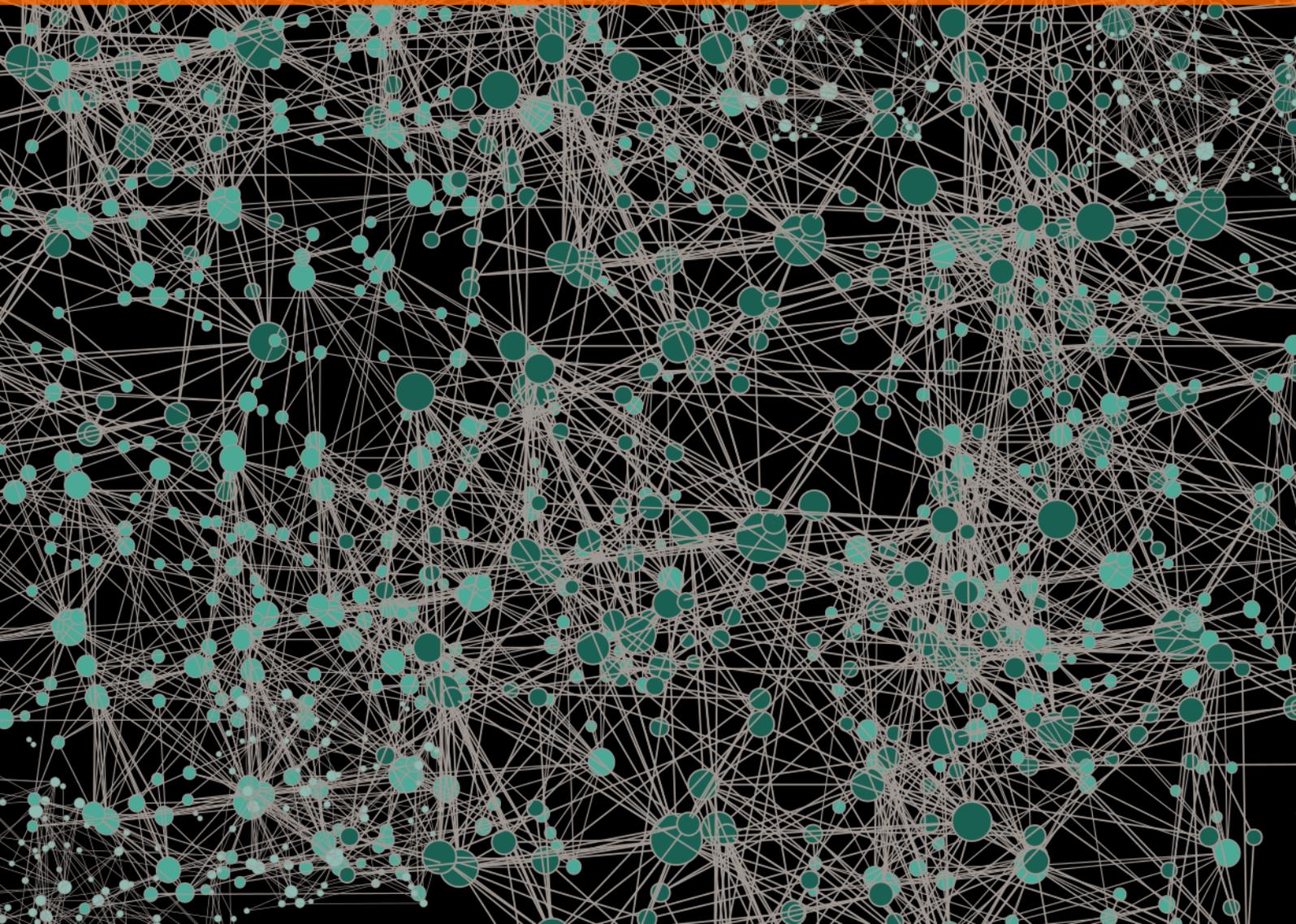


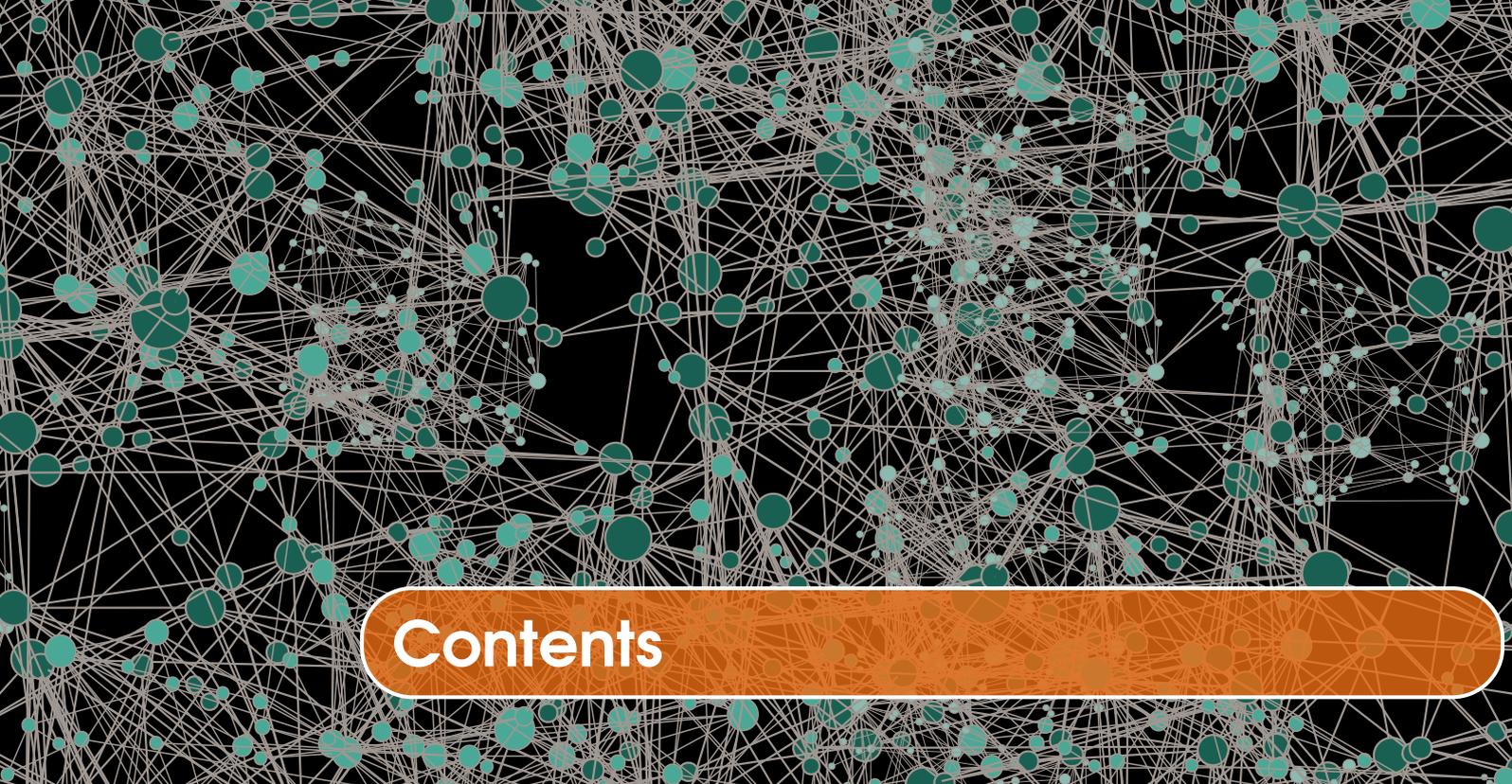
# LinkPred Tutorials

A High Performance Library for Link  
Prediction in Complex Networks

Said Kerrache







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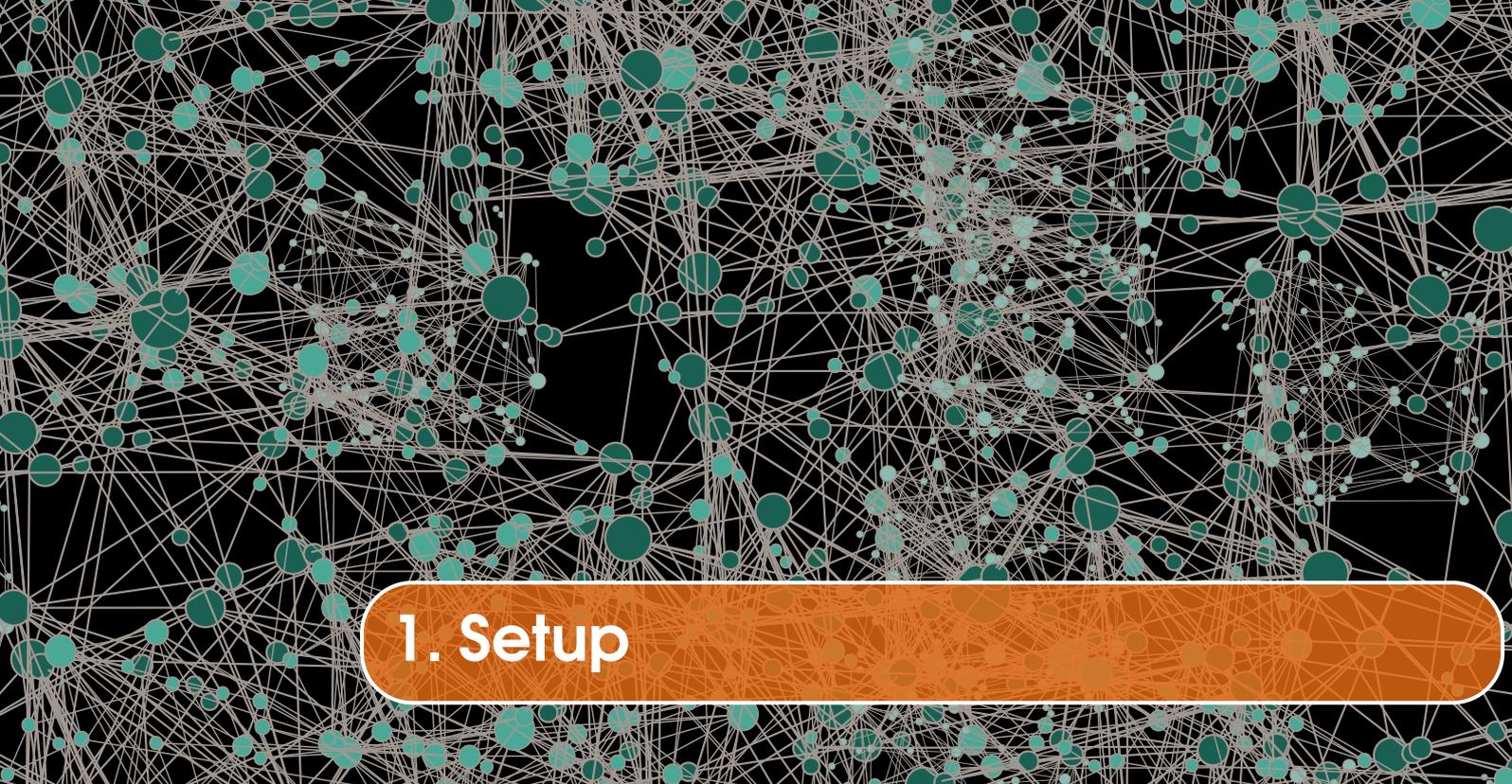
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# 1. Setup

This chapter contains two tutorials, the first on how to install LinkPred, and the second explains the compilation process of programs that use LinkPred.

## 1.1 Tutorial: Installing LinkPred

This tutorial shows the installation steps under Linux:

1. Get the latest version of the library from Github: <https://github.com/kerrache/linkpred>
2. Make sure you have all required softwares. See the user guide Section 1.3.
3. Create a build directory in the root of the LinkPred source directory:

```
$ mkdir build
```

4. Configure the library:

```
$ cd build  
$ cmake ../
```

 Build options can be set by editing the file `CMakeLists.txt` or through the user interface if GUI CMake is used.

5. If you do not need Java and Python bindings, you can disable the option in `CMakeLists.txt` (search for `LINKPRED_WITH_BINDINGS`). Note that finding Python requires a recent version of `cmake`. However, even if `cmake` fails to configure the bindings, the library can still be built successfully.

6. Build the library:

```
$ make
```

7. Build documentation (optional): this step requires Doxygen and generates documentation in HTML and Latex:

```
$ make doc
```

8. If you want to install the library:

```
$ make install
```

To install the library system-wide, you may need root privilege:

```
$ sudo make install
```

If you prefer a local install instead (which is usually the case when working on institution-wide HPC clusters/supercomputers), you need to set the install directory in the configuration step:

```
$ cmake -DCMAKE_INSTALL_PREFIX=YOUR_PATH ../
```

9. You may need to refresh `ld` cache by running:

```
$ sudo ldconfig
```

10. If you install the library in a non-default path, you will need to add that path to the environment variable `LD_LIBRARY_PATH`.

## 1.2 Tutorial: Compilation

This tutorial shows how to compile your code and link it with LinkPred. We assume that the library was successfully installed in the default directory.

1. In a file named `cne.cpp` copy the following code:

```
#include <linkpred.hpp>
#include <iostream>
using namespace LinkPred;
int main() {
    auto net = UNetwork<>::read("Infectious.edges");
    UCNEPredictor<> predictor(net);
    predictor.init();
    predictor.learn();
    std::cout << "#Start\tEnd\tScore\n";
    for (auto it=net->nonEdgesBegin(); it!=net->nonEdgesEnd(); ++it){
        auto i = net->getLabel(net->start(*it));
        auto j = net->getLabel(net->end(*it));
        double sc = predictor.score(*it);
        std::cout << i << "\t" << j << "\t" << sc << std::endl;
    }
    return 0;
}
```

 This code is available in: `tutorials/code/setup/compilation`

2. Compile your code. For example, if you compiled LinkPred with MPI an OpenMP enabled:

```
$ mpiCC cne.cpp -o cne -fopenmp -lLinkPred
```

 This assumes using a recent compiler. If you face any dialect-related complaints from the compiler, you may need to add the option: `-std=c++14`. Also, depending on the LinkPred functionalities used in your code, you may need to additionally link against the MKL library (using `-lmkl_rt`) and/or gsl (using `-lgsl -lgslcblas`).

