, 79.2MB/s]
37%|###6     | 35.4M/96.0M [00:00<00:00, 83.5MB/s]
46%|####5    | 44.1M/96.0M [00:00<00:00, 85.7MB/s]
55%|#####5  | 52.8M/96.0M [00:00<00:00, 87.7MB/s]
64%|#####4  | 61.8M/96.0M [00:00<00:00, 89.7MB/s]
74%|#####3  | 70.9M/96.0M [00:00<00:00, 91.1MB/s]
83%|#####3  | 80.0M/96.0M [00:01<00:00, 92.3MB/s]
93%|#####2  | 88.9M/96.0M [00:01<00:00, 92.7MB/s]
100%|#####  | 96.0M/96.0M [00:01<00:00, 85.0MB/s]

```

## Matching by CIE model

See [cie\(\)](#) for the API reference.

```

path = pygm.utils.download('vgg16_cie_voc_pytorch.pt', 'https://drive.google.com/u/0/uc?
↪export=download&confirm=Z-AR&id=1oRwcnw06t1rCbrIN_7p8TJZY-XkBOFEp')
cnn.load_state_dict(torch.load(path, map_location=map_location), strict=False)

with torch.set_grad_enabled(False):
    feat1_local, feat1_global = cnn(torch_img1)
    feat2_local, feat2_global = cnn(torch_img2)

```

Downloading to /home/docs/.cache/pygmtools/vgg16\_cie\_voc\_pytorch.pt...

```

0%|          | 0/217351064 [00:00<?, ?it/s]

```

(continues on next page)

(continued from previous page)

0%		848k/207M	[00:00<00:25, 8.64MB/s]
4% 4		8.47M/207M	[00:00<00:04, 50.6MB/s]
8% 8		16.8M/207M	[00:00<00:02, 67.3MB/s]
12% #2		25.2M/207M	[00:00<00:02, 75.3MB/s]
16% #6		33.6M/207M	[00:00<00:02, 80.0MB/s]
20% ##		42.0M/207M	[00:00<00:02, 82.7MB/s]
24% ###4		50.5M/207M	[00:00<00:01, 84.6MB/s]
28% ###8		58.8M/207M	[00:00<00:01, 85.6MB/s]
32% ###2		67.3M/207M	[00:00<00:01, 86.6MB/s]
37% ###6		75.7M/207M	[00:01<00:01, 87.0MB/s]
41% ####		84.2M/207M	[00:01<00:01, 87.5MB/s]
45% ####4		92.6M/207M	[00:01<00:01, 87.6MB/s]
49% ####8		101M/207M	[00:01<00:01, 87.9MB/s]
53% #####2		109M/207M	[00:01<00:01, 87.9MB/s]
57% #####6		118M/207M	[00:01<00:01, 88.2MB/s]
61% #####		126M/207M	[00:01<00:00, 88.1MB/s]
65% #####5		135M/207M	[00:01<00:00, 88.1MB/s]
69% #####9		143M/207M	[00:01<00:00, 88.1MB/s]
73% #####3		152M/207M	[00:01<00:00, 88.2MB/s]
77% #####7		160M/207M	[00:02<00:00, 88.1MB/s]
81% #####1		169M/207M	[00:02<00:00, 88.5MB/s]
85% #####5		177M/207M	[00:02<00:00, 88.2MB/s]
90% #####9		186M/207M	[00:02<00:00, 88.5MB/s]
94% #####3		194M/207M	[00:02<00:00, 88.5MB/s]
98% #####7		203M/207M	[00:02<00:00, 88.5MB/s]
100% #####		207M/207M	[00:02<00:00, 84.8MB/s]

Normalize the features

```
def l2norm(node_feat):
    return torch.nn.functional.local_response_norm(
        node_feat, node_feat.shape[1] * 2, alpha=node_feat.shape[1] * 2, beta=0.5, k=0)

feat1_local = l2norm(feat1_local)
feat1_global = l2norm(feat1_global)
feat2_local = l2norm(feat2_local)
feat2_global = l2norm(feat2_global)
```

Up-sample the features to the original image size and concatenate

```
feat1_local_upsample = torch.nn.functional.interpolate(feat1_local, obj_resize, mode=
    ↪ 'bilinear')
feat1_global_upsample = torch.nn.functional.interpolate(feat1_global, obj_resize, mode=
    ↪ 'bilinear')
feat2_local_upsample = torch.nn.functional.interpolate(feat2_local, obj_resize, mode=
    ↪ 'bilinear')
feat2_global_upsample = torch.nn.functional.interpolate(feat2_global, obj_resize, mode=
    ↪ 'bilinear')
feat1_upsample = torch.cat((feat1_local_upsample, feat1_global_upsample), dim=1)
feat2_upsample = torch.cat((feat2_local_upsample, feat2_global_upsample), dim=1)
num_features = feat1_upsample.shape[1]
```

```
/home/docs/checkouts/readthedocs.org/user_builds/pygmtools/envs/0.3.0/lib/python3.7/site-
→packages/torch/nn/functional.py:3121: UserWarning: Default upsampling behavior when
→mode=bilinear is changed to align_corners=False since 0.4.0. Please specify align_
→corners=True if the old behavior is desired. See the documentation of nn.Upsample for
→details.
    "See the documentation of nn.Upsample for details.".format(mode))
```

Extract node features by nearest interpolation

```
rounded_kpts1 = torch.round(kpts1).to(dtype=torch.long)
rounded_kpts2 = torch.round(kpts2).to(dtype=torch.long)
node1 = feat1_upsample[0, :, rounded_kpts1[0], rounded_kpts1[1]].t() # shape: Nx C
node2 = feat2_upsample[0, :, rounded_kpts2[0], rounded_kpts2[1]].t() # shape: Nx C
```

Build edge features as edge lengths

```
kpts1_dis = (kpts1.unsqueeze(1) - kpts1.unsqueeze(2))
kpts1_dis = torch.norm(kpts1_dis, p=2, dim=0).detach()
kpts2_dis = (kpts2.unsqueeze(1) - kpts2.unsqueeze(2))
kpts2_dis = torch.norm(kpts2_dis, p=2, dim=0).detach()