If you built LinkPred without MPI and OpenMP, compile as follows:

```
$ g++ cne.cpp -o cne -lLinkPred
```

3. If you face errors in compilation, such as linkPred headers not found, you can specify the path to the headers using the `-I` option.
4. If the linker cannot find the library, you may specify its path using `-L` option or by using the environment variable `LIBRARY_PATH`.
5. Run your code:

```
$ ./cne
```

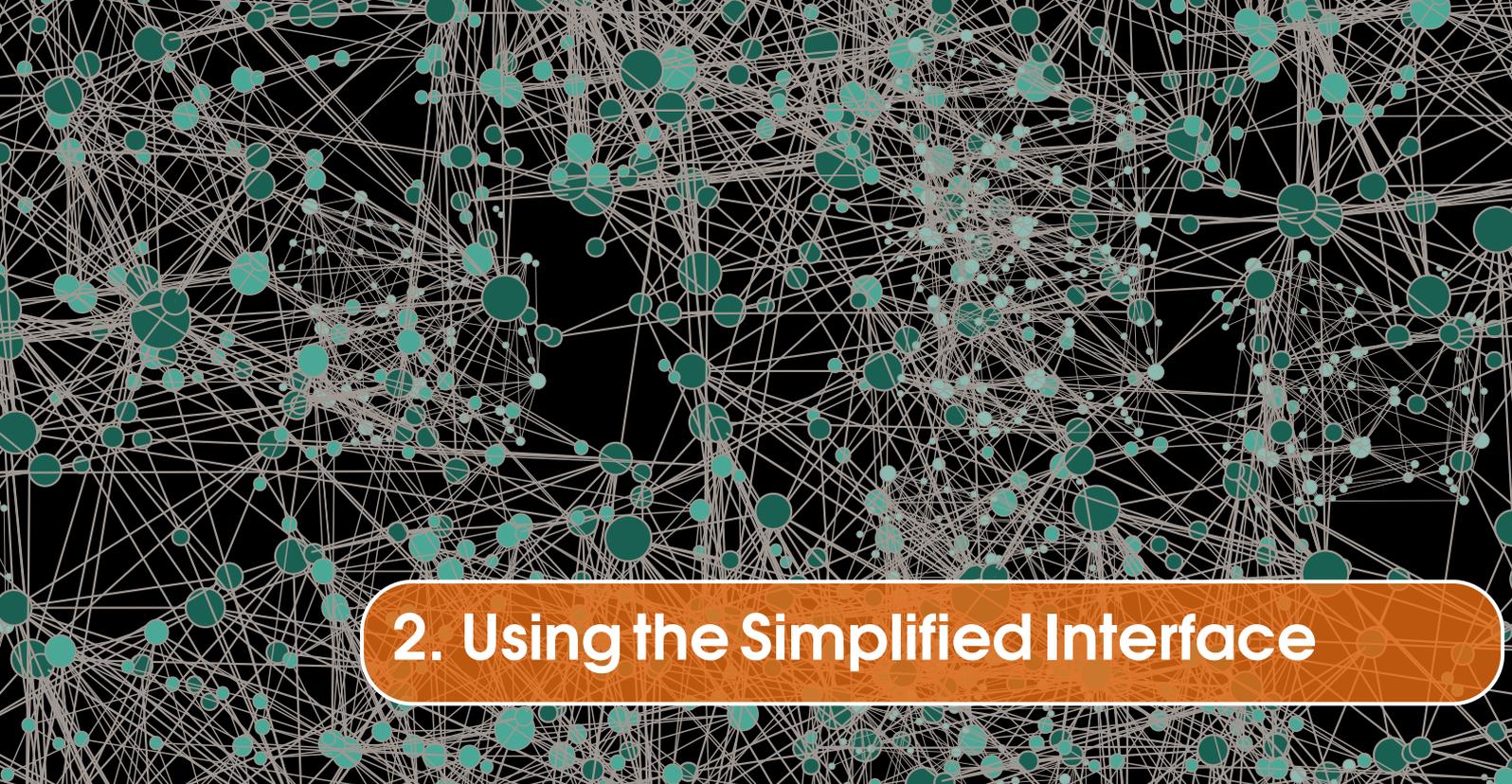
The first few lines of this programs' output are as follows:

```
#Start  End  Score
100 10  0
100 11  0
100 113 7
```

```
100 12 0
100 13 0
100 14 0
100 15 0
100 16 0
100 107 10
...
```

- R** Make sure that the library is located in the load path. Under Linux, you may need to set the environment variable `LD_LIBRARY_PATH`. In the case of a default system-wide install, LinkPred will be installed to the default directory, which is already in the load path. You may, however, need to refresh the `ld` cache by running:

```
$ sudo ldconfig
```



## 2. Using the Simplified Interface

The easiest and fastest way to start using `linkPred` is by using its simplified interface, that is, the classes available under the namespace `LinkPred::Simp`. This chapter contains tutorials on using this simplified interface in C++, Java, and Python.

## 2.1 C++

The two main classes in the namespace are `Simp::Predictor` and `Simp::Evaluator`. This section contains several tutorials showing how to use these classes for predicting links and evaluating performance.

### 2.1.1 Tutorial: Computing all scores using the class `Simp::Predictor`

This tutorial shows how to use the simplified interface, more precisely `Simp::Predictor` to compute the scores of all non-existing edges in a network. For more information on the simplified interface, consult Chapter 2 of the user guide.

1. In a file named `pred-all.cpp` write the following code:

```
#include <linkpred.hpp>
#include <iostream>
using namespace LinkPred::Simp;
int main() {
    // Create a predictor object
    Predictor p;
    // Load network from file
    p.loadnet("Zakarays_Karate_Club.edges");
    // Predict the score of all non-existing edges using Adamic
    // Adar index
    std::vector<EdgeScore> esv = p.predAllADA();
    // Print the scores
    for (auto it = esv.begin(); it != esv.end(); ++it) {
        std::cout << it->i << "\t" << it->j << "\t" << it->score
            << std::endl;
    }
    return 0;
}
```

 This code is available in: `tutorials/code/simp/cpp/predAll`

2. Compile your code:

```
$ mpiCC predAll.cpp -o predAll -fopenmp -lLinkPred
```

 Check Tutorial 1.2 if you face any compilation issues.

3. Run your code:

```
$ ./predAll
```

The first few lines of this programs' output are as follows:

```
1      31      1.07645
1      10      0.434294
1      28      0.434294
1      29      0.992405
1      33      1.61374
1      17      1.4427
1      34      2.71102
1      15      0
1      16      0
1      19      0
...
```

### 2.1.2 Tutorial: Computing scores of specific edges using the class `Simp::Predictor`

This tutorial shows how to use the simplified interface, more precisely `Simp::Predictor` to compute the scores of specific edges. For more information on the simplified interface, consult Chapter 2 of the user guide.

1. In a file named `pred.cpp` write the following code:

```
#include <linkpred.hpp>
#include <iostream>
using namespace LinkPred::Simp;
int main() {
    // Create a predictor object
    Predictor p;
    // Load network from file
    p.loadnet("Zakarays_Karate_Club.edges");
    // Compute the score for the two edges (1, 34) and (26,34)
    std::vector<EdgeScore> esv = {"1","34"}, {"26","34"};
    p.predADA(esv);
    // Print the scores
    for (auto it = esv.begin(); it != esv.end(); ++it) {
        std::cout << it->i << "\t" << it->j << "\t" << it->score
            << std::endl;
    }
    return 0;
}
```

**R** This code is available in: `tutorials/code/simp/cpp/pred`

**R** The edges to be predicted are passed using the nodes' labels (as they appear in the network file) and are of type `std::string`.

2. Compile your code:

```
$ mpiCC pred.cpp -o pred -fopenmp -lLinkPred
```

**R** Check Tutorial 1.2 if you face any compilation issues.

3. Run your code:

```
$ ./pred
```

The output of this program is as follows:

```
1      34      2.71102
26     34      1.17945
```

### 2.1.3 Tutorial: Computing top scores using the class `Simp::Predictor`

This tutorial shows how to use the simplified interface, more precisely `Simp::Predictor` to compute the top edge scores. For more information on the simplified interface, consult Chapter 2 of the user guide.

1. In a file named `predTop.cpp` write the following code:

```
#include <linkpred.hpp>
#include <iostream>
using namespace LinkPred::Simp;
int main() {
    int k = 10; // Find top 10
    // Create a predictor object
    Predictor p;
    // Load network from file
    p.loadnet("Zakarays_Karate_Club.edges");
    // Predict the top k edges using Adamic Adar index
    std::vector<EdgeScore> esv = p.predTopADA(k);
    // Print the scores
    for (auto it = esv.begin(); it != esv.end(); ++it) {
        std::cout << it->i << "\t" << it->j << "\t" << it->score
            << std::endl;
    }
    return 0;
}
```

 This code is available in: `tutorials/code/simp/cpp/predTop`

2. Compile your code:

```
$ mpiCC predTop.cpp -o predTop -fopenmp -lLinkPred
```

 Check Tutorial 1.2 if you face any compilation issues.

3. Run your code:

```
$ ./predTop
```

The output of this program is as follows:

```
1      33      1.61374
1      34      2.71102
2      34      2.25292
3      32      1.67334
3      34      4.71938
5      6       1.99226
7      11      1.99226
8      14      1.8082
32     24      1.66562
24     25      1.63159
```

### 2.1.4 Tutorial: Encoder-classifier prediction using the class `Simp::Predictor`

This tutorial shows how to predict links using an encoder-classifier using `Simp::Predictor`. For more information on the simplified interface, consult Chapter 2 of the user guide. For information on link prediction using graph-embedding methods consult Section 5.2.3.

1. In a file named `ecl.cpp` write the following code:

```
#include <linkpred.hpp>
#include <iostream>
using namespace LinkPred::Simp;
int main() {
    int k = 10;
    // Create a predictor object
    Predictor p;
    // Load network from file
    p.loadnet("Zakarays_Karate_Club.edges");
    // Predict top k scores using an encoder-classifier
    // predictor with Node2Vec as encoder and logistic
    // regression as classifier
    auto esv = p.predTopECL(k, "N2V", "LGR");
    // Print scores
    std::cout << "N2V-LGR\n";
    for (auto it = esv.begin(); it != esv.end(); ++it) {
        std::cout << it->i << "\t" << it->j << "\t" << it->score
            << std::endl;
    }
    // Predict top k scores using an encoder-classifier
    // predictor with LINE as encoder and feed-forward neural
    // network as classifier
    esv = p.predTopECL(k, "LIN", "FFN"); // FFN requires mlpack
    // Print scores
    std::cout << "LIN-FFN\n";
    for (auto it = esv.begin(); it != esv.end(); ++it) {
        std::cout << it->i << "\t" << it->j << "\t" << it->score
            << std::endl;
    }
    return 0;
}
```

 This code is available in: `tutorials/code/simp/cpp/ecl`

 For the names of available encoders and classifiers, consult the library documentation.

2. Compile your code:

```
$ mpiCC ecl.cpp -o ecl -fopenmp -lLinkPred
```

 Check Tutorial 1.2 if you face any compilation issues.

3. Run your code:

```
$ ./ecl
```

The output of this program is as follows:

```
N2V-LGR
1      34      0.638526
9      11      0.637297
9      13      0.543905
9      14      0.55602
9      18      0.534107
32     31      0.615972
32     10      0.666815
32     28      0.506243
32     17      0.641181
33     17      0.667946
LIN-FFN
3       7      0.416399
3      13      0.402937
3      34      0.400492
11     13      0.430696
11     34      0.42946
11     24      0.380592
10     19      0.394202
10     24      0.437404
10     30      0.393994
15     24      0.396383
```

### 2.1.5 Tutorial: Encoder-similarity prediction using the class `Simp::Predictor`

This tutorial shows how to predict links using an encoder-similarity using `Simp::Predictor`. For more information on the simplified interface, consult Chapter 2 of the user guide. For information on link prediction using graph-embedding methods consult Section 5.2.3.

1. In a file named `esm.cpp` write the following code:

```
#include <linkpred.hpp>
#include <iostream>
using namespace LinkPred::Simp;
int main() {
    int k = 10;
    // Create a predictor object
    Predictor p;
    // Load network from file
    p.loadnet("Zakarays_Karate_Club.edges");
    // Predict top k scores using an encoder-classifier
    // predictor with Node2Vec as encoder and L2 similarity
    auto esv = p.predTopESM(k, "N2V", "L2");
    // Print scores
    std::cout << "N2V-L2\n";
    for (auto it = esv.begin(); it != esv.end(); ++it) {
        std::cout << it->i << "\t" << it->j << "\t" << it->score
            << std::endl;
    }
    // Predict top k scores using an encoder-similarity measure
    // predictor with LINE as encoder and cosine similarity
    esv = p.predTopESM(k, "LIN", "CSM");
    // Print scores
    std::cout << "LIN-CSM\n";
    for (auto it = esv.begin(); it != esv.end(); ++it) {
        std::cout << it->i << "\t" << it->j << "\t" << it->score
            << std::endl;
    }
    return 0;
}
```

 This code is available in: `tutorials/code/simp/cpp/esm`

 For the names of available encoders and similarity measures, consult the library documentation.

2. Compile your code:

```
$ mpiCC esm.cpp -o esm -fopenmp -lLinkPred
```

 Check Tutorial 1.2 if you face any compilation issues.

3. Run your code:

```
$ ./esm
```

The output of this program is as follows:

```
N2V-L2
13    14    -0.552179
13    18    -0.537708
18    22    -0.414516
15    16    -0.394946
15    21    -0.431844
15    23    -0.533414
16    21    -0.388185
16    23    -0.374324
19    21    -0.471841
21    23    -0.385193
LIN-CSM
1     21    0.620443
2     5     0.693219
9     13    0.702609
12    19    0.621401
14    30    0.688929
20    21    0.708784
22    21    0.609064
31    30    0.905744
10    15    0.617589
16    25    0.674067
```

### 2.1.6 Tutorial: Performance evaluation with automatically generated test data using the class `Simp::Evaluator`

This tutorial shows how to evaluate the performance of link prediction algorithm with test data automatically generated from a ground-truth network using `Simp::Evaluator`. For more information on the simplified interface, consult Chapter 2 of the user guide.

1. In a file named `eval-auto.cpp` write the following code:

```
#include <linkpred.hpp>
#include <iostream>
using namespace LinkPred::Simp;
int main() {
    int nbRuns = 10;
    double edgeRemRatio = 0.1;
    // Create an evaluator object
    Evaluator eval;
    // Add predictors to be evaluated
    eval.addCNE();
    eval.addADA();
    eval.addKAB();
    // Add performance measures
    eval.addROC();
    eval.addTPR();
    // Run experiment on the specified network
    eval.run("Zakarays_Karate_Club.edges", nbRuns, edgeRemRatio);
    return 0;
}
```

 This code is available in: `tutorials/code/simp/cpp/eval-auto`

2. Compile your code:

```
$ mpiCC eval-auto.cpp -o eval-auto -fopenmp -lLinkPred
```

 Check Tutorial 1.2 if you face any compilation issues.

3. Run your code:

```
$ ./eval-auto
```

The output of this program is as follows:

```
# n: 34 m: 78
#ratio  ROCADA  ROCCNE  ROCKAB  TPRADA  TPRCNE  TPRKAB
0.10    0.7737  0.7149  0.8280  0.1250  0.1932  0.1250
0.10    0.6593  0.6333  0.7030  0.1250  0.0000  0.1250
0.10    0.5967  0.5762  0.6095  0.1875  0.1818  0.2500
0.10    0.8464  0.7913  0.9343  0.1875  0.1290  0.3750
0.10    0.8324  0.7785  0.8967  0.1250  0.1750  0.1250
0.10    0.7240  0.6953  0.7547  0.0000  0.2222  0.0000
0.10    0.6753  0.6610  0.7262  0.0000  0.1591  0.1250
0.10    0.6048  0.5792  0.6672  0.0000  0.0000  0.0000
0.10    0.7627  0.7547  0.7808  0.2917  0.3194  0.3750
0.10    0.6442  0.5835  0.6727  0.1250  0.1250  0.1250
#Time: 97.2945 ms
```

4. The output above is a trace generated from within the evaluation method. You may also access the results as follows. In a file named `eval-auto-print.cpp` write the following code:

```
#include <linkpred.hpp>
#include <iostream>
using namespace LinkPred::Simp;
int main() {
    int nbRuns = 10;
    double edgeRemRatio = 0.1;
    // Create an evaluator object
    Evaluator eval;
    // Add predictors to be evaluated
    eval.addCNE();
    eval.addADA();
    eval.addKAB();
    // Add performance measures
    eval.addROC();
    eval.addTPR();
    // Run experiment on the specified network
    eval.run("Zakarays_Karate_Club.edges", nbRuns, edgeRemRatio);
    // Print the header row
    auto res = eval.getPerfRes(0);
    for (auto it = res.begin(); it != res.end(); ++it) {
        std::cout << it->name << "\t" ;
    }
    std::cout << "\n";
    // Print the results of each iteration
    for(int i = 0; i < nbRuns; i++) {
        auto res = eval.getPerfRes(i);
        for (auto it = res.begin(); it != res.end(); ++it) {
            std::cout << it->res << "\t";
        }
        std::cout << "\n";
    }
    return 0;
}
```

 This code is available in: `tutorials/code/simp/cpp/eval-auto`

5. Compile your code:

```
$ mpiCC eval-auto-print.cpp -o eval-auto-print -
    fopenmp -lLinkPred
```

6. Run your code:

```
$ ./eval-auto-print
```

The output of this program is as follows:

```
# n: 34 m: 78
#ratio  ROCADA  ROCCNE  ROCKAB  TPRADA  TPRCNE  TPRKAB
0.10    0.7737  0.7149  0.8280  0.1250  0.1932  0.1250
0.10    0.6593  0.6333  0.7030  0.1250  0.0000  0.1250
0.10    0.5967  0.5762  0.6095  0.1875  0.1818  0.2500
```

```
0.10 0.8464 0.7913 0.9343 0.1875 0.1290 0.3750
0.10 0.8324 0.7785 0.8967 0.1250 0.1750 0.1250
0.10 0.7240 0.6953 0.7547 0.0000 0.2222 0.0000
0.10 0.6753 0.6610 0.7262 0.0000 0.1591 0.1250
0.10 0.6048 0.5792 0.6672 0.0000 0.0000 0.0000
0.10 0.7627 0.7547 0.7808 0.2917 0.3194 0.3750
0.10 0.6442 0.5835 0.6727 0.1250 0.1250 0.1250
#Time: 91.2499 ms
ROCADA ROCCNE ROCKAB TPRADA TPRCNE TPRKAB
0.7737 0.7149 0.8280 0.1250 0.1932 0.1250
0.6593 0.6333 0.7030 0.1250 0.0000 0.1250
0.5967 0.5762 0.6095 0.1875 0.1818 0.2500
0.8464 0.7913 0.9343 0.1875 0.1290 0.3750
0.8324 0.7785 0.8967 0.1250 0.1750 0.1250
0.7240 0.6953 0.7547 0.0000 0.2222 0.0000
0.6753 0.6610 0.7262 0.0000 0.1591 0.1250
0.6048 0.5792 0.6672 0.0000 0.0000 0.0000
0.7627 0.7547 0.7808 0.2917 0.3194 0.3750
0.6442 0.5835 0.6727 0.1250 0.1250 0.1250
```

### 2.1.7 Tutorial: Performance evaluation with pre-generated test data using the class `Simp::Evaluator`

This tutorial shows how to evaluate the performance of link prediction algorithm with pre-generated test data using `Simp::Evaluator`. For more information on the simplified interface, consult Chapter 2 of the user guide.

1. In a file named `eval-pregenerated.cpp` write the following code:

```
#include <linkpred.hpp>
#include <iostream>
using namespace LinkPred::Simp;
int main() {
    // Create an evaluator object
    Evaluator eval;
    // Add predictors to be evaluated
    eval.addADA();
    eval.addRAL();
    // Add performance measures
    eval.addPR();
    eval.addTPR();
    // Run experiment on the specified network
    eval.run("Zakarays_Karate_Club_Train.edges", "
            Zakarays_Karate_Club_Test.edges");
    return 0;
}
```

The file `Zakarays_Karate_Club_Train.edges` contains the set of observed edges, whereas `Zakarays_Karate_Club_Test.edges` contains the set of edges that have been removed, i.e. the test set.

 This code is available in: `tutorials/code/simp/cpp/eval-pregenerated`

2. Compile your code:

```
$ mpiCC eval-pregenerated.cpp -o eval-pregenerated -fopenmp -lLinkPred
```

 Check Tutorial 1.2 if you face any compilation issues.

3. Run your code:

```
$ ./eval-pregenerated
```

The output of this program is as follows:

```
PRADA  PRRAL  TPRADA  TPRRAL
0.1561  0.1568  0.1250  0.1250
```

4. The output above is a trace generated from within the evaluation method. You may also access the results as follows. In a file named `eval-pregenerated-print.cpp` write the following code:

```
#include <linkpred.hpp>
#include <iostream>
using namespace LinkPred::Simp;
int main() {
    // Create an evaluator object
```

```

Evaluator eval;
// Add predictors to be evaluated
eval.addADA();
eval.addRAL();
// Add performance measures
eval.addPR();
eval.addTPR();
// Run experiment on the specified network
eval.run("Zakarays_Karate_Club_Train.edges", "
        Zakarays_Karate_Club_Test.edges");
auto res = eval.getPerfRes(0);
for (auto it = res.begin(); it != res.end(); ++it) {
    std::cout << it->name << "\t" ;
}
std::cout << "\n";
for (auto it = res.begin(); it != res.end(); ++it) {
    std::cout << it->res << "\t" ;
}
std::cout << "\n";
return 0;
}

```

 This code is available in: tutorials/code/simp/cpp/eval-pregenerated

#### 5. Compile your code:

```
$ mpiCC eval-pregenerated-print.cpp -o eval-pregenerated-
print -fopenmp -lLinkPred
```

#### 6. Run your code:

```
$ ./eval-pregenerated-print
```

The output of this program is as follows:

```
PRADA   PRRAL   TPRADA  TPRRAL
0.1561  0.1568  0.1250  0.1250
PRADA   PRRAL   TPRADA  TPRRAL
0.1561  0.1568  0.1250  0.1250
```

### 2.1.8 Tutorial: Performance evaluation of external prediction results using the class `Simp::Evaluator`

This tutorial shows how to evaluate external link prediction results obtained by a user link prediction algorithm. For more information on the simplified interface, consult Chapter 2 of the user guide.

**R** It is possible to implement new link prediction algorithms and integrate them into LinkPred, which allows for better use of the library's performance evaluation routines. See Section 5.4 of the user guide for more details.

1. The first step consists in generating test data. If you already have a ready test data, split into training and test sets, you can skip this part (go directly to Step 5 of this tutorial).
2. In a file name `gen-data.cpp` write the following code:

```
#include <linkpred.hpp>
#include <iostream>
using namespace LinkPred::Simp;
int main() {
    // We remove 10% of the edges
    double edgeRemRatio = 0.1;
    // We will not keep the network connected when removing
    // edges
    bool keepConnected = false;
    // Seed of the random number generator
    long int seed = 0;
    // Create an Evaluator object
    Evaluator eval;
    // The ground truth network "Zakarays_Karate_Club.edges" is
    // split into an observed network stored in "
    // Zakarays_Train.edges" and a list of removed edges stored
    // in "Zakarays_Test.edges"
    eval.genTestData("Zakarays_Karate_Club.edges", "
    Zakarays_Train.edges", "Zakarays_Test.edges",
    edgeRemRatio, keepConnected, seed);
    return 0;
}
```

The file `Zakarays_Train.edges` will contain the set of observed edges, whereas `Zakarays_Test.edges` will contain the set of edges that have been removed, i.e. the test set.

3. Compile your code:

```
$ mpiCC gen-data.cpp -o gen-data -fopenmp -lLinkPred
```

**R** Check Tutorial 1.2 if you face any compilation issues.

4. Run your code:

```
$ ./gen-data
```

- R** The method `addPST` is used to load the pre-stored results by internally creating a `PST` predictor. For more details about this predictor consult Section 5.2.4 of the user guide.

The first few lines of `Zakarays_Train.edges` and the file `Zakarays_Test.edges` generated by this program are as follows:

```
# First few lines of the file Zakarays_Train.edges
1      2
1      3
1      4
1      5
1      6
1      7
1      8
1      9
1     11
...
# The file Zakarays_Test.edges
2     22
3      4
24    26
33    24
9     34
32    33
33    30
28    25
```

5. At this stage, we have two files: `Zakarays_Train.edges` which contains the set of observed edges and `Zakarays_Test.edges` which contains the set of removed edges. Train your algorithm on the file `Zakarays_Train.edges` and computed the scores of all non-existing links in that network. This includes the edges that have been removed (contained in `Zakarays_Test.edges`) and those that are absent from the ground truth network (true negative links). Store the scores in a file name "pst.txt" in the following format (the first line is a comment and can be safely omitted):

```
#Start  End    Score
1      31     0.41374
1      10     0.276687
1      28     0.283587
1      29     0.374494
1      33     0.463135
1      17     0.531863
1      34     0.49409
1      26     0.325087
1      25     0.325087
...
```

6. In a file name `eval-pst.cpp` write the following code:

```
#include <linkpred.hpp>
#include <iostream>
using namespace LinkPred::Simp;
int main() {
    // Create an evaluator object
    Evaluator eval;
    // Add predictors to be evaluated
```

```
eval.addADA();  
// Use the method addPST to create a predictor that loads  
// scores from pst.txt  
eval.addPST("PST", "pst.txt");  
eval.addRAL();  
// Add performance measures  
eval.addPR();  
eval.addTPR();  
// Run experiment on the specified network  
eval.run("Zakarays_Train.edges", "Zakarays_Test.edges");  
return 0;  
}
```

### 7. Compile your code:

```
$ mpiCC eval-pst.cpp -o eval-pst -fopenmp -lLinkPred
```

 Check Tutorial 1.2 if you face any compilation issues.

### 8. Run your code:

```
$ ./eval-pst
```

The output of this program is as follows:

PRADA	PRPST	PRRAL	TPRADA	TPRPST	TPRRAL
0.0510	0.0510	0.0391	0.1250	0.1250	0.1250

## 2.2 Java

LinkPred bindings are optional (by default on). To change this setting, edit the file `CMakeLists.txt` in the root of the library source directory (search for the option `LINKPRED_WITH_BINDINGS`). Upon successful building, the library `LinkPredJava` will be generated (named `libLinkPredJava.so` in Linux). This library will be loaded when running your program, and for that, it must be accessible to the Java virtual machine.

- Ⓡ In Linux, you can make the library accessible to the JVM by including its path in the environment variable `LD_LIBRARY_PATH`. If LinkPred is installed in the default location, this can be accomplished using the following command:

```
$ export LD_LIBRARY_PATH = $LD_LIBRARY_PATH:/usr/local/  
lib
```

The Java proxy classes needed to interface with the library can be found in source form and JAR compiled form (`LinkPredJava.jar`) in the source directory of LinkPred in `/bindings/Java`. These classes (either in source or as JAR) must be included in the class path during compilation and at run-time.

### 2.2.1 Tutorial: Computing all scores using the class `Predictor`

This tutorial shows how to use the Java bindings of the simplified interface, more precisely the class `Predictor` to compute the scores of all non-existing edges in a network. For more information on the simplified interface, consult Chapter 2 of the user guide.