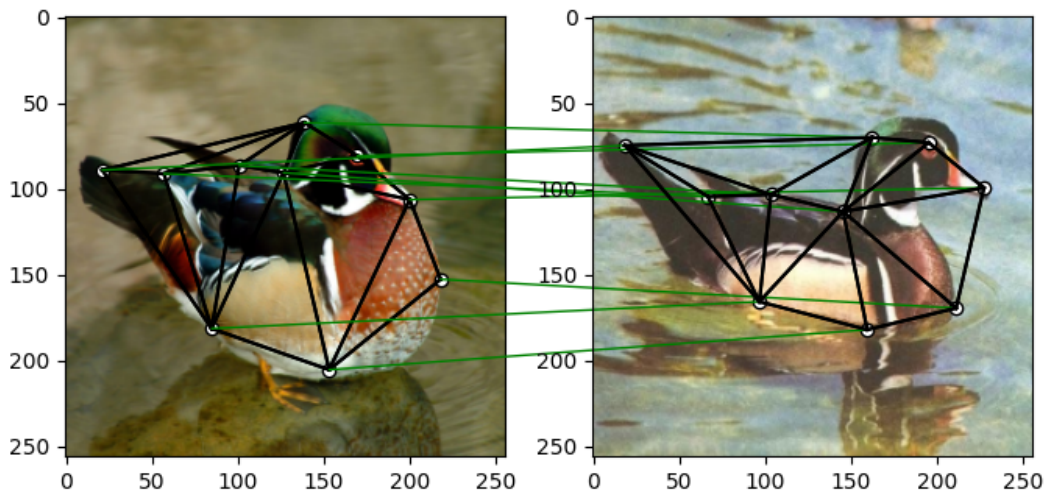
Q1 = torch.exp(-kpts1_dis / obj_resize[0]).unsqueeze(-1).to(dtype=torch.float32)
Q2 = torch.exp(-kpts2_dis / obj_resize[0]).unsqueeze(-1).to(dtype=torch.float32)
```

Call CIE matching model

```
X = pygm.cie(node1, node2, A1, A2, Q1, Q2, pretrain='voc')
X = pygm.hungarian(X)

plt.figure(figsize=(8, 4))
plt.suptitle('Image Matching Result by CIE')
ax1 = plt.subplot(1, 2, 1)
plot_image_with_graph(img1, kpts1, A1)
ax2 = plt.subplot(1, 2, 2)
plot_image_with_graph(img2, kpts2, A2)
for i in range(X.shape[0]):
    j = torch.argmax(X[i]).item()
    con = ConnectionPatch(xyA=kpts1[:, i], xyB=kpts2[:, j], coordsA="data", coordsB="data
→",
                        axesA=ax1, axesB=ax2, color="red" if i != j else "green")
    plt.gca().add_artist(con)
```

Image Matching Result by CIE



Downloading to /home/docs/.cache/pygmtools/cie\_voc\_pytorch.pt...

```

0%|          | 0/134288927 [00:00<?, ?it/s]
1%|          | 896k/128M [00:00<00:14, 9.12MB/s]
6%|6        | 8.02M/128M [00:00<00:02, 43.8MB/s]
13%|#2      | 16.5M/128M [00:00<00:01, 63.5MB/s]
20%|#9      | 25.1M/128M [00:00<00:01, 73.6MB/s]
26%|##6     | 33.7M/128M [00:00<00:01, 79.1MB/s]
33%|###2    | 42.2M/128M [00:00<00:01, 82.7MB/s]
40%|###9    | 50.8M/128M [00:00<00:00, 85.0MB/s]
46%|####6   | 59.3M/128M [00:00<00:00, 86.3MB/s]
53%|#####3 | 67.9M/128M [00:00<00:00, 87.4MB/s]
60%|#####9 | 76.5M/128M [00:01<00:00, 88.2MB/s]
66%|#####6 | 85.1M/128M [00:01<00:00, 88.7MB/s]
73%|#####3 | 93.7M/128M [00:01<00:00, 89.1MB/s]
80%|#####9 | 102M/128M [00:01<00:00, 89.2MB/s]
87%|#####6 | 111M/128M [00:01<00:00, 89.8MB/s]
94%|#####3 | 120M/128M [00:01<00:00, 90.6MB/s]
100%|##### | 128M/128M [00:01<00:00, 83.3MB/s]

```

## Training a deep graph matching model

In this section, we show how to build a deep graph matching model which supports end-to-end training. For the image matching problem considered here, the model is composed of a CNN feature extractor and a learnable matching module. Take the PCA-GM model as an example.

**Note:** This simple example is intended to show you how to do the basic forward and backward pass when training an end-to-end deep graph matching neural network. A ‘more formal’ deep learning pipeline should involve asynchronous data loader, batched operations, CUDA support and so on, which are all omitted in consideration of simplicity. You may refer to [ThinkMatch](#) which is a research protocol with all these advanced features.

Let's firstly define the neural network model. By passing None to `pca_gm()`, it will simply return the network object.

```
class GMNet(torch.nn.Module):
    def __init__(self):
        super(GMNet, self).__init__()
        self.gm_net = pygm.utils.get_network(pygm.pca_gm, pretrain=False) # fetch the
↪ network object
        self.cnn = CNNNet(vgg16_cnn)

    def forward(self, img1, img2, kpts1, kpts2, A1, A2):
        # CNN feature extractor layers
        feat1_local, feat1_global = self.cnn(img1)
        feat2_local, feat2_global = self.cnn(img2)
        feat1_local = l2norm(feat1_local)
        feat1_global = l2norm(feat1_global)
        feat2_local = l2norm(feat2_local)
        feat2_global = l2norm(feat2_global)

        # upsample feature map
        feat1_local_upsample = torch.nn.functional.interpolate(feat1_local, obj_resize,
↪ mode='bilinear')
        feat1_global_upsample = torch.nn.functional.interpolate(feat1_global, obj_resize,
↪ mode='bilinear')
        feat2_local_upsample = torch.nn.functional.interpolate(feat2_local, obj_resize,
↪ mode='bilinear')
        feat2_global_upsample = torch.nn.functional.interpolate(feat2_global, obj_resize,
↪ mode='bilinear')
        feat1_upsample = torch.cat((feat1_local_upsample, feat1_global_upsample), dim=1)
        feat2_upsample = torch.cat((feat2_local_upsample, feat2_global_upsample), dim=1)

        # assign node features
        rounded_kpts1 = torch.round(kpts1).to(dtype=torch.long)
        rounded_kpts2 = torch.round(kpts2).to(dtype=torch.long)
        node1 = feat1_upsample[0, :, rounded_kpts1[0], rounded_kpts1[1]].t() # shape:
↪ Nx C
        node2 = feat2_upsample[0, :, rounded_kpts2[0], rounded_kpts2[1]].t() # shape:
↪ Nx C

        # PCA-GM matching layers
        X = pygm.pca_gm(node1, node2, A1, A2, network=self.gm_net) # the network object
↪ is reused
        return X

model = GMNet()
```

## Define optimizer

```
optim = torch.optim.Adam(model.parameters(), lr=1e-3)
```

## Forward pass

```
X = model(torch_img1, torch_img2, kpts1, kpts2, A1, A2)
```

```
/home/docs/checkouts/readthedocs.org/user_builds/pygmtools/envs/0.3.0/lib/python3.7/site-
↳ packages/torch/nn/functional.py:3121: UserWarning: Default upsampling behavior when
↳ mode=bilinear is changed to align_corners=False since 0.4.0. Please specify align_
↳ corners=True if the old behavior is desired. See the documentation of nn.Upsample for
↳ details.
  "See the documentation of nn.Upsample for details.".format(mode))
```

## Compute loss

In this example, the ground truth matching matrix is a diagonal matrix. We calculate the loss function via `permutation_loss()`

```
X_gt = torch.eye(X.shape[0])
loss = pygm.utils.permutation_loss(X, X_gt)
print(f'loss={loss:.4f}')
```

```
loss=3.0041
```

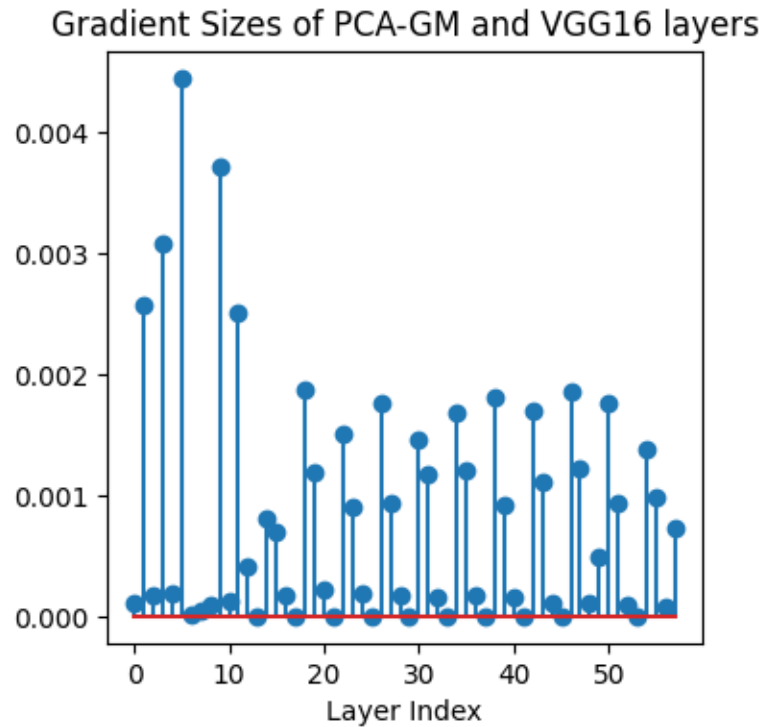
## Backward Pass

```
loss.backward()
```

Visualize the gradients

```
plt.figure(figsize=(4, 4))
plt.title('Gradient Sizes of PCA-GM and VGG16 layers')
plt.gca().set_xlabel('Layer Index')
plt.gca().set_ylabel('Average Gradient Size')
grad_size = []
for param in model.parameters():
    grad_size.append(torch.abs(param.grad).mean().item())
print(grad_size)
plt.stem(grad_size)
```





```
[0.00010975256009260193, 0.0025820708833634853, 0.0001791776594473049, 0.
→ 003091256134212017, 0.00019184016855433583, 0.004451952874660492, 9.98683572106529e-06,
→ 4.676436947192997e-05, 9.653159213485196e-05, 0.0037215095944702625, 0.
→ 00012330709432717413, 0.0025161956436932087, 0.0004079950740560889, 9.495846775564587e-
→ 09, 0.0008160851430147886, 0.0006923370528966188, 0.00016938714543357491, 8.
→ 247080351964087e-09, 0.0018779300153255463, 0.0011980452109128237, 0.
→ 00021563969494309276, 2.068021531798081e-09, 0.001510141883045435, 0.
→ 0009055724949575961, 0.0001880597264971584, 3.660260761151335e-09, 0.
→ 0017704766942188144, 0.0009336725925095379, 0.0001807412481866777, 1.0506436831647648e-
→ 09, 0.0014650675002485514, 0.001176448306068778, 0.00015496666310355067, 1.
→ 5817932519368583e-09, 0.001682713278569281, 0.0012110973475500941, 0.
→ 00016743903688620776, 1.7945213093284451e-09, 0.0018167807720601559, 0.
→ 0009177665924653411, 0.0001519177749287337, 4.470540881928997e-10, 0.
→ 0016938832122832537, 0.001109698903746903, 0.00011667542275972664, 6.756070702884642e-
→ 10, 0.0018534527625888586, 0.001221839222125709, 0.00011477413499960676, 0.
→ 0004964273539371789, 0.0017710058018565178, 0.0009307056316174567, 9.207324183080345e-
→ 05, 2.3413559979701404e-10, 0.001390282646752894, 0.0009812040952965617, 8.
→ 179757423931733e-05, 0.0007362457108683884]
```

<StemContainer object of 3 artists>

Update the model parameters. A deep learning pipeline should iterate the forward pass and backward pass steps until convergence.

```
optim.step()
optim.zero_grad()
```

**Note:** This example supports both GPU and CPU, and the online documentation is built by a CPU-only machine. The



efficiency will be significantly improved if you run this code on GPU.

**Total running time of the script:** ( 1 minutes 2.536 seconds)

### Model Fusion by Graph Matching

This example shows how to fuse different models into a single model by `pygmtools`. Model fusion aims to fuse multiple models into one, such that the fused model could have higher performance. The neural networks can be regarded as graphs (channels - nodes, update functions between channels - edges; node feature - bias, edge feature - weights), and fusing the models is equivalent to solving a graph matching problem. In this example, the given models are trained on MNIST data from different distributions, and the fused model could combine the knowledge from two input models and can reach higher accuracy when testing.

```
# Author: Chang Liu <only-changer@sjtu.edu.cn>
#         Runzhong Wang <runzhong.wang@sjtu.edu.cn>
#
# License: Mulan PSL v2 License
```

**Note:** This is a simplified implementation of the ideas in Liu et al. [Deep Neural Network Fusion via Graph Matching with Applications to Model Ensemble and Federated Learning](#). ICML 2022. For more details, please refer to the paper and the [official code repository](#).

**Note:** The following solvers are included in this example:

- `sm()` (classic solver)
- `hungarian()` (linear solver)

```
import torch
import torch.nn as nn
import torch.nn.functional as F
import torchvision
import torchvision.transforms as transforms
import time
from PIL import Image
import matplotlib.pyplot as plt
import pygmtools as pygm

pygm.BACKEND = 'pytorch'
device = torch.device('cuda:0' if torch.cuda.is_available() else 'cpu')
```

## Define a simple CNN classifier network

```
class SimpleNet(nn.Module):
    def __init__(self):
        super(SimpleNet, self).__init__()
        self.conv1 = nn.Conv2d(1, 32, 5, padding=1, padding_mode='replicate', bias=False)
        self.max_pool = nn.MaxPool2d(2, padding=1)
        self.conv2 = nn.Conv2d(32, 64, 5, padding=1, padding_mode='replicate',
↪ bias=False)
        self.fc1 = nn.Linear(3136, 32, bias=False)
        self.fc2 = nn.Linear(32, 10, bias=False)

    def forward(self, x):
        output = F.relu(self.conv1(x))
        output = self.max_pool(output)
        output = F.relu(self.conv2(output))
        output = self.max_pool(output)
        output = output.view(output.shape[0], -1)
        output = self.fc1(output)
        output = self.fc2(output)
        return output
```

## Load the trained models to be fused

```
model1 = SimpleNet()
model2 = SimpleNet()
model1.load_state_dict(torch.load('../data/example_model_fusion_1.dat', map_
↪ location=device))
model2.load_state_dict(torch.load('../data/example_model_fusion_2.dat', map_
↪ location=device))
model1.to(device)
model2.to(device)
test_dataset = torchvision.datasets.MNIST(
    root='../data/mnist_data', # the directory to store the dataset
    train=False, # the dataset is used to test
    transform=transforms.ToTensor(), # the dataset is in the form of tensors
    download=True)
test_loader = torch.utils.data.DataLoader(
    dataset=test_dataset,
    batch_size=32,
    shuffle=False)
```