1. In a file named `PredAll.java` write the following code:

```
public class PredAll {
    static {
        // Load the library
        System.loadLibrary("LinkPredJava");
    }
    public static void main(String[] args) {
        // Create a prtedictor object
        Predictor p = new Predictor();
        // Load network from file
        p.loadnet("Zakarays_Karate_Club.edges");
        // Predict the score of all non-exisitng edges using
        // Adamic Adar index
        EdgeScoreVec esv = p.predAllADA();
        // Print the scores
        for (int i = 0; i < esv.size(); i++) {
            EdgeScore es = esv.get(i);
            System.out.println(es.getI() + "\t" + es.getJ() + "\t"
                + es.getScore());
        }
    }
}
```

 This code is available in: `tutorials/code/simp/java/predAll`

2. Compile your code:

```
$ javac -cp ../LinkPredJava.jar PredAll.java
```

3. Run your code:

```
$ java -cp ../LinkPredJava.jar PredAll
```

The first few lines of this programs' output are as follows:

```
1      31      1.0764545478730305
1      10      0.43429448190325176
1      28      0.43429448190325176
1      29      0.9924051084544989
1      33      1.613740043014111
1      17      1.4426950408889634
1      34      2.7110197222973085
1      15      0.0
1      16      0.0
1      19      0.0
...
```

### 2.2.2 Tutorial: Computing scores of specific edges using the class `Predictor`

This tutorial shows how to use the Java bindings of the simplified interface, more precisely the class `Predictor` to compute the scores of specific edges. For more information on the simplified interface, consult Chapter 2 of the user guide.

1. In a file name `Pred.java` write the following code:

```
public class Pred {
    static {
        // Load the library
        System.loadLibrary("LinkPredJava");
    }
    public static void main(String[] args) {
        // Create a prtredictor object
        Predictor p = new Predictor();
        // Load network from file
        p.loadnet("Zakarays_Karate_Club.edges");
        // Compute the score for the two edges (1, 34) and
        // (26,34)
        EdgeScoreVec esv = new EdgeScoreVec();
        EdgeScore es;
        es = new EdgeScore();
        es.setI("1");
        es.setJ("34");
        esv.add(es);
        es = new EdgeScore();
        es.setI("26");
        es.setJ("34");
        esv.add(es);
        p.predADA(esv);
        // Print the scores
        for (int i = 0; i < esv.size(); i++) {
            es = esv.get(i);
            System.out.println(es.getI() + "\t" + es.getJ() + "\t"
                + es.getScore());
        }
    }
}
```

 This code is available in: `tutorials/code/simp/java/pred`

2. Compile your code:

```
$ javac -cp ../LinkPredJava.jar Pred.java
```

3. Run your code:

```
$ java -cp ../LinkPredJava.jar Pred
```

The first few lines of this programs' output are as follows:

```
1      34      2.7110197222973085
26     34      1.179445561110859
```

### 2.2.3 Tutorial: Computing top scores using the class `Predictor`

This tutorial shows how to use the simplified interface, more precisely `Predictor` to compute the top edge scores. For more information on the simplified interface, consult Chapter 2 of the user guide.

1. In a file name `PredTop.java` write the following code:

```
public class PredTop {
    static {
        // Load the library
        System.loadLibrary("LinkPredJava");
    }
    public static void main(String [] args) {
        int k = 10; // Find top 10
        // Create a predictor object
        Predictor p = new Predictor();
        // Load network from file
        p.loadnet("Zakarays_Karate_Club.edges");
        // Predict the top k edges using Adamic Adar index
        EdgeScoreVec esv = p.predTopADA(k);
        // Print the scores
        for (int i = 0; i < esv.size(); i++) {
            EdgeScore es = esv.get(i);
            System.out.println(es.getI() + "\t" + es.getJ() + "\t"
                + es.getScore());
        }
    }
}
```

 This code is available in: `tutorials/code/simp/java/predTop`

2. Compile your code:

```
$ javac -cp ../LinkPredJava.jar PredTop.java
```

3. Run your code:

```
$ java -cp ../LinkPredJava.jar PredTop
```

The first few lines of this programs' output are as follows:

```
1      33      1.613740043014111
1      34      2.7110197222973085
2      34      2.252921681630931
3      32      1.6733425912309228
3      34      4.719381261461351
5      6       1.9922605072935597
7      11      1.9922605072935597
8      14      1.8081984819901584
32     24      1.6656249548734432
24     25      1.631586747071319
```

### 2.2.4 Tutorial: Encoder-classifier prediction using the class `Predictor`

This tutorial shows how to predict links using an encoder-classifier using `Predictor`. For more information on the simplified interface, consult Chapter 2 of the user guide. For information on link prediction using graph-embedding methods consult Section 5.2.3.

1. In a file name `ECL.java` write the following code:

```
public class ECL {
    static {
        // Load the library
        System.loadLibrary("LinkPredJava");
    }
    public static void main(String[] args) {
        int k = 10;
        // Create a prtedictor object
        Predictor p = new Predictor();
        // Load network from file
        p.loadnet("Zakarays_Karate_Club.edges");
        // Predict top k scores using an encoder-classifier
        // predictor with Node2Vec as encoder and logistic
        // regression as classifier
        EdgeScoreVec esv = p.predTopECL(k, "N2V", "LGR");
        // Print scores
        System.out.println("N2V-LGR");
        for (int i = 0; i < esv.size(); i++) {
            EdgeScore es = esv.get(i);
            System.out.println(es.getI() + "\t" + es.getJ() + "\t"
                + es.getScore());
        }
        // Predict top k scores using an encoder-classifier
        // predictor with LINE as encoder and feed-forward neural
        // network as classifier
        esv = p.predTopECL(k, "LIN", "FFN"); // FFN requires
        // mlpack
        // Print scores
        System.out.println("LIN-FFN");
        for (int i = 0; i < esv.size(); i++) {
            EdgeScore es = esv.get(i);
            System.out.println(es.getI() + "\t" + es.getJ() + "\t"
                + es.getScore());
        }
    }
}
```

 This code is available in: `tutorials/code/simp/java/ecl`

 For the names of available encoders and classifiers, consult the library reference manual.

2. Compile your code:

```
$ javac -cp ../LinkPredJava.jar ECL.java
```

3. Run your code:

```
$ java -cp ../LinkPredJava.jar ECL
```

The output of this program is as follows:

```
N2V-LGR
1      34      0.6385261305821565
9      11      0.6372967584173628
9      13      0.5439045029916033
9      14      0.5560201995865949
9      18      0.5341066259961504
32     31      0.6159717145419226
32     10      0.6668148165127163
32     28      0.5062429834583236
32     17      0.6411806541242171
33     17      0.6679461676338299
LIN-FFN
3      7      0.4163985044250176
3      13     0.40293727072886226
3      34     0.40049178211918146
11     13     0.4306964396488587
11     34     0.42945998491801923
11     24     0.380591821298675
10     19     0.3942022523784909
10     24     0.43740409522018153
10     30     0.3939938517366693
15     24     0.3963832972307969
```

### 2.2.5 Tutorial: Encoder-similarity prediction using the class `Predictor`

This tutorial shows how to predict links using an encoder-similarity using `Predictor`. For more information on the simplified interface, consult Chapter 2 of the user guide. For information on link prediction using graph-embedding methods consult Section 5.2.3.

1. In a file name `ESM.java` write the following code:

```
public class ESM {
    static {
        // Load the library
        System.loadLibrary("LinkPredJava");
    }
    public static void main(String[] args) {
        int k = 10;
        // Create a predictor object
        Predictor p = new Predictor();
        // Load network from file
        p.loadnet("Zakarays_Karate_Club.edges");
        // Predict top k scores using an encoder-classifier
        // predictor with Node2Vec as encoder and L2 similarity
        EdgeScoreVec esv = p.predTopESM(k, "N2V", "L2");
        // Print scores
        System.out.println("N2V-L2");
        for (int i = 0; i < esv.size(); i++) {
            EdgeScore es = esv.get(i);
            System.out.println(es.getI() + "\t" + es.getJ() + "\t"
                + es.getScore());
        }
        // Predict top k scores using an encoder-similarity
        // measure predictor with LINE as encoder and cosine
        // similarity
        esv = p.predTopESM(k, "LIN", "CSM");
        // Print scores
        System.out.println("LIN-CSM");
        for (int i = 0; i < esv.size(); i++) {
            EdgeScore es = esv.get(i);
            System.out.println(es.getI() + "\t" + es.getJ() + "\t"
                + es.getScore());
        }
    }
}
```

 This code is available in: `tutorials/code/simp/java/esm`

 For the names of available encoders and similarity measures, consult the library reference manual.

2. Compile your code:

```
$ javac -cp ../LinkPredJava.jar ESM.java
```

3. Run your code:

```
$ java -cp ../LinkPredJava.jar ESM
```

The output of this program is as follows:

```
N2V-L2
13    14    -0.5521786311666944
13    18    -0.5377083804555659
18    22    -0.41451576606008234
15    16    -0.39494585351335626
15    21    -0.43184372730810316
15    23    -0.533414287409406
16    21    -0.388184764773398
16    23    -0.3743242327498225
19    21    -0.4718410793861365
21    23    -0.3851929020614546
LIN-CSM
1     21    0.6204433804816786
2     5     0.6932189050437948
9     13    0.7026086708697828
12    19    0.6214013483476032
14    30    0.6889288481459729
20    21    0.708784319919729
22    21    0.6090643830619246
31    30    0.9057438074014044
10    15    0.6175888844497922
16    25    0.674066958588203
```

### 2.2.6 Tutorial: Performance evaluation with automatically generated test data using the class `Evaluator`

This tutorial shows how to evaluate the performance of link prediction algorithm with test data automatically generated from a ground-truth network using `Evaluator`. For more information on the simplified interface, consult Chapter 2 of the user guide.

1. In a file name `EvalAuto.java` write the following code:

```
public class EvalAuto {
    static {
        // Load the library
        System.loadLibrary("LinkPredJava");
    }
    public static void main(String[] args) {
        int nbRuns = 10;
        double edgeRemRatio = 0.1;
        // Create an evaluator object
        Evaluator eval = new Evaluator();
        // Add predictors to be evaluated
        eval.addCNE();
        eval.addADA();
        eval.addKAB();
        // Add performance measures
        eval.addROC();
        eval.addTPR();
        // Run experiment on the specified network
        eval.run("Zakarays_Karate_Club.edges", nbRuns,
            edgeRemRatio);
    }
}
```

 This code is available in: `tutorials/code/simp/java/eval-auto`

 For the names of available predictors and performance measures, consult the library reference manual.

2. Compile your code:

```
$ javac -cp ../LinkPredJava.jar EvalAuto.java
```

3. Run your code:

```
$ java -cp ../LinkPredJava.jar EvalAuto
```

The output of this program is as follows:

```
# n: 34 m: 78
#ratio  ROCADA  ROCCNE  ROCKAB  TPRADA  TPRCNE  TPRKAB
0.10    0.7737  0.7149  0.8280  0.1250  0.1932  0.1250
0.10    0.6593  0.6333  0.7030  0.1250  0.0000  0.1250
0.10    0.5967  0.5762  0.6095  0.1875  0.1818  0.2500
0.10    0.8464  0.7913  0.9343  0.1875  0.1290  0.3750
0.10    0.8324  0.7785  0.8967  0.1250  0.1750  0.1250
0.10    0.7240  0.6953  0.7547  0.0000  0.2222  0.0000
0.10    0.6753  0.6610  0.7262  0.0000  0.1591  0.1250
0.10    0.6048  0.5792  0.6672  0.0000  0.0000  0.0000
```

```
0.10 0.7627 0.7547 0.7808 0.2917 0.3194 0.3750
0.10 0.6442 0.5835 0.6727 0.1250 0.1250 0.1250
#Time: 93.0054 ms
```

4. The output above is a trace generated from within the evaluation method. You may also access the results as follows. In a file name `EvalAutoPrint.java` write the following code:

```
public class EvalAutoPrint {
    static {
        // Load the library
        System.loadLibrary("LinkPredJava");
    }
    public static void main(String[] args) {
        int nbRuns = 10;
        double edgeRemRatio = 0.1;
        // Create an evaluator object
        Evaluator eval = new Evaluator();
        // Add predictors to be evaluated
        eval.addCNE();
        eval.addADA();
        eval.addKAB();
        // Add performance measures
        eval.addROC();
        eval.addTPR();
        // Run experiment on the specified network
        eval.run("Zakarays_Karate_Club.edges", nbRuns,
            edgeRemRatio);
        // Print the header row
        PerfResVec res = eval.getPerfRes(0);
        for (int j = 0; j < res.size(); j++) {
            System.out.print(res.get(j).getName() + "\t" );
        }
        System.out.println();
        // Print the results of each iteration
        for(int i = 0; i < nbRuns; i++) {
            res = eval.getPerfRes(i);
            for (int j = 0; j < res.size(); j++) {
                System.out.printf("%.4f\t", res.get(j).getRes());
            }
            System.out.println();
        }
    }
}
```

 This code is available in: `tutorials/code/simp/java/eval-auto`

5. Compile your code:

```
$ javac -cp ../LinkPredJava.jar EvalAutoPrint.java
```

6. Run your code:

```
$ java -cp ../LinkPredJava.jar EvalAutoPrint
```

The output of this program is as follows:

```
# n: 34 m: 78
```

```

#ratio  ROCADA  ROCCNE  ROCKAB  TPRADA  TPRCNE  TPRKAB
0.10    0.7737  0.7149  0.8280  0.1250  0.1932  0.1250
0.10    0.6593  0.6333  0.7030  0.1250  0.0000  0.1250
0.10    0.5967  0.5762  0.6095  0.1875  0.1818  0.2500
0.10    0.8464  0.7913  0.9343  0.1875  0.1290  0.3750
0.10    0.8324  0.7785  0.8967  0.1250  0.1750  0.1250
0.10    0.7240  0.6953  0.7547  0.0000  0.2222  0.0000
0.10    0.6753  0.6610  0.7262  0.0000  0.1591  0.1250
0.10    0.6048  0.5792  0.6672  0.0000  0.0000  0.0000
0.10    0.7627  0.7547  0.7808  0.2917  0.3194  0.3750
0.10    0.6442  0.5835  0.6727  0.1250  0.1250  0.1250
#Time: 86.0519 ms
ROCADA  ROCCNE  ROCKAB  TPRADA  TPRCNE  TPRKAB
0.7737  0.7149  0.8280  0.1250  0.1932  0.1250
0.6593  0.6333  0.7030  0.1250  0.0000  0.1250
0.5967  0.5762  0.6095  0.1875  0.1818  0.2500
0.8464  0.7913  0.9343  0.1875  0.1290  0.3750
0.8324  0.7785  0.8967  0.1250  0.1750  0.1250
0.7240  0.6953  0.7547  0.0000  0.2222  0.0000
0.6753  0.6610  0.7262  0.0000  0.1591  0.1250
0.6048  0.5792  0.6672  0.0000  0.0000  0.0000
0.7627  0.7547  0.7808  0.2917  0.3194  0.3750
0.6442  0.5835  0.6727  0.1250  0.1250  0.1250

```

### 2.2.7 Tutorial: Performance evaluation with pre-generated test data using the class `Evaluator`

This tutorial shows how to evaluate the performance of link prediction algorithm with pre-generated test data using `Evaluator`. For more information on the simplified interface, consult Chapter 2 of the user guide.