```
Using downloaded and verified file: ../data/mnist_data/MNIST/raw/train-images-idx3-ubyte.
↪ gz
Extracting ../data/mnist_data/MNIST/raw/train-images-idx3-ubyte.gz to ../data/mnist_data/
↪ MNIST/raw
Using downloaded and verified file: ../data/mnist_data/MNIST/raw/train-labels-idx1-ubyte.
↪ gz
Extracting ../data/mnist_data/MNIST/raw/train-labels-idx1-ubyte.gz to ../data/mnist_data/
↪ MNIST/raw
Using downloaded and verified file: ../data/mnist_data/MNIST/raw/t10k-images-idx3-ubyte.
```

(continues on next page)

(continued from previous page)

```

↪gz
Extracting ../data/mnist_data/MNIST/raw/t10k-images-idx3-ubyte.gz to ../data/mnist_data/
↪MNIST/raw
Using downloaded and verified file: ../data/mnist_data/MNIST/raw/t10k-labels-idx1-ubyte.
↪gz
Extracting ../data/mnist_data/MNIST/raw/t10k-labels-idx1-ubyte.gz to ../data/mnist_data/
↪MNIST/raw
Processing...
/home/docs/checkouts/readthedocs.org/user_builds/pygmtools/envs/0.3.0/lib/python3.7/site-
↪packages/torchvision/datasets/mnist.py:469: UserWarning: The given NumPy array is not
↪writeable, and PyTorch does not support non-writeable tensors. This means you can
↪write to the underlying (supposedly non-writeable) NumPy array using the tensor. You
↪may want to copy the array to protect its data or make it writeable before converting
↪it to a tensor. This type of warning will be suppressed for the rest of this program.
↪(Triggered internally at /pytorch/torch/csrc/utils/tensor_numpy.cpp:141.)
    return torch.from_numpy(parsed.astype(m[2], copy=False)).view(*s)
Done!

```

Print the layers of the simple CNN model:

```
print(model1)
```

```

SimpleNet(
  (conv1): Conv2d(1, 32, kernel_size=(5, 5), stride=(1, 1), padding=(1, 1), bias=False,
↪padding_mode=replicate)
  (max_pool): MaxPool2d(kernel_size=2, stride=2, padding=1, dilation=1, ceil_mode=False)
  (conv2): Conv2d(32, 64, kernel_size=(5, 5), stride=(1, 1), padding=(1, 1), bias=False,
↪padding_mode=replicate)
  (fc1): Linear(in_features=3136, out_features=32, bias=False)
  (fc2): Linear(in_features=32, out_features=10, bias=False)
)

```

## Test the input models

```

with torch.no_grad():
    n_correct1 = 0
    n_correct2 = 0
    n_samples = 0
    for images, labels in test_loader:
        images = images.to(device)
        labels = labels.to(device)
        outputs1 = model1(images)
        outputs2 = model2(images)
        _, predictions1 = torch.max(outputs1, 1)
        _, predictions2 = torch.max(outputs2, 1)
        n_samples += labels.shape[0]
        n_correct1 += (predictions1 == labels).sum().item()
        n_correct2 += (predictions2 == labels).sum().item()
    acc1 = 100 * n_correct1 / n_samples
    acc2 = 100 * n_correct2 / n_samples

```

Testing results (two separate models):

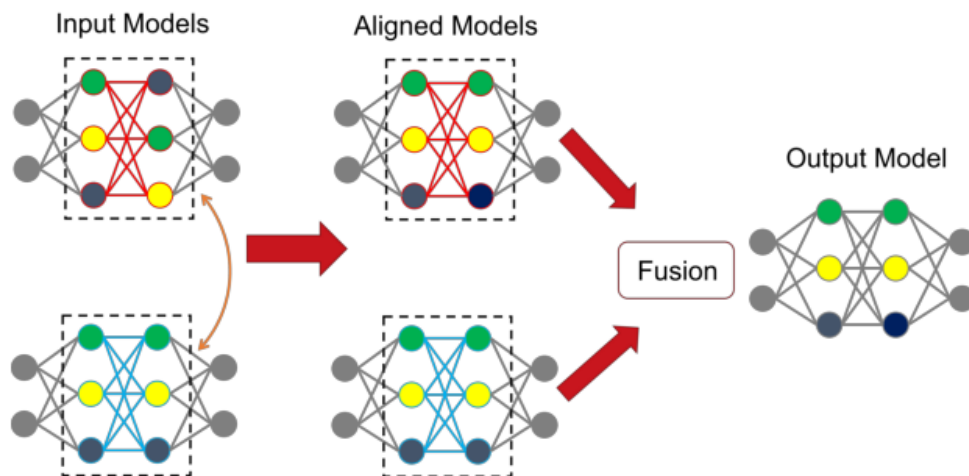
```
print(f'model1 accuracy = {acc1}%, model2 accuracy = {acc2}%')
```

```
model1 accuracy = 84.18%, model2 accuracy = 83.81%
```

### Build the affinity matrix for graph matching

As shown in the following plot, the neural networks can be regarded as graphs. The weights corresponds to the edge features, and the bias corresponds to the node features. In this example, the neural network does not have bias so that there are only edge features.

```
plt.figure(figsize=(8, 4))
img = Image.open('../data/model_fusion.png')
plt.imshow(img)
plt.axis('off')
st_time = time.perf_counter()
```



Define the graph matching affinity metric function

```
class Ground_Metric_GM:
    def __init__(self,
        model_1_param: torch.tensor = None,
        model_2_param: torch.tensor = None,
        conv_param: bool = False,
        bias_param: bool = False,
        pre_conv_param: bool = False,
        pre_conv_image_size_squared: int = None):
        self.model_1_param = model_1_param
        self.model_2_param = model_2_param
        self.conv_param = conv_param
        self.bias_param = bias_param
```

(continues on next page)

(continued from previous page)

```

    # bias, or fully-connected from linear
    if bias_param is True or (conv_param is False and pre_conv_param is False):
        self.model_1_param = self.model_1_param.reshape(1, -1, 1)
        self.model_2_param = self.model_2_param.reshape(1, -1, 1)
    # fully-connected from conv
    elif conv_param is False and pre_conv_param is True:
        self.model_1_param = self.model_1_param.reshape(1, -1, pre_conv_image_size_
↪squared)
        self.model_2_param = self.model_2_param.reshape(1, -1, pre_conv_image_size_
↪squared)
    # conv
    else:
        self.model_1_param = self.model_1_param.reshape(1, -1, model_1_param.shape[-
↪1])
        self.model_2_param = self.model_2_param.reshape(1, -1, model_2_param.shape[-
↪1])

    def process_distance(self, p: int = 2):
        return torch.cdist(
            self.model_1_param.to(torch.float),
            self.model_2_param.to(torch.float),
            p=p)[0]

    def process_soft_affinity(self, p: int = 2):
        return torch.exp(0 - self.process_distance(p=p))

```

Define the affinity function between two neural networks. This function takes multiple neural network modules, and construct the corresponding affinity matrix which is further processed by the graph matching solver.

```

def graph_matching_fusion(networks: list):
    def total_node_num(network: torch.nn.Module):
        # count the total number of nodes in the network [network]
        num_nodes = 0
        for idx, (name, parameters) in enumerate(network.named_parameters()):
            if 'bias' in name:
                continue
            if idx == 0:
                num_nodes += parameters.shape[1]
            num_nodes += parameters.shape[0]
        return num_nodes

    n1 = total_node_num(network=networks[0])
    n2 = total_node_num(network=networks[1])
    assert (n1 == n2)
    affinity = torch.zeros([n1 * n2, n1 * n2], device=device)
    num_layers = len(list(zip(networks[0].parameters(), networks[1].parameters())))
    num_nodes_before = 0
    num_nodes_incremental = []
    num_nodes_layers = []
    pre_conv_list = []
    cur_conv_list = []
    conv_kernel_size_list = []

```

(continues on next page)

(continued from previous page)

```

num_nodes_pre = 0
is_conv = False
pre_conv = False
pre_conv_out_channel = 1
is_final_bias = False
perm_is_complete = True
named_weight_list_0 = [named_parameter for named_parameter in networks[0].named_
↳parameters()]
    for idx, ((_, fc_layer0_weight), (_, fc_layer1_weight)) in \
        enumerate(zip(networks[0].named_parameters(), networks[1].named_
↳parameters())):
        assert fc_layer0_weight.shape == fc_layer1_weight.shape
        layer_shape = fc_layer0_weight.shape
        num_nodes_cur = fc_layer0_weight.shape[0]
        if len(layer_shape) > 1:
            if is_conv is True and len(layer_shape) == 2:
                num_nodes_pre = pre_conv_out_channel
            else:
                num_nodes_pre = fc_layer0_weight.shape[1]
        if idx >= 1 and len(named_weight_list_0[idx - 1][1].shape) == 1:
            pre_bias = True
        else:
            pre_bias = False
        if len(layer_shape) > 2:
            is_bias = False
            if not pre_bias:
                pre_conv = is_conv
                pre_conv_list.append(pre_conv)
            is_conv = True
            cur_conv_list.append(is_conv)
            fc_layer0_weight_data = fc_layer0_weight.data.view(
                fc_layer0_weight.shape[0], fc_layer0_weight.shape[1], -1)
            fc_layer1_weight_data = fc_layer1_weight.data.view(
                fc_layer1_weight.shape[0], fc_layer1_weight.shape[1], -1)
        elif len(layer_shape) == 2:
            is_bias = False
            if not pre_bias:
                pre_conv = is_conv
                pre_conv_list.append(pre_conv)
            is_conv = False
            cur_conv_list.append(is_conv)
            fc_layer0_weight_data = fc_layer0_weight.data
            fc_layer1_weight_data = fc_layer1_weight.data
        else:
            is_bias = True
            if not pre_bias:
                pre_conv = is_conv
                pre_conv_list.append(pre_conv)
            is_conv = False
            cur_conv_list.append(is_conv)
            fc_layer0_weight_data = fc_layer0_weight.data
            fc_layer1_weight_data = fc_layer1_weight.data

```

(continues on next page)

(continued from previous page)

```

if is_conv:
    pre_conv_out_channel = num_nodes_cur
if is_bias is True and idx == num_layers - 1:
    is_final_bias = True
if idx == 0:
    for a in range(num_nodes_pre):
        affinity[(num_nodes_before + a) * n2 + num_nodes_before + a] \
            [(num_nodes_before + a) * n2 + num_nodes_before + a] \
            = 1
if idx == num_layers - 2 and 'bias' in named_weight_list_0[idx + 1][0] or \
    idx == num_layers - 1 and 'bias' not in named_weight_list_0[idx][0]:
    for a in range(num_nodes_cur):
        affinity[(num_nodes_before + num_nodes_pre + a) * n2 + num_nodes_before_
↪ + num_nodes_pre + a] \
            [(num_nodes_before + num_nodes_pre + a) * n2 + num_nodes_before +_
↪ num_nodes_pre + a] \
            = 1
if is_bias is False:
    ground_metric = Ground_Metric_GM(
        fc_layer0_weight_data, fc_layer1_weight_data, is_conv, is_bias,
        pre_conv, int(fc_layer0_weight_data.shape[1] / pre_conv_out_channel))
else:
    ground_metric = Ground_Metric_GM(
        fc_layer0_weight_data, fc_layer1_weight_data, is_conv, is_bias,
        pre_conv, 1)

layer_affinity = ground_metric.process_soft_affinity(p=2)

if is_bias is False:
    pre_conv_kernel_size = fc_layer0_weight.shape[3] if is_conv else None
    conv_kernel_size_list.append(pre_conv_kernel_size)
if is_bias is True and is_final_bias is False:
    for a in range(num_nodes_cur):
        for c in range(num_nodes_cur):
            affinity[(num_nodes_before + a) * n2 + num_nodes_before + c] \
                [(num_nodes_before + a) * n2 + num_nodes_before + c] \
                = layer_affinity[a][c]
elif is_final_bias is False:
    for a in range(num_nodes_pre):
        for b in range(num_nodes_cur):
            affinity[
                (num_nodes_before + a) * n2 + num_nodes_before:
                (num_nodes_before + a) * n2 + num_nodes_before + num_nodes_pre,
                (num_nodes_before + num_nodes_pre + b) * n2 + num_nodes_before + num_
↪ nodes_pre:
                (num_nodes_before + num_nodes_pre + b) * n2 + num_nodes_before + num_
↪ nodes_pre + num_nodes_cur] \
                = layer_affinity[a + b * num_nodes_pre].view(num_nodes_cur, num_
↪ nodes_pre).transpose(0, 1)
if is_bias is False:
    num_nodes_before += num_nodes_pre
    num_nodes_incremental.append(num_nodes_before)

```

(continues on next page)

(continued from previous page)

```

        num_nodes_layers.append(num_nodes_cur)
    # affinity = (affinity + affinity.t()) / 2
    return affinity, [n1, n2, num_nodes_incremental, num_nodes_layers, cur_conv_list,
    ↪conv_kernel_size_list]

```

Get the affinity (similarity) matrix between model1 and model2.

```
K, params = graph_matching_fusion([model1, model2])
```

## Align the models by graph matching

Align the channels of model1 & model2 by maximize the affinity (similarity) via graph matching algorithms.