1. In a file name `EvalPregenerated.java` write the following code:

```
public class EvalPregenerated {
    static {
        // Load the library
        System.loadLibrary("LinkPredJava");
    }
    public static void main(String[] args) {
        // Create an evaluator object
        Evaluator eval = new Evaluator();
        // Add predictors to be evaluated
        eval.addADA();
        eval.addRAL();
        // Add performance measures
        eval.addPR();
        eval.addTPR();
        // Run experiment on the specified train and test set
        eval.run("Zakarays_Karate_Club_Train.edges", "
                Zakarays_Karate_Club_Test.edges");
    }
}
```

The file `Zakarays_Karate_Club_Train.edges` contains the set of observed edges, whereas `Zakarays_Karate_Club_Test.edges` contains the set of edges that have been removed, i.e. the test set.

 This code is available in: `tutorials/code/simp/java/eval-pregenerated`

2. Compile your code:

```
$ javac -cp ../LinkPredJava.jar EvalPregenerated.java
```

3. Run your code:

```
$ java -cp ../LinkPredJava.jar EvalPregenerated
```

The output of this program is as follows:

```
PRADA  PRRAL  TPRADA  TPRRAL
0.1561  0.1568  0.1250  0.1250
```

4. The output above is a trace generated from within the evaluation method. You may also access the results as follows. In a file name `EvalPregeneratedPrint.java` write the following code:

```
public class EvalPregeneratedPrint {
    static {
        // Load the library
        System.loadLibrary("LinkPredJava");
    }
    public static void main(String[] args) {
```

```

// Create an evaluator object
Evaluator eval = new Evaluator();
// Add predictors to be evaluated
eval.addADA();
eval.addRAL();
// Add performance measures
eval.addPR();
eval.addTPR();
// Run experiment on the specified train and test set
eval.run("Zakarays_Karate_Club_Train.edges", "
        Zakarays_Karate_Club_Test.edges");
// Print the header row
PerfResVec res = eval.getPerfRes(0);
for (int j = 0; j < res.size(); j++) {
    System.out.print(res.get(j).getName() + "\t" );
}
System.out.println();
// Print the results
for (int j = 0; j < res.size(); j++) {
    System.out.printf("%.4f\t", res.get(j).getRes());
}
System.out.println();
}
}

```

 This code is available in: `tutorials/code/simp/java/eval-pregenerated`

##### 5. Compile your code:

```
$ javac -cp ../LinkPredJava.jar EvalPregeneratedPrint.java
```

##### 6. Run your code:

```
$ java -cp ../LinkPredJava.jar EvalPregeneratedPrint
```

The output of this program is as follows:

```

PRADA   PRRAL   TPRADA  TPRRAL
0.1561  0.1568  0.1250  0.1250
PRADA   PRRAL   TPRADA  TPRRAL
0.1561  0.1568  0.1250  0.1250

```

### 2.2.8 Tutorial: Performance evaluation of external prediction results using the class `Evaluator`

This tutorial shows how to evaluate external link prediction results obtained by a user link prediction algorithm. For more information on the simplified interface, consult Chapter 2 of the user guide.

**R** It is possible to implement new link prediction algorithms and integrate them into LinkPred, which allows for better use of the library's performance evaluation routines. See Section 5.4 of the user guide for more details.

1. The first step consists in generating test data. If you already have a ready test data, split into training and test sets, you can skip this part (go directly to Step 5 of this tutorial).
2. In a file name `GenData.java` write the following code:

```
public class GenData {
    static {
        // Load the library
        System.loadLibrary("LinkPredJava");
    }
    public static void main(String[] args) {
        // We remove 10% of the edges
        double edgeRemRatio = 0.1;
        // We will not keep the network connected when removing
        // edges
        boolean keepConnected = false;
        // Seed of the random number generator
        int seed = 0;
        // Create an Evaluator object
        Evaluator eval = new Evaluator();
        // The ground truth network "Zakarays_Karate_Club.edges"
        // is split into an observed network stored in "
        // Zakarays_Train.edges" and a list of removed edges
        // stored in "Zakarays_Test.edges"
        eval.genTestData("Zakarays_Karate_Club.edges", "
            Zakarays_Train.edges", "Zakarays_Test.edges",
            edgeRemRatio, keepConnected, seed);
    }
}
```

The file `Zakarays_Train.edges` will contain the set of observed edges, whereas `Zakarays_Test.edges` will contain the set of edges that have been removed, i.e. the test set.

3. Compile your code:

```
$ javac -cp ../LinkPredJava.jar GenData.java
```

4. Run your code:

```
$ java -cp ../LinkPredJava.jar GenData
```

**R** The method `addPST` is used to load the pre-stored results by internally creating a `PST` predictor. For more details about this predictor consult Section 5.2.4 of the user guide.

The first few lines of `Zakarays_Train.edges` and the file `Zakarays_Test.edges` generated by this program are as follows:

```
# First few lines of the file Zakarays_Train.edges
1      2
1      3
1      4
1      5
1      6
1      7
1      8
1      9
1     11
...
# The file Zakarays_Test.edges
2     22
3      4
24    26
33    24
9     34
32    33
33    30
28    25
```

- At this stage, we have two files: `Zakarays_Train.edges` which contains the set of observed edges and `Zakarays_Test.edges` which contains the set of removed edges. Train your algorithm on the file `Zakarays_Train.edges` and computed the scores of all non-existing links in that network. This includes the edges that have been removed (contained in `Zakarays_Test.edges`) and those that are absent from the ground truth network (true negative links). Store the scores in a file name "pst.txt" in the following format (the first line is a comment and can be safely omitted):

```
#Start  End      Score
1      31      0.41374
1      10      0.276687
1      28      0.283587
1      29      0.374494
1      33      0.463135
1      17      0.531863
1      34      0.49409
1      26      0.325087
1      25      0.325087
...
```

- In a file name `EvalPST.java` write the following code:

```
public class EvalPST {
    static {
        // Load the library
        System.loadLibrary("LinkPredJava");
    }
    public static void main(String[] args) {
        // Create an evaluator object
        Evaluator eval = new Evaluator();
        // Add predictors to be evaluated
        eval.addADA();
    }
}
```

```
// Use the method addPST to create a predictor that loads
// scores from pst.txt
eval.addPST("PST", "pst.txt");
eval.addRAL();
// Add performance measures
eval.addPR();
eval.addTPR();
// Run experiment on the specified network
eval.run("Zakarays_Train.edges", "Zakarays_Test.edges");
}
}
```

7. Compile your code:

```
$ javac -cp ../LinkPredJava.jar EvalPST.java
```

8. Run your code:

```
$ java -cp ../LinkPredJava.jar EvalPST
```

The output of this program is as follows:

PRADA	PRPST	PRRAL	TPRADA	TPRPST	TPRRAL
0.0510	0.0510	0.0391	0.1250	0.1250	0.1250

## 2.3 Python

LinkPred bindings are optional (by default on). To change this setting, edit the file `CMakeLists.txt` in the root of the library source directory (search for the option `LINKPRED_WITH_BINDINGS`). Upon successful building, the library `_LinkPredPython` will be generated (named `_LinkPredPython.so` in Linux). This library will be loaded when running your program, and for that, it must be accessible to Python.

- R** In Linux, you can make the library accessible to Python by including its path in the environment variable `PYTHONPATH`. If LinkPred is installed in the default location, this can be accomplished using the following command:

```
$ export PYTHONPATH=$PYTHONPATH:/usr/local/lib
```

The Python module `LinkPredPython` containing the proxy classes needed to interface with `LinkPred` is located in `/bindings/Python`. Python programs that use `LinkPred` must import this module, which must therefore be in the Python module search path (for instance, in the same directory as your code).

### 2.3.1 Tutorial: Computing all scores using the class `Predictor`

This tutorial shows how to use the Java bindings of the simplified interface, more precisely the class `Predictor` to compute the scores of all non-existing edges in a network. For more information on the simplified interface, consult Chapter 2 of the user guide.

1. In a file name `predAll.py` write the following code:

```
# Import the module
import LinkPredPython as lpp
# Create a predictor object
p = lpp.Predictor();
# Load network from file
p.loadnet("Zakarays_Karate_Club.edges");
# Predict the score of all non-existing edges using Adamic
  Adar index
esv = p.predAllADA();
# Print the scores
for es in esv:
    print(es.i + "\t" + es.j + "\t" + "{:.4f}".format(es.score)
          );
```

 This code is available in: `tutorials/code/simp/python/predAll`

2. Run your code:

```
$ python predAll.py
```

The first few lines of this programs' output are as follows:

```
1      31      1.0765
1      10      0.4343
1      28      0.4343
1      29      0.9924
1      33      1.6137
1      17      1.4427
1      34      2.7110
1      15      0.0000
1      16      0.0000
1      19      0.0000
...
```

### 2.3.2 Tutorial: Computing scores of specific edges using the class `Predictor`

This tutorial shows how to use the Java bindings of the simplified interface, more precisely the class `Predictor` to compute the scores of specific edges. For more information on the simplified interface, consult Chapter 2 of the user guide.

1. In a file name `pred.py` write the following code:

```
# Import the module
import LinkPredPython as lpp
# Create a predictor object
p = lpp.Predictor();
# Load network from file
p.loadnet("Zakarays_Karate_Club.edges");
# Compute the score for the two edges (1, 34) and (26,34)
esv = lpp.EdgeScoreVec();
es = lpp.EdgeScore();
es.i = "1";
es.j = "34";
esv.push_back(es);
es.i = "26";
es.j = "34";
esv.push_back(es);
p.predKAB(esv);
# Print the scores
for es in esv:
    print(es.i + "\t" + es.j + "\t" + "{:.4f}".format(es.score)
          );
```

 This code is available in: `tutorials/code/simp/python/pred`

2. Run your code:

```
$ python pred.py
```

The first few lines of this programs' output are as follows:

```
1      34      0.5420
26     34      0.4688
```

### 2.3.3 Tutorial: Computing top scores using the class `Predictor`

This tutorial shows how to use the simplified interface, more precisely `Predictor` to compute the top edge scores. For more information on the simplified interface, consult Chapter 2 of the user guide.

1. In a file name `predTop.py` write the following code:

```
# Import the module
import LinkPredPython as lpp
k = 10;
# Create a predictor object
p = lpp.Predictor();
# Load network from file
p.loadnet("Zakarays_Karate_Club.edges");
# Predict the top k edges using Adamic Adar index
esv = p.predTopADA(k);
# Print the scores
for es in esv:
    print(es.i + "\t" + es.j + "\t" + "{:.4f}".format(es.score)
          );
```

 This code is available in: `tutorials/code/simp/python/predTop`

2. Run your code:

```
$ python predTop.py
```

The first few lines of this programs' output are as follows:

```
1      33      1.6137
1      34      2.7110
2      34      2.2529
3      32      1.6733
3      34      4.7194
5      6       1.9923
7      11      1.9923
8      14      1.8082
32     24      1.6656
24     25      1.6316
```

### 2.3.4 Tutorial: Encoder-classifier prediction using the class `Predictor`

This tutorial shows how to predict links using an encoder-classifier using `Predictor`. For more information on the simplified interface, consult Chapter 2 of the user guide. For information on link prediction using graph-embedding methods consult Section 5.2.3.

1. In a file name `ecl.py` write the following code:

```
# Import the module
import LinkPredPython as lpp
k = 10;
# Create a predictor object
p = lpp.Predictor();
# Load network from file
p.loadnet("Zakarays_Karate_Club.edges");
# Predict top k scores using an encoder-classifier predictor
  with Node2Vec as encoder and logistic regression as
  classifier
esv = p.predTopECL(k, "N2V", "LGR");
# Print the scores
print("N2V-LGR");
for es in esv:
    print(es.i + "\t" + es.j + "\t" + "{:.4f}".format(es.score)
          );
# Predict top k scores using an encoder-classifier predictor
  with LINE as encoder and feed-forward neural network as
  classifier
esv = p.predTopECL(k, "LIN", "FFN"); # FFN requires mlpack
# Print the scores
print("LIN-FFN");
for es in esv:
    print(es.i + "\t" + es.j + "\t" + "{:.4f}".format(es.score)
          );
```

 This code is available in: `tutorials/code/simp/python/ecl`

 For the names of available encoders and classifiers, consult the library reference manual.

2. Run your code:

```
$ python ecl.py
```

The output of this program is as follows:

```
N2V-LGR
1      34      0.6385
9      11      0.6373
9      13      0.5439
9      14      0.5560
9      18      0.5341
32     31      0.6160
32     10      0.6668
32     28      0.5062
32     17      0.6412
33     17      0.6679
```

LIN-FFN		
3	7	0.4164
3	13	0.4029
3	34	0.4005
11	13	0.4307
11	34	0.4295
11	24	0.3806
10	19	0.3942
10	24	0.4374
10	30	0.3940
15	24	0.3964

### 2.3.5 Tutorial: Encoder-similarity prediction using the class `Predictor`

This tutorial shows how to predict links using an encoder-similarity using `Predictor`. For more information on the simplified interface, consult Chapter 2 of the user guide. For information on link prediction using graph-embedding methods consult Section 5.2.3.

1. In a file name `esm.py` write the following code:

```
# Import the module
import LinkPredPython as lpp
k = 10;
# Create a predictor object
p = lpp.Predictor();
# Load network from file
p.loadnet("Zakarays_Karate_Club.edges");
# Predict top k scores using an encoder-classifier predictor
  with Node2Vec as encoder and L2 similarity
esv = p.predTopESM(k, "N2V", "L2");
# Print the scores
print("N2V-L2");
for es in esv:
    print(es.i + "\t" + es.j + "\t" + "{:.4f}".format(es.score)
          );
# Predict top k scores using an encoder-similarity measure
  predictor with LINE as encoder and cosine similarity
esv = p.predTopESM(k, "LIN", "CSM");
# Print the scores
print("LIN-CSM");
for es in esv:
    print(es.i + "\t" + es.j + "\t" + "{:.4f}".format(es.score)
          );
```

 This code is available in: `tutorials/code/simp/python/esm`

 For the names of available encoders and similarity measures, consult the library reference manual.

2. Run your code:

```
$ python esm.py
```

The output of this program is as follows:

```
N2V-L2
13      14      -0.5522
13      18      -0.5377
18      22      -0.4145
15      16      -0.3949
15      21      -0.4318
15      23      -0.5334
16      21      -0.3882
16      23      -0.3743
19      21      -0.4718
21      23      -0.3852
LIN-CSM
1       21      0.6204
```

---

2	5	0.6932
9	13	0.7026
12	19	0.6214
14	30	0.6889
20	21	0.7088
22	21	0.6091
31	30	0.9057
10	15	0.6176
16	25	0.6741

### 2.3.6 Tutorial: Performance evaluation with automatically generated test data using the class `Evaluator`

This tutorial shows how to evaluate the performance of link prediction algorithm with test data automatically generated from a ground-truth network using `Evaluator`. For more information on the simplified interface, consult Chapter 2 of the user guide.

1. In a file name `eval-auto.py` write the following code:

```
# Import the module
import LinkPredPython as lpp
nbRuns = 10;
edgeRemRatio = 0.1;
# Create an evaluator object
ev = lpp.Evaluator();
# Add predictors to be evaluated
ev.addCNE();
ev.addADA();
ev.addKAB();
# Add performance measures
ev.addROC();
ev.addTPR();
# Run experiment on the specified network
ev.run("Zakarays_Karate_Club.edges", nbRuns, edgeRemRatio);
```

 This code is available in: `tutorials/code/simp/python/eval-auto`

 For the names of available predictors and performance measures, consult the library reference manual.

2. Run your code:

```
$ python eval-auto.py
```

The output of this program is as follows:

```
# n: 34 m: 78
#ratio  ROCADA  ROCCNE  ROCKAB  TPRADA  TPRCNE  TPRKAB
0.10    0.7737  0.7149  0.8280  0.1250  0.1932  0.1250
0.10    0.6593  0.6333  0.7030  0.1250  0.0000  0.1250
0.10    0.5967  0.5762  0.6095  0.1875  0.1818  0.2500
0.10    0.8464  0.7913  0.9343  0.1875  0.1290  0.3750
0.10    0.8324  0.7785  0.8967  0.1250  0.1750  0.1250
0.10    0.7240  0.6953  0.7547  0.0000  0.2222  0.0000
0.10    0.6753  0.6610  0.7262  0.0000  0.1591  0.1250
0.10    0.6048  0.5792  0.6672  0.0000  0.0000  0.0000
0.10    0.7627  0.7547  0.7808  0.2917  0.3194  0.3750
0.10    0.6442  0.5835  0.6727  0.1250  0.1250  0.1250
#Time: 88.3233 ms
```

3. The output above is a trace generated from within the evaluation method. You may also access the results as follows. In a file name `eval-auto-print.py` write the following code:

```
# Import the module
import LinkPredPython as lpp
nbRuns = 10;
```

```

edgeRemRatio = 0.1;
# Create an evaluator object
ev = lpp.Evaluator();
# Add predictors to be evaluated
ev.addCNE();
ev.addADA();
ev.addKAB();
# Add performance measures
ev.addROC();
ev.addTPR();
# Run experiment on the specified network
ev.run("Zakarays_Karate_Club.edges", nbRuns, edgeRemRatio);
import sys # For printing
# Print the header row
res = ev.getPerfRes(0);
for r in res:
    sys.stdout.write(r.name + "\t");
sys.stdout.write("\n");
# Print the results of each iteration
for i in range(nbRuns):
    res = ev.getPerfRes(i);
    for r in res:
        sys.stdout.write("{:.4f}".format(r.res) + "\t");
    sys.stdout.write("\n");

```

 This code is available in: [tutorials/code/simp/python/eval-auto](https://tutorials.code.simp/python/eval-auto)

#### 4. Run your code:

```
$ python eval-auto-print.py
```

The output of this program is as follows:

```

# n: 34 m: 78
#ratio  ROCADA  ROCCNE  ROCKAB  TPRADA  TPRCNE  TPRKAB
0.10    0.7737  0.7149  0.8280  0.1250  0.1932  0.1250
0.10    0.6593  0.6333  0.7030  0.1250  0.0000  0.1250
0.10    0.5967  0.5762  0.6095  0.1875  0.1818  0.2500
0.10    0.8464  0.7913  0.9343  0.1875  0.1290  0.3750
0.10    0.8324  0.7785  0.8967  0.1250  0.1750  0.1250
0.10    0.7240  0.6953  0.7547  0.0000  0.2222  0.0000
0.10    0.6753  0.6610  0.7262  0.0000  0.1591  0.1250
0.10    0.6048  0.5792  0.6672  0.0000  0.0000  0.0000
0.10    0.7627  0.7547  0.7808  0.2917  0.3194  0.3750
0.10    0.6442  0.5835  0.6727  0.1250  0.1250  0.1250
#Time: 91.3887 ms
ROCADA  ROCCNE  ROCKAB  TPRADA  TPRCNE  TPRKAB
0.7737  0.7149  0.8280  0.1250  0.1932  0.1250
0.6593  0.6333  0.7030  0.1250  0.0000  0.1250
0.5967  0.5762  0.6095  0.1875  0.1818  0.2500
0.8464  0.7913  0.9343  0.1875  0.1290  0.3750
0.8324  0.7785  0.8967  0.1250  0.1750  0.1250
0.7240  0.6953  0.7547  0.0000  0.2222  0.0000
0.6753  0.6610  0.7262  0.0000  0.1591  0.1250
0.6048  0.5792  0.6672  0.0000  0.0000  0.0000
0.7627  0.7547  0.7808  0.2917  0.3194  0.3750
0.6442  0.5835  0.6727  0.1250  0.1250  0.1250

```

### 2.3.7 Tutorial: Performance evaluation with pre-generated test data using the class `Evaluator`

This tutorial shows how to evaluate the performance of link prediction algorithm with pre-generated test data using `Evaluator`. For more information on the simplified interface, consult Chapter 2 of the user guide.

1. In a file name `eval-pregenerated.py` write the following code:

```
# Import the module
import LinkPredPython as lpp
# Create an evaluator object
ev = lpp.Evaluator();
# Add predictors to be evaluated
ev.addADA();
ev.addRAL();
# Add performance measures
ev.addPR();
ev.addTPR();
# Run experiment on the specified network
ev.run("Zakarays_Karate_Club_Train.edges", "
      Zakarays_Karate_Club_Test.edges");
```

The file `Zakarays_Karate_Club_Train.edges` contains the set of observed edges, whereas `Zakarays_Karate_Club_Test.edges` contains the set of edges that have been removed, i.e. the test set.

 This code is available in: `tutorials/code/simp/python/eval-pregenerated`

2. Run your code:

```
$ python eval-pregenerated.py
```

The output of this program is as follows:

```
PRADA   PRRAL   TPRADA  TPRRAL
0.1561  0.1568  0.1250  0.1250
```

3. The output above is a trace generated from within the evaluation method. You may also access the results as follows. In a file name `eval-pregenerated-print.py` write the following code:

```
# Import the module
import LinkPredPython as lpp
# Create an evaluator object
ev = lpp.Evaluator();
# Add predictors to be evaluated
ev.addADA();
ev.addRAL();
# Add performance measures
ev.addPR();
ev.addTPR();
# Run experiment on the specified network
ev.run("Zakarays_Karate_Club_Train.edges", "
      Zakarays_Karate_Club_Test.edges");
import sys # For printing
res = ev.getPerfRes(0);
for r in res:
```

```
sys.stdout.write(r.name + "\t");
sys.stdout.write("\n");
for r in res:
    sys.stdout.write("{:.4f}".format(r.res) + "\t");
sys.stdout.write("\n");
```

 This code is available in: `tutorials/code/simp/python/eval-pregenerated`

#### 4. Run your code:

```
$ python eval-pregenerated-print.py
```

The output of this program is as follows:

```
PRADA   PRRAL   TPRADA  TPRRAL
0.1561  0.1568  0.1250  0.1250
PRADA   PRRAL   TPRADA  TPRRAL
0.1561  0.1568  0.1250  0.1250
```

### 2.3.8 Tutorial: Performance evaluation of external prediction results using the class `Evaluator`

This tutorial shows how to evaluate external link prediction results obtained by a user link prediction algorithm. For more information on the simplified interface, consult Chapter 2 of the user guide.

**R** It is possible to implement new link prediction algorithms and integrate them into LinkPred, which allows for better use of the library's performance evaluation routines. See Section 5.4 of the user guide for more details.

1. The first step consists in generating test data. If you already have a ready test data, split into training and test sets, you can skip this part (go directly to Step 4 of this tutorial).
2. In a file name `gen-data.py` write the following code:

```
# Import the module
import LinkPredPython as lpp
# We remove 10% of the edges
edgeRemRatio = 0.1;
# We will not keep the network connected when removing edges
keepConnected = False;
# Seed of the random number generator
seed = 0;
# Create an Evaluator object
ev = lpp.Evaluator();
# The ground truth network "Zakarays_Karate_Club.edges" is
# split into an observed network stored in "Zakarays_Train.
# edges" and a list of removed edges stored in "
# Zakarays_Test.edges"
ev.genTestData("Zakarays_Karate_Club.edges", "Zakarays_Train.
edges", "Zakarays_Test.edges", edgeRemRatio, keepConnected
, seed);
```

The file `Zakarays_Train.edges` will contain the set of observed edges, whereas `Zakarays_Test.edges` will contain the set of edges that have been removed, i.e. the test set.

3. Run your code:

```
$ python gen-data.py
```

**R** The method `addPST` is used to load the pre-stored results by internally creating a PST predictor. For more details about this predictor consult Section 5.2.4 of the user guide.

The first few lines of `Zakarays_Train.edges` and the file `Zakarays_Test.edges` generated by this program are as follows:

```
# First few lines of the file Zakarays_Train.edges
1      2
1      3
1      4
1      5
1      6
```

```

1      7
1      8
1      9
1     11
...
# The file Zakarays_Test.edges
2     22
3      4
24     26
33     24
9      34
32     33
33     30
28     25

```

4. At this stage, we have two files: `Zakarays_Train.edges` which contains the set of observed edges and `Zakarays_Test.edges` which contains the set of removed edges. Train your algorithm on the file `Zakarays_Train.edges` and computed the scores of all non-existing links in that network. This includes the edges that have been removed (contained in `Zakarays_Test.edges`) and those that are absent from the ground truth network (true negative links). Store the scores in a file name "pst.txt" in the following format (the first line is a comment and can be safely omitted):

```

#Start  End      Score
1      31      0.41374
1      10      0.276687
1      28      0.283587
1      29      0.374494
1      33      0.463135
1      17      0.531863
1      34      0.49409
1      26      0.325087
1      25      0.325087
...

```

5. In a file name `eval-pst.py` write the following code:

```

# Import the module
import LinkPredPython as lpp
# Create an evaluator object
ev = lpp.Evaluator();
# Add predictors to be evuated
ev.addADA();
# Use the method addPST to create a predictor that loads
  scores from pst.txt
ev.addPST("PST", "pst.txt");
ev.addRAL();
# Add performance measures
ev.addPR();
ev.addTPR();
# Run experiment on the specified network
ev.run("Zakarays_Train.edges", "Zakarays_Test.edges");

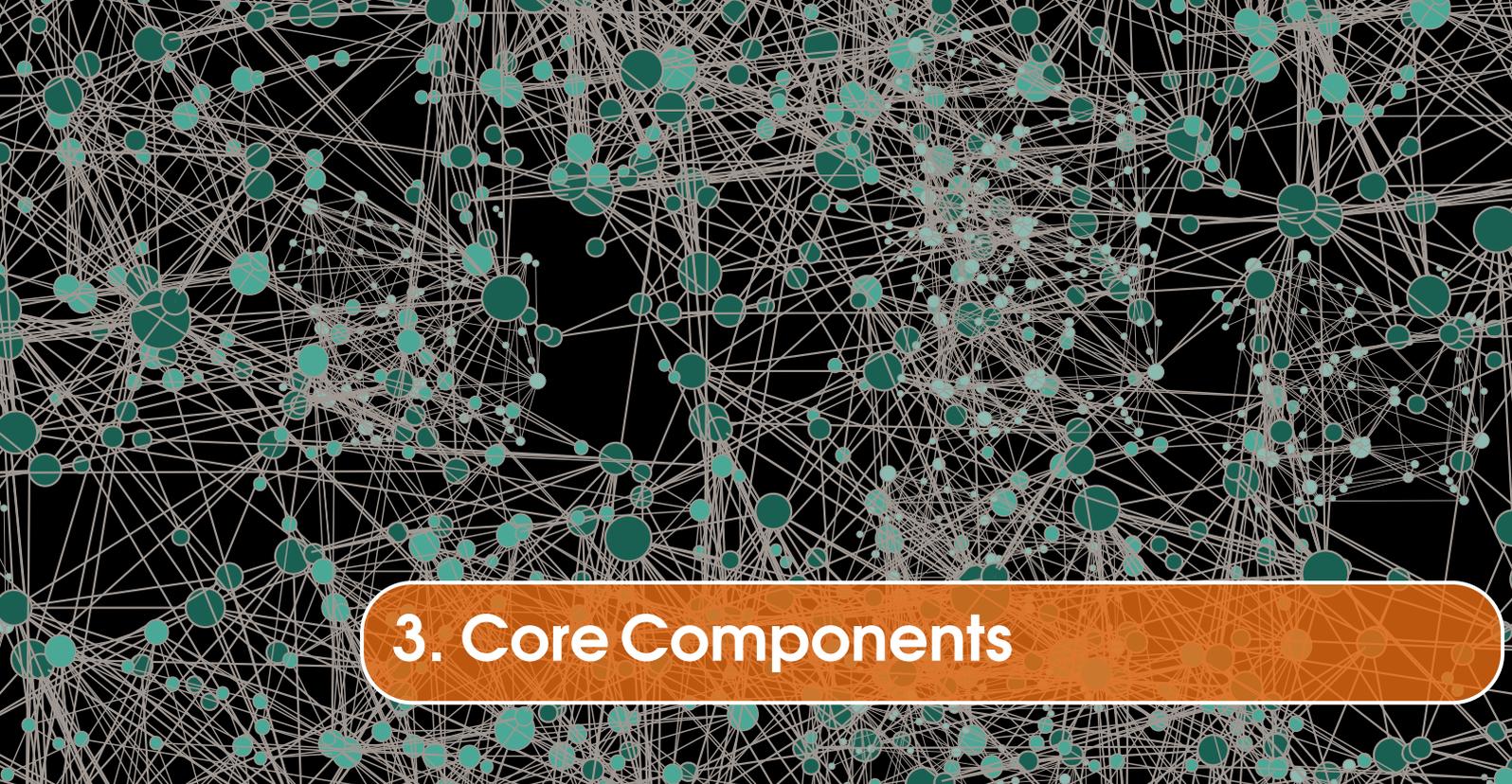
```

6. Run your code:

```
$ python eval-pst.py
```

The output of this program is as follows:

PRADA	PRPST	PRRAL	TPRADA	TPRPST	TPRRAL
0.0510	0.0510	0.0391	0.1250	0.1250	0.1250



## 3. Core Components

This chapter contains tutorials on core components of LinkPred, namely, network data structures and maps.