```

n1 = params[0]
n2 = params[1]
X = pygm.sm(K, n1, n2)

```

Project X to neural network matching result. The neural network matching matrix is built by applying Hungarian to small blocks of X, because only the channels from the same neural network layer can be matched.

---

**Note:** In this example, we assume the last FC layer is aligned and need not to be matched.

---

```

new_X = torch.zeros_like(X)
new_X[:params[2][0], :params[2][0]] = torch.eye(params[2][0], device=device)
for start_idx, length in zip(params[2][:-1], params[3][:-1]): # params[2] and params[3]
    ↪are the indices of layers
    slicing = slice(start_idx, start_idx + length)
    new_X[slicing, slicing] = pygm.hungarian(X[slicing, slicing])
# assume the last FC layer is aligned
slicing = slice(params[2][-1], params[2][-1] + params[3][-1])
new_X[slicing, slicing] = torch.eye(params[3][-1], device=device)
X = new_X

```

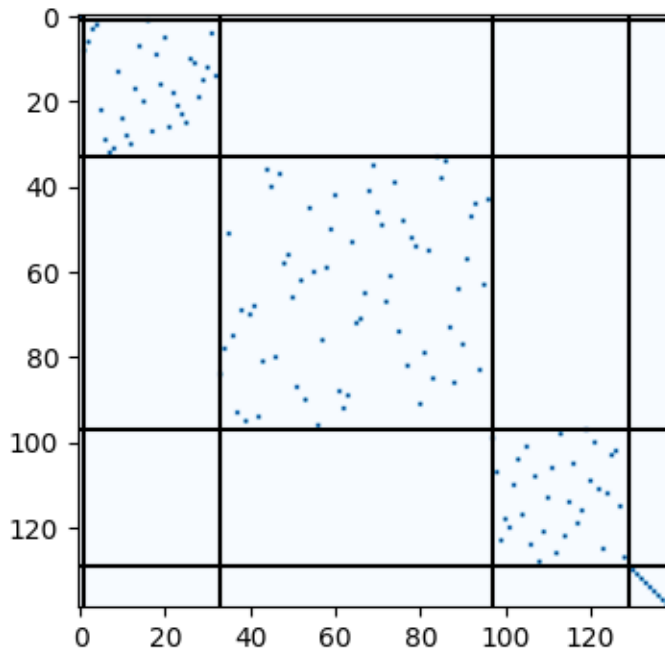
Visualization of the matching result. The black lines splits the channels of different layers.

```

plt.figure(figsize=(4, 4))
plt.imshow(X.cpu().numpy(), cmap='Blues')
for idx in params[2]:
    plt.axvline(x=idx, color='k')
    plt.axhline(y=idx, color='k')

```





Define the alignment function: fuse the models based on matching result

```
def align(solution, fusion_proportion, networks: list, params: list):
    [_, _, num_nodes_incremental, num_nodes_layers, cur_conv_list, conv_kernel_size_]
    ↪ list] = params
    named_weight_list_0 = [named_parameter for named_parameter in networks[0].named_
    ↪ parameters()]
    aligned_wt_0 = [parameter.data for name, parameter in named_weight_list_0]
    idx = 0
    num_layers = len(aligned_wt_0)
    for num_before, num_cur, cur_conv, cur_kernel_size in \
        zip(num_nodes_incremental, num_nodes_layers, cur_conv_list, conv_kernel_size_
    ↪ list):
        perm = solution[num_before:num_before + num_cur, num_before:num_before + num_cur]
        assert 'bias' not in named_weight_list_0[idx][0]
        if len(named_weight_list_0[idx][1].shape) == 4:
            aligned_wt_0[idx] = (perm.transpose(0, 1).to(torch.float64) @
            ↪ aligned_wt_0[idx].to(torch.float64).permute(2, 3, 0, 1)
            ↪ 1)) \
                .permute(2, 3, 0, 1)
        else:
            aligned_wt_0[idx] = perm.transpose(0, 1).to(torch.float64) @ aligned_wt_
            ↪ 0[idx].to(torch.float64)
            idx += 1
            if idx >= num_layers:
                continue
            if 'bias' in named_weight_list_0[idx][0]:
                aligned_wt_0[idx] = aligned_wt_0[idx].to(torch.float64) @ perm.to(torch.
            ↪ float64)
```

(continues on next page)

(continued from previous page)

```

        idx += 1
    if idx >= num_layers:
        continue
    if cur_conv and len(named_weight_list_0[idx][1].shape) == 2:
        aligned_wt_0[idx] = (aligned_wt_0[idx].to(torch.float64)
                               .reshape(aligned_wt_0[idx].shape[0], 64, -1)
                               .permute(0, 2, 1)
                               @ perm.to(torch.float64)) \
        .permute(0, 2, 1) \
        .reshape(aligned_wt_0[idx].shape[0], -1)
    elif len(named_weight_list_0[idx][1].shape) == 4:
        aligned_wt_0[idx] = (aligned_wt_0[idx].to(torch.float64)
                               .permute(2, 3, 0, 1)
                               @ perm.to(torch.float64)) \
        .permute(2, 3, 0, 1)
    else:
        aligned_wt_0[idx] = aligned_wt_0[idx].to(torch.float64) @ perm.to(torch.
↪float64)
    assert idx == num_layers

    averaged_weights = []
    for idx, parameter in enumerate(networks[1].parameters()):
        averaged_weights.append((1 - fusion_proportion) * aligned_wt_0[idx] + fusion_
↪proportion * parameter)
    return averaged_weights

```

### Test the fused model

The `fusion_proportion` variable denotes the contribution to the new model. For example, if `fusion_proportion=0.2`, the fused model = 80% model1 + 20% model2.

```

def align_model_and_test(X):
    acc_list = []
    for fusion_proportion in torch.arange(0, 1.1, 0.1):
        fused_weights = align(X, fusion_proportion, [model1, model2], params)

        fused_model = SimpleNet()
        state_dict = fused_model.state_dict()
        for idx, (key, _) in enumerate(state_dict.items()):
            state_dict[key] = fused_weights[idx]
        fused_model.load_state_dict(state_dict)
        fused_model.to(device)
        test_loss = 0
        correct = 0
        for data, target in test_loader:
            data = data.to(device)
            target = target.to(device)
            output = fused_model(data)
            test_loss += F.nll_loss(output, target, reduction='sum').item()
            pred = output.data.max(1, keepdim=True)[1]
            correct += pred.eq(target.data.view_as(pred)).sum()

```

(continues on next page)

(continued from previous page)

```

    test_loss /= len(test_loader.dataset)
    acc = 100. * correct / len(test_loader.dataset)
    print(
        f"{1 - fusion_proportion:.2f} model1 + {fusion_proportion:.2f} model2 ->
↪ fused model accuracy: {acc:.2f}%"
    )
    acc_list.append(acc)
    return torch.tensor(acc_list)