### 3.1 Representing undirected networks using the class `UNetwork`

The class `UNetwork` is used to efficiently represent undirected networks. This section contains a number of tutorials that demonstrate how to build and access network information using this class.

### 3.1.1 Tutorial: Reading a network from file and printing it

This tutorial shows how to read a network from file and print it. For more information on the core components of LinkPred, consult Chapter 3 of the user guide.

1. In a file name `read-print.cpp` write the following code:

```
#include <linkpred.hpp>
using namespace LinkPred;
int main() {
    // Read network from file
    auto net = UNetwork<>::read("Zakarays_Karate_Club.edges");
    // Print to standard output
    net->print();
    return 0;
}
```

**R** This code is available in: `tutorials/code/core/unetwork/read-print`

**R** The method `read` returns a shared pointer to an object of type `UNetwork`.

2. Compile your code:

```
$ mpiCC read-print.cpp -o read-print -fopenmp -lLinkPred
```

**R** Check Tutorial 1.2 if you face any compilation issues.

3. Run your code:

```
$ ./read-print
```

The following is a partial output of this program:

```
1      2
1      3
1      4
1      5
1      6
1      7
1      8
1      9
1     11
1     12
...
```

### 3.1.2 Tutorial: Building a network

This tutorial shows how to build a network by adding nodes and connecting them by edges. For more information on the core components of LinkPred, consult Chapter 3 of the user guide.

1. In a file name `net-build.cpp` write the following code:

```
#include <linkpred.hpp>
#include <iostream>
using namespace LinkPred;
int main() {
    // Create a network object
    UNetwork<> net;
    // Add nodes
    net.addNode("A");
    net.addNode("B");
    net.addNode("C");
    net.addNode("D");
    // Add edges
    net.addEdge(net.getID("A"), net.getID("B"));
    net.addEdge(net.getID("B"), net.getID("C"));
    net.addEdge(net.getID("C"), net.getID("D"));
    net.addEdge(net.getID("D"), net.getID("A"));
    // Assemble the network
    net.assemble();
    // Print the network
    net.print();
    return 0;
}
```

- R This code is available in: `tutorials/code/core/unetwork/net-build`
- R The method `addEdge` uses node IDs (**and not labels**) to identify nodes. This is why the method `getID` is used.
- R It is important to assemble the network before using it.

2. Compile your code:

```
$ mpiCC net-build.cpp -o net-build -fopenmp -lLinkPred
```

- R Check Tutorial 1.2 if you face any compilation issues.

3. Run your code:

```
$ ./net-build
```

The following is the output of this program:

```
A      B
A      D
B      C
C      D
```

### 3.1.3 Tutorial: Accessing network information

This tutorial shows how to access network information including:

- Listing all nodes in the network.
- Translating node labels to IDs.
- Translating node IDs to labels.
- List all edges in the network.
- List the neighbors of every node.

For more information on the core components of LinkPred, consult Chapter 3 of the user guide.

1. In a file name `net-access-nodes.cpp` write the following code:

```
#include <linkpred.hpp>
#include <iostream>
using namespace LinkPred;
int main() {
    // Create a network object
    UNetwork<> net;
    // Add nodes
    net.addNode("A");
    net.addNode("B");
    net.addNode("C");
    net.addNode("D");
    // Add edges
    net.addEdge(net.getID("A"), net.getID("B"));
    net.addEdge(net.getID("B"), net.getID("C"));
    net.addEdge(net.getID("C"), net.getID("D"));
    net.addEdge(net.getID("D"), net.getID("A"));
    // Assemble the network
    net.assemble();
    // Accessing nodes
    std::cout << "Nodes:\n";
    std::cout << "ID\tLabel\n";
    for (auto it = net.nodesBegin(); it != net.nodesEnd(); ++it
        ) {
        std::cout << it->first << "\t" << it->second << std::endl
            ;
    }
    std::cout << "Translating labels to IDs\n";
    std::cout << "A->" << net.getID("A") << std::endl;
    std::cout << "B->" << net.getID("B") << std::endl;
    std::cout << "C->" << net.getID("C") << std::endl;
    std::cout << "D->" << net.getID("D") << std::endl;
    std::cout << "Translating IDs to labels\n";
    for (std::size_t i = 0; i < net.getNbNodes(); i++) {
        std::cout << i << "->" << net.getLabel(i) << std::endl;
    }
    return 0;
}
```

 This code is available in: `tutorials/code/core/unetwork/net-access`

2. Compile your code:

```
$ mpiCC net-access-nodes.cpp -o net-access-nodes -fopenmp -lLinkPred
```

 Check Tutorial 1.2 if you face any compilation issues.

### 3. Run your code:

```
$ ./net-access-nodes
```

The following is the output of this program:

```
Nodes:
ID      Label
0       A
1       B
2       C
3       D
Translating labels to IDs
A -> 0
B -> 1
C -> 2
D -> 3
Translating IDs to labels
0 -> A
1 -> B
2 -> C
3 -> D
```

### 4. In a file name net-access-nodes.cpp write the following code:

```
#include <linkpred.hpp>
#include <iostream>
using namespace LinkPred;
int main() {
    // Create a network object
    UNetwork<> net;
    // Add nodes
    net.addNode("A");
    net.addNode("B");
    net.addNode("C");
    net.addNode("D");
    // Add edges
    net.addEdge(net.getID("A"), net.getID("B"));
    net.addEdge(net.getID("B"), net.getID("C"));
    net.addEdge(net.getID("C"), net.getID("D"));
    net.addEdge(net.getID("D"), net.getID("A"));
    // Assemble the network
    net.assemble();
    // Accessing nodes
    std::cout << "Nodes:\n";
    std::cout << "ID\tLabel\n";
    for (auto it = net.nodesBegin(); it != net.nodesEnd(); ++it)
    {
        std::cout << it->first << "\t" << it->second << std::endl
        ;
    }
    std::cout << "Translating labels to IDs\n";
```

```
std::cout << "A->" << net.getID("A") << std::endl;
std::cout << "B->" << net.getID("B") << std::endl;
std::cout << "C->" << net.getID("C") << std::endl;
std::cout << "D->" << net.getID("D") << std::endl;
std::cout << "Translating IDs to labels\n";
for (std::size_t i = 0; i < net.getNbNodes(); i++) {
    std::cout << i << "->" << net.getLabel(i) << std::endl;
}
return 0;
}
```

**R** This code is available in: `tutorials/code/core/unetwork/net-access`

#### 5. Compile your code:

```
$ mpiCC net-access-nodes.cpp -o net-access-nodes -fopenmp -
  lLinkPred
```

**R** Check Tutorial 1.2 if you face any compilation issues.

#### 6. Run your code:

```
$ ./net-access-nodes
```

The following is the output of this program:

```
Nodes:
ID      Label
0       A
1       B
2       C
3       D
Translating labels to IDs
A -> 0
B -> 1
C -> 2
D -> 3
Translating IDs to labels
0 -> A
1 -> B
2 -> C
3 -> D
```

#### 7. In a file name `net-access-edges.cpp` write the following code:

```

#include <linkpred.hpp>
#include <iostream>
using namespace LinkPred;
int main() {
    // Create a network object
    UNetwork<> net;
    // Add nodes
    net.addNode("A");
    net.addNode("B");
    net.addNode("C");
    net.addNode("D");
    // Add edges
    net.addEdge(net.getID("A"), net.getID("B"));
    net.addEdge(net.getID("B"), net.getID("C"));
    net.addEdge(net.getID("C"), net.getID("D"));
    net.addEdge(net.getID("D"), net.getID("A"));
    // Assemble the network
    net.assemble();
    // Accessing edges
    std::cout << "Edges:\n";
    std::cout << "Start\tEnd\n";
    for (auto it = net.edgesBegin(); it != net.edgesEnd(); ++it
        ) {
        std::cout << net.start(*it) << "\t" << net.end(*it) <<
            std::endl;
    }
    // Neighbors
    for (std::size_t i = 0; i < net.getNbNodes(); i++) {
        std::cout << "Neighbors of " << i << std::endl;
        for (auto it = net.neighbBegin(i); it != net.neighbEnd(i)
            ; ++it) {
            std::cout << net.end(*it) << std::endl;
        }
    }
    return 0;
}

```

 This code is available in: `tutorials/code/core/unetwork/net-access`

#### 8. Compile your code:

```
$ mpiCC net-access-edges.cpp -o net-access-edges -fopenmp -lLinkPred
```

#### 9. Run your code:

```
$ ./net-access-edges
```

The following is the output of this program:

```
Edges:
Start  End
0      1
0      3
1      2
2      3
Neighbors of 0
```

```
1
3
Neighbors of 1
0
2
Neighbors of 2
1
3
Neighbors of 3
0
2
```

## 3.2 Representing directed networks using the class `DNetwork`

The class `DNetwork` is used to efficiently represent directed networks. This section contains a number of tutorials that demonstrate how to build and access network information using this class.

### 3.2.1 Tutorial: Reading a network from file and printing it

This tutorial shows how to read a network from file and print it. For more information on the core components of LinkPred, consult Chapter 3 of the user guide.

1. In a file name `read-print.cpp` write the following code:

```
#include <linkpred.hpp>
using namespace LinkPred;
int main() {
    // Read network from file
    auto net = DNetwork<>::read("Zakarays_Karate_Club.edges");
    // Print to standard output
    net->print();
    return 0;
}
```

**R** This code is available in: `tutorials/code/core/dnetwork/read-print`

**R** The method `read` returns a shared pointer to an object of type `DNetwork`.

2. Compile your code:

```
$ mpiCC read-print.cpp -o read-print -fopenmp -lLinkPred
```

**R** Check Tutorial 1.2 if you face any compilation issues.

3. Run your code:

```
$ ./read-print
```

The following is a partial output of this program:

```
1      2
1      3
1      4
1      5
1      6
1      7
1      8
1      9
1     11
1     12
...
```

### 3.2.2 Tutorial: Building a network

This tutorial shows how to build a network by adding nodes and connecting them by edges. For more information on the core components of LinkPred, consult Chapter 3 of the user guide.

1. In a file name `net-build.cpp` write the following code:

```
#include <linkpred.hpp>
#include <iostream>
using namespace LinkPred;
int main() {
    // Create a network object
    DNetwork<> net;
    // Add nodes
    net.addNode("A");
    net.addNode("B");
    net.addNode("C");
    net.addNode("D");
    // Add edges
    net.addEdge(net.getID("A"), net.getID("B"));
    net.addEdge(net.getID("B"), net.getID("C"));
    net.addEdge(net.getID("C"), net.getID("D"));
    net.addEdge(net.getID("D"), net.getID("A"));
    // Assemble the network
    net.assemble();
    // Print the network
    net.print();
    return 0;
}
```

- R This code is available in: `tutorials/code/core/dnetwork/net-build`
- R The method `addEdge` uses node IDs (**and not labels**) to identify nodes. This is why the method `getID` is used.
- R It is important to assemble the network before using it.

2. Compile your code:

```
$ mpiCC net-build.cpp -o net-build -fopenmp -lLinkPred
```

- R Check Tutorial 1.2 if you face any compilation issues.

3. Run your code:

```
$ ./net-build
```

The following is the output of this program:

```
A      B
B      C
C      D
D      A
```

### 3.2.3 Tutorial: Accessing network information

This tutorial shows how to access network information including:

- Listing all nodes in the network.
- Translating node labels to IDs.
- Translating node IDs to labels.
- List all edges in the network.
- List the neighbors of every node.

For more information on the core components of LinkPred, consult Chapter 3 of the user guide.

1. In a file name `net-access-nodes.cpp` write the following code:

```
#include <linkpred.hpp>
#include <iostream>
using namespace LinkPred;
int main() {
    // Create a network object
    DNetwork<> net;
    // Add nodes
    net.addNode("A");
    net.addNode("B");
    net.addNode("C");
    net.addNode("D");
    // Add edges
    net.addEdge(net.getID("A"), net.getID("B"));
    net.addEdge(net.getID("B"), net.getID("C"));
    net.addEdge(net.getID("C"), net.getID("D"));
    net.addEdge(net.getID("D"), net.getID("A"));
    // Assemble the network
    net.assemble();
    // Accessing nodes
    std::cout << "Nodes:\n";
    std::cout << "ID\tLabel\n";
    for (auto it = net.nodesBegin(); it != net.nodesEnd(); ++it
        ) {
        std::cout << it->first << "\t" << it->second << std::endl
            ;
    }
    std::cout << "Translating labels to IDs\n";
    std::cout << "A->" << net.getID("A") << std::endl;
    std::cout << "B->" << net.getID("B") << std::endl;
    std::cout << "C->" << net.getID("C") << std::endl;
    std::cout << "D->" << net.getID("D") << std::endl;
    std::cout << "Translating IDs to labels\n";
    for (std::size_t i = 0; i < net.getNbNodes(); i++) {
        std::cout << i << "->" << net.getLabel(i) << std::endl;
    }
    return 0;
}
```

 This code is available in: `tutorials/code/core/dnetwork/net-access`

2. Compile your code:

```
$ mpiCC net-access-nodes.cpp -o net-access-nodes -fopenmp -lLinkPred
```

 Check Tutorial 1.2 if you face any compilation issues.