print('Graph Matching Fusion')
gm_acc_list = align_model_and_test(X)

```

```

Graph Matching Fusion
1.00 model1 + 0.00 model2 -> fused model accuracy: 84.18%
0.90 model1 + 0.10 model2 -> fused model accuracy: 85.12%
0.80 model1 + 0.20 model2 -> fused model accuracy: 85.21%
0.70 model1 + 0.30 model2 -> fused model accuracy: 82.52%
0.60 model1 + 0.40 model2 -> fused model accuracy: 71.11%
0.50 model1 + 0.50 model2 -> fused model accuracy: 53.74%
0.40 model1 + 0.60 model2 -> fused model accuracy: 63.26%
0.30 model1 + 0.70 model2 -> fused model accuracy: 78.51%
0.20 model1 + 0.80 model2 -> fused model accuracy: 82.81%
0.10 model1 + 0.90 model2 -> fused model accuracy: 83.97%
0.00 model1 + 1.00 model2 -> fused model accuracy: 83.81%

```

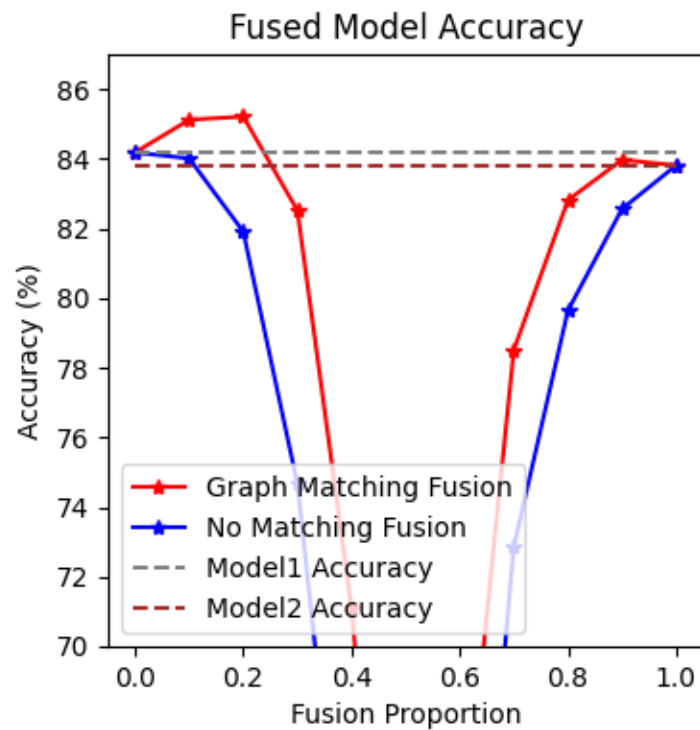
Compare with vanilla model fusion (no matching), graph matching method stabilizes the fusion step:

```

print('No Matching Fusion')
vanilla_acc_list = align_model_and_test(torch.eye(n1, device=device))

plt.figure(figsize=(4, 4))
plt.title('Fused Model Accuracy')
plt.plot(torch.arange(0, 1.1, 0.1).numpy(), gm_acc_list.cpu().numpy(), 'r*-', label=
↪ 'Graph Matching Fusion')
plt.plot(torch.arange(0, 1.1, 0.1).numpy(), vanilla_acc_list.cpu().numpy(), 'b*-', label=
↪ 'No Matching Fusion')
plt.plot(torch.arange(0, 1.1, 0.1).numpy(), [acc1] * 11, '--', color="gray", label=
↪ 'Model1 Accuracy')
plt.plot(torch.arange(0, 1.1, 0.1).numpy(), [acc2] * 11, '--', color="brown", label=
↪ 'Model2 Accuracy')
plt.gca().set_xlabel('Fusion Proportion')
plt.gca().set_ylabel('Accuracy (%)')
plt.ylim((70, 87))
plt.legend(loc=3)
plt.show()

```



#### No Matching Fusion

```

1.00 model1 + 0.00 model2 -> fused model accuracy: 84.18%
0.90 model1 + 0.10 model2 -> fused model accuracy: 84.01%
0.80 model1 + 0.20 model2 -> fused model accuracy: 81.91%
0.70 model1 + 0.30 model2 -> fused model accuracy: 74.67%
0.60 model1 + 0.40 model2 -> fused model accuracy: 60.39%
0.50 model1 + 0.50 model2 -> fused model accuracy: 47.16%
0.40 model1 + 0.60 model2 -> fused model accuracy: 55.34%
0.30 model1 + 0.70 model2 -> fused model accuracy: 72.86%
0.20 model1 + 0.80 model2 -> fused model accuracy: 79.64%
0.10 model1 + 0.90 model2 -> fused model accuracy: 82.56%
0.00 model1 + 1.00 model2 -> fused model accuracy: 83.81%

```

#### Print the result summary

```

end_time = time.perf_counter()
print(f'time consumed for model fusion: {end_time - st_time:.2f} seconds')
print(f'model1 accuracy = {acc1}%, model2 accuracy = {acc2}%')
print(f"best fused model accuracy: {torch.max(gm_acc_list):.2f}%")

```

```

time consumed for model fusion: 105.46 seconds
model1 accuracy = 84.18%, model2 accuracy = 83.81%
best fused model accuracy: 85.21%

```

**Note:** This example supports both GPU and CPU, and the online documentation is built by a CPU-only machine. The

efficiency will be significantly improved if you run this code on GPU.

---

**Total running time of the script:** ( 1 minutes 54.211 seconds)

## 9.6 Contributing to pygmtools

First, thank you for contributing to pygmtools!

### 9.6.1 How to contribute

The preferred workflow for contributing to pygmtools is to fork the [main repository](#) on GitHub, clone, and develop on a branch. Steps:

1. Fork the [project repository](#) by clicking on the ‘Fork’ button near the top right of the page. This creates a copy of the code under your GitHub user account. For more details on how to fork a repository see [this guide](#).
2. Clone your fork of the repo from your GitHub account to your local disk:

```
$ git clone git@github.com:YourUserName/pygmtools.git
$ cd pygmtools
```

3. Create a feature branch to hold your development changes:

```
$ git checkout -b my-feature
```

Always use a feature branch. It is good practice to never work on the master branch!

4. Develop the feature on your feature branch. Add changed files using `git add` and then `git commit` files:

```
$ git add modified_files
$ git commit
```

to record your changes in Git, then push the changes to your GitHub account with:

```
$ git push -u origin my-feature
```

5. Follow [these instructions](#) to create a pull request from your fork. This will email the committers and an automatic check will run.

(If any of the above seems like magic to you, please look up the [Git documentation](#) on the web, or ask a friend or another contributor for help.)

### 9.6.2 Pull Request Checklist

We recommended that your contribution complies with the following rules before you submit a pull request:

- Follow the PEP8 Guidelines.
- If your pull request addresses an issue, please use the pull request title to describe the issue and mention the issue number in the pull request description. This will make sure a link back to the original issue is created.
- All public methods should have informative docstrings with sample usage presented as doctests when appropriate.

- When adding additional functionality, provide at least one example script in the `examples/` folder. Have a look at other examples for reference. Examples should demonstrate why the new functionality is useful in practice and, if possible, compare it to other methods available in `pygmtools`.
- Documentation and high-coverage tests are necessary for enhancements to be accepted. Bug-fixes or new features should be provided with [non-regression tests](#). These tests verify the correct behavior of the fix or feature. In this manner, further modifications on the code base are granted to be consistent with the desired behavior. For the Bug-fixes case, at the time of the PR, these tests should fail for the code base in master and pass for the PR code.
- At least one paragraph of narrative documentation with links to references in the literature and the example.

You can also check for common programming errors with the following tools:

- No pyflakes warnings, check with:

```
$ pip install pyflakes
$ pyflakes path/to/module.py
```

- No PEP8 warnings, check with:

```
$ pip install pep8
$ pep8 path/to/module.py
```

- AutoPEP8 can help you fix some of the easy redundant errors:

```
$ pip install autopep8
$ autopep8 path/to/pep8.py
```

### 9.6.3 Filing bugs

We use Github issues to track all bugs and feature requests; feel free to open an issue if you have found a bug or wish to see a feature implemented.

It is recommended to check that your issue complies with the following rules before submitting:

- Verify that your issue is not being currently addressed by other [issues](#) or [pull requests](#).
- Please ensure all code snippets and error messages are formatted in appropriate code blocks. See [Creating and highlighting code blocks](#).
- Please include your operating system type and version number, as well as your Python, `pygmtools`, `numpy`, and `scipy` versions. Please also provide the name of your running backend, and the GPU/CUDA versions if you are using GPU. This information can be found by running the following environment report (`pygmtools>=0.2.9`):

```
$ python3 -c 'import pygmtools; pygmtools.env_report()'
```

If you are using GPU, make sure to install `pynvml` before running the above script: `pip install pynvml`.

- Please be specific about what estimators and/or functions are involved and the shape of the data, as appropriate; please include a [reproducible](#) code snippet or link to a [gist](#). If an exception is raised, please provide the traceback.

### 9.6.4 Documentation

We are glad to accept any sort of documentation: function docstrings, reStructuredText documents, tutorials, examples, etc. reStructuredText documents live in the source code repository under the `doc/` directory.

You can edit the documentation using any text editor and then generate the HTML output by typing `make html` from the `docs/` directory. The resulting HTML files are in `docs/_build/` and are viewable in any web browser. The example files in `examples/` are also built. If you want to skip building the examples, please use the command `make html-noplot`.

For building the documentation, you will need the packages listed in `docs/requirements.txt`. Please use `python>=3.7` because the packages for earlier Python versions are outdated.

When you are writing documentation, it is important to keep a good compromise between mathematical and algorithmic details, and give intuition to the reader on what the algorithm does. It is best to always start with a small paragraph with a hand-waving explanation of what the method does to the data.

This Contribution guide is strongly inspired by the one of the [scikit-learn](#) team.





## PYTHON MODULE INDEX

### p

- `pygmtools.benchmark`, 96
- `pygmtools.classic_solvers`, 47
- `pygmtools.dataset`, 98
- `pygmtools.linear_solvers`, 30
- `pygmtools.multi_graph_solvers`, 60
- `pygmtools.neural_solvers`, 68
- `pygmtools.utils`, 83



## B

Benchmark (class in `pygertools.benchmark`), 96  
 build\_aff\_mat() (in module `pygertools.utils`), 84  
 build\_batch() (in module `pygertools.utils`), 86

## C

cao() (in module `pygertools.multi_graph_solvers`), 61  
 cie() (in module `pygertools.neural_solvers`), 68  
 compute\_affinity\_score() (in module `pygertools.utils`), 88  
 compute\_img\_num() (`pygertools.benchmark.Benchmark` method), 96  
 compute\_length() (`pygertools.benchmark.Benchmark` method), 96  
 CUB2011 (class in `pygertools.dataset`), 99

## D

dense\_to\_sparse() (in module `pygertools.utils`), 89  
 download() (in module `pygertools.utils`), 91  
 download() (`pygertools.dataset.CUB2011` method), 99  
 download() (`pygertools.dataset.IMC_PT_SparseGM` method), 99  
 download() (`pygertools.dataset.PascalVOC` method), 100  
 download() (`pygertools.dataset.SPair71k` method), 100  
 download() (`pygertools.dataset.WillowObject` method), 101

## E

eval() (`pygertools.benchmark.Benchmark` method), 97  
 eval\_cls() (`pygertools.benchmark.Benchmark` method), 97

## F

from\_numpy() (in module `pygertools.utils`), 91  
 from\_numpy() (`pygertools.utils.MultiMatchingResult` static method), 95  
 from\_numpy\_() (`pygertools.utils.MultiMatchingResult` method), 95

## G

gamgm() (in module `pygertools.multi_graph_solvers`), 63

gaussian\_aff\_fn() (in module `pygertools.utils`), 92  
 generate\_isomorphic\_graphs() (in module `pygertools.utils`), 92  
 get\_data() (`pygertools.benchmark.Benchmark` method), 97  
 get\_id\_combination() (`pygertools.benchmark.Benchmark` method), 98  
 get\_network() (in module `pygertools.utils`), 92

## H

hungarian() (in module `pygertools.linear_solvers`), 30

## I

IMC\_PT\_SparseGM (class in `pygertools.dataset`), 99  
 inner\_prod\_aff\_fn() (in module `pygertools.utils`), 93  
 ipca\_gm() (in module `pygertools.neural_solvers`), 72  
 ipfp() (in module `pygertools.classic_solvers`), 47

## M

mgm\_floyd() (in module `pygertools.multi_graph_solvers`), 66  
 module  
   `pygertools.benchmark`, 96  
   `pygertools.classic_solvers`, 47  
   `pygertools.dataset`, 98  
   `pygertools.linear_solvers`, 30  
   `pygertools.multi_graph_solvers`, 60  
   `pygertools.neural_solvers`, 68  
   `pygertools.utils`, 83  
 MultiMatchingResult (class in `pygertools.utils`), 95

## N

ngm() (in module `pygertools.neural_solvers`), 76

## P

PascalVOC (class in `pygertools.dataset`), 100  
 pca\_gm() (in module `pygertools.neural_solvers`), 80  
 permutation\_loss() (in module `pygertools.utils`), 94  
 process() (`pygertools.dataset.CUB2011` method), 99  
 process() (`pygertools.dataset.IMC_PT_SparseGM` method), 99

`process()` (*pygmtools.dataset.PascalVOC method*), 100  
`process()` (*pygmtools.dataset.SPair71k method*), 101  
`process()` (*pygmtools.dataset.WillowObject method*), 101  
`pygmtools.benchmark`  
    module, 96  
`pygmtools.classic_solvers`  
    module, 47  
`pygmtools.dataset`  
    module, 98  
`pygmtools.linear_solvers`  
    module, 30  
`pygmtools.multi_graph_solvers`  
    module, 60  
`pygmtools.neural_solvers`  
    module, 68  
`pygmtools.utils`  
    module, 83

## R

`rand_get_data()` (*pygmtools.benchmark.Benchmark method*), 98  
`rm_gt_cache()` (*pygmtools.benchmark.Benchmark method*), 98  
`rrwm()` (*in module pygmtools.classic\_solvers*), 51

## S

`sinkhorn()` (*in module pygmtools.linear\_solvers*), 37  
`sm()` (*in module pygmtools.classic\_solvers*), 56  
`SPair71k` (*class in pygmtools.dataset*), 100

## T

`to_numpy()` (*in module pygmtools.utils*), 94  
`to_numpy()` (*pygmtools.utils.MultiMatchingResult static method*), 95  
`to_numpy_()` (*pygmtools.utils.MultiMatchingResult method*), 96

## W

`WillowObject` (*class in pygmtools.dataset*), 101