### 3. Run your code:

```
$ ./net-access-nodes
```

The following is the output of this program:

```
Nodes:
ID      Label
0       A
1       B
2       C
3       D
Translating labels to IDs
A -> 0
B -> 1
C -> 2
D -> 3
Translating IDs to labels
0 -> A
1 -> B
2 -> C
3 -> D
```

### 4. In a file name net-access-nodes.cpp write the following code:

```
#include <linkpred.hpp>
#include <iostream>
using namespace LinkPred;
int main() {
    // Create a network object
    DNetwork<> net;
    // Add nodes
    net.addNode("A");
    net.addNode("B");
    net.addNode("C");
    net.addNode("D");
    // Add edges
    net.addEdge(net.getID("A"), net.getID("B"));
    net.addEdge(net.getID("B"), net.getID("C"));
    net.addEdge(net.getID("C"), net.getID("D"));
    net.addEdge(net.getID("D"), net.getID("A"));
    // Assemble the network
    net.assemble();
    // Accessing nodes
    std::cout << "Nodes:\n";
    std::cout << "ID\tLabel\n";
    for (auto it = net.nodesBegin(); it != net.nodesEnd(); ++it) {
        std::cout << it->first << "\t" << it->second << std::endl;
    }
    std::cout << "Translating labels to IDs\n";
```

```
std::cout << "A->" << net.getID("A") << std::endl;
std::cout << "B->" << net.getID("B") << std::endl;
std::cout << "C->" << net.getID("C") << std::endl;
std::cout << "D->" << net.getID("D") << std::endl;
std::cout << "Translating IDs to labels\n";
for (std::size_t i = 0; i < net.getNbNodes(); i++) {
    std::cout << i << "->" << net.getLabel(i) << std::endl;
}
return 0;
}
```

**R** This code is available in: `tutorials/code/core/dnetwork/net-access`

#### 5. Compile your code:

```
$ mpiCC net-access-nodes.cpp -o net-access-nodes -fopenmp -
  lLinkPred
```

**R** Check Tutorial 1.2 if you face any compilation issues.

#### 6. Run your code:

```
$ ./net-access-nodes
```

The following is the output of this program:

```
Nodes:
ID      Label
0       A
1       B
2       C
3       D
Translating labels to IDs
A -> 0
B -> 1
C -> 2
D -> 3
Translating IDs to labels
0 -> A
1 -> B
2 -> C
3 -> D
```

#### 7. In a file name `net-access-edges.cpp` write the following code:

```

#include <linkpred.hpp>
#include <iostream>
using namespace LinkPred;
int main() {
    // Create a network object
    DNetwork<> net;
    // Add nodes
    net.addNode("A");
    net.addNode("B");
    net.addNode("C");
    net.addNode("D");
    // Add edges
    net.addEdge(net.getID("A"), net.getID("B"));
    net.addEdge(net.getID("B"), net.getID("C"));
    net.addEdge(net.getID("C"), net.getID("D"));
    net.addEdge(net.getID("D"), net.getID("A"));
    // Assemble the network
    net.assemble();
    // Accessing edges
    std::cout << "Edges:\n";
    std::cout << "Start\tEnd\n";
    for (auto it = net.edgesBegin(); it != net.edgesEnd(); ++it
        ) {
        std::cout << net.start(*it) << "\t" << net.end(*it) <<
            std::endl;
    }
    // Neighbors
    for (std::size_t i = 0; i < net.getNbNodes(); i++) {
        std::cout << "Neighbors of " << i << std::endl;
        for (auto it = net.neighbBegin(i); it != net.neighbEnd(i)
            ; ++it) {
            std::cout << net.end(*it) << std::endl;
        }
    }
    return 0;
}

```

 This code is available in: `tutorials/code/core/dnetwork/net-access`

#### 8. Compile your code:

```
$ mpiCC net-access-edges.cpp -o net-access-edges -fopenmp -lLinkPred
```

#### 9. Run your code:

```
$ ./net-access-edges
```

The following is the output of this program:

```
Edges:
Start  End
0      1
1      2
2      3
3      0
Neighbors of 0
```

```
1  
Neighbors of 1  
2  
Neighbors of 2  
3  
Neighbors of 3  
0
```

### 3.3 Maps

Maps are a useful way to associate data to nodes or edges. Two types of maps are available in LinkPred: *node maps* (class `NodeMap`) and *edge maps* (class `EdgeMap`), both member of `UNetwork` and `DNetwork`. The first assigns data to the nodes of the network, whereas the latter maps data to edges. This section contains tutorials on how to use maps to associate data to nodes and edges.

### 3.3.1 Tutorial: Node maps

This tutorial shows how to associate data to nodes using node maps. For more information on the core components of LinkPred, consult Chapter 3 of the user guide.

1. In a file name `node-map.cpp` write the following code:

```
#include <linkpred.hpp>
#include <iostream>
using namespace LinkPred;
int main(int argc, char*argv[]) {
    // Create a network object
    UNetwork<> net;
    // Add nodes
    net.addNode("A");
    net.addNode("B");
    net.addNode("C");
    net.addNode("D");
    // Add edges
    net.addEdge(net.getID("A"), net.getID("B"));
    net.addEdge(net.getID("B"), net.getID("C"));
    net.addEdge(net.getID("C"), net.getID("D"));
    net.addEdge(net.getID("D"), net.getID("A"));
    // Assemble the network
    net.assemble();
    // Create a node map that associates a double to every node
    auto nodeMap = net.template createNodeMap<double>();
    // Fill the map
    for (std::size_t i = 0; i < net.getNbNodes(); i++) {
        nodeMap[i] = i / 2.0;
    }
    // Access the map
    std::cout << "Label\tValue" << std::endl;
    for (std::size_t i = 0; i < net.getNbNodes(); i++) {
        std::cout << net.getLabel(i) << "\t" << nodeMap[i] << std::endl;
    }
    return 0;
}
```

 This code is available in: `tutorials/code/core/maps/node-map`

2. Compile your code:

```
$ mpiCC node-map.cpp -o node-map -fopenmp -lLinkPred
```

 Check Tutorial 1.2 if you face any compilation issues.

3. Run your code:

```
$ ./node-map
```

The following is a partial output of this program:

Label	Value
A	0
B	0.5
C	1
D	1.5

### 3.3.2 Tutorial: Edge maps

This tutorial shows how to associate data to edges using edge maps. For more information on the core components of LinkPred, consult Chapter 3 of the user guide.

1. In a file name `edge-map.cpp` write the following code:

```
#include <linkpred.hpp>
#include <iostream>
using namespace LinkPred;
int main(int argc, char*argv[]) {
    // Create a network object
    UNetwork<> net;
    // Add nodes
    net.addNode("A");
    net.addNode("B");
    net.addNode("C");
    net.addNode("D");
    // Add edges
    net.addEdge(net.getID("A"), net.getID("B"));
    net.addEdge(net.getID("B"), net.getID("C"));
    net.addEdge(net.getID("C"), net.getID("D"));
    net.addEdge(net.getID("D"), net.getID("A"));
    // Assemble the network
    net.assemble();
    // Create a node map that associates an integer to every
    edge
    auto edgeMap = net.template createEdgeMap<int>();
    edgeMap[net.makeEdge(0, 1)] = 3;
    edgeMap[net.makeEdge(1, 2)] = 2;
    edgeMap[net.makeEdge(2, 3)] = 5;
    edgeMap[net.makeEdge(3, 0)] = 4;
    // Access the map
    std::cout << "Start\tEnd\tValue" << std::endl;
    for (auto it = net.edgesBegin(); it != net.edgesEnd(); ++it
        ) {
        auto i = net.start(*it);
        auto j = net.end(*it);
        std::cout << net.getLabel(i) << "\t" << net.getLabel(j)
            << "\t" << edgeMap.at(*it) << std::endl;
    }
    return 0;
}
```

 This code is available in: `tutorials/code/core/maps/edge-map`

2. Compile your code:

```
$ mpiCC edge-map.cpp -o edge-map -fopenmp -lLinkPred
```

 Check Tutorial 1.2 if you face any compilation issues.

3. Run your code:

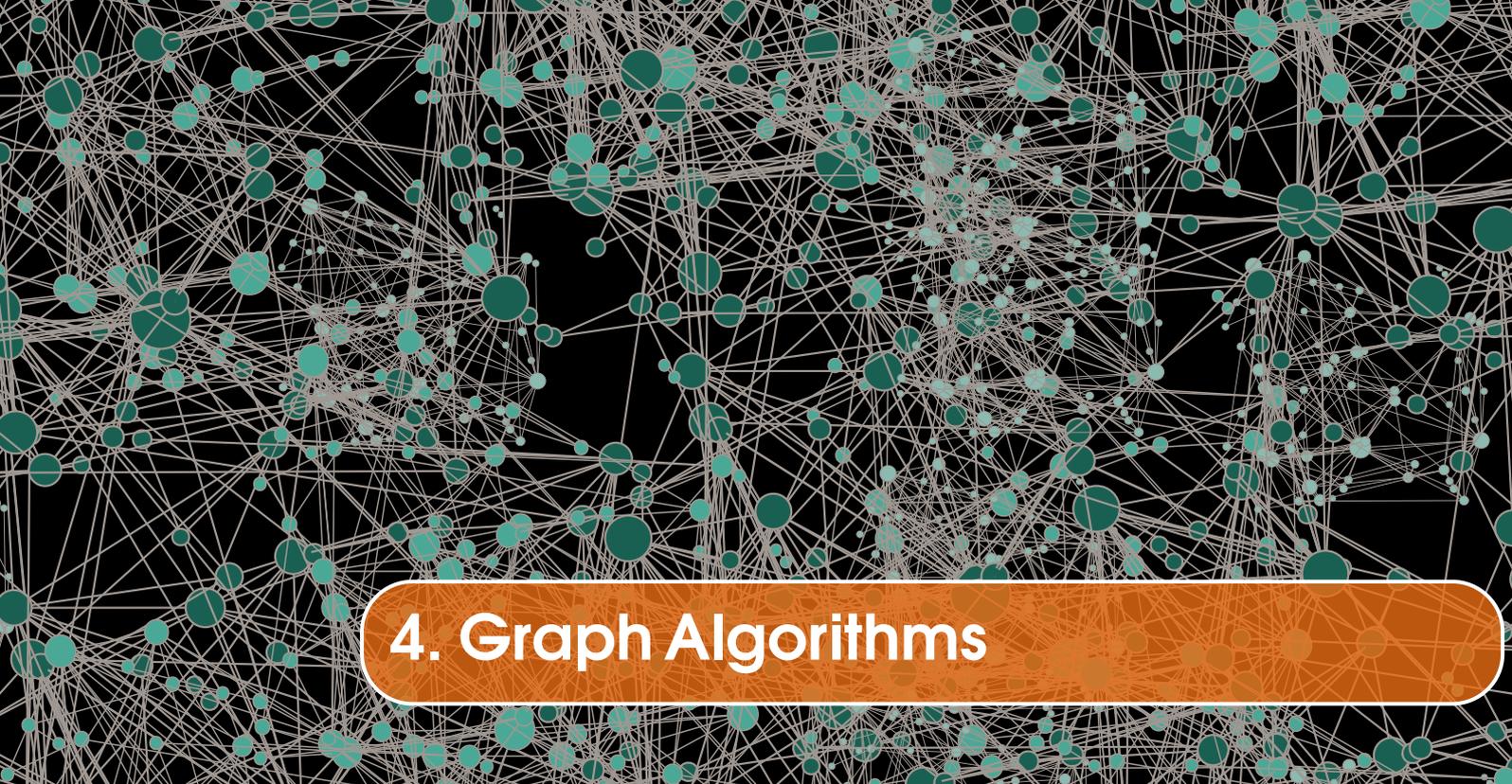
```
$ ./edge-map
```

The following is a partial output of this program:

---

Start	End	Value
A	B	3
A	D	4
B	C	2
C	D	5





## 4. Graph Algorithms

This chapter contains tutorials on graph algorithms available in LinkPred, namely, traversal algorithms, shortest path algorithms, and graph embedding algorithms.

## 4.1 Traversing a network

LinkPred provides two classes for graph traversal: `BFS`, for Breadth First traversal, and `DFS` for Depth First traversal. They can be used to process nodes as they are being visited. The library offers two useful node processing classes: `Counter`, which simply counts the visited nodes, and `Collector`, which collects the visited nodes' IDs into a queue in the order of their visit.

### 4.1.1 Tutorial: Traverse a network in BFS

This tutorial shows how to traverse a network in BFS (Breadth-First Search). For more information on graph algorithms available in LinkPred, consult Chapter 4 of the user guide.

1. In a file name `bfs.cpp` write the following code:

```
#include <linkpred.hpp>
#include <iostream>
using namespace LinkPred;
int main() {
    // Read network from file
    auto net = UNetwork<>::read("net-traversal.edges");
    // Create a BFS objec
    BFS<> bfs(net);
    // We collect nodes during traversal
    Collector<> col;
    // We start traversal at node 1
    bfs.traverse(net->getID("1"), col);
    // Retrieve the set of visited nodes
    auto visited = col.getVisited();
    // Print visited nodes
    std::cout << "Visited nodes:" << std::endl;
    while (!visited.empty()) {
        auto i = visited.front();
        visited.pop();
        std::cout << net->getLabel(i) << std::endl;
    }
    return 0;
}
```

 This code is available in: `tutorials/code/graphalg/traversal/bfs`

 BFS and DFS are class templates with two template parameters: the network (with default value `UNetwork<>`) and the node processor (with default value `Collector`). In this example, `BFS` is instantiated with the default parameters.

2. Compile your code:

```
$ mpiCC bfs.cpp -o bfs -fopenmp -lLinkPred
```

 Check Tutorial 1.2 if you face any compilation issues.

3. Run your code:

```
$ ./bfs
```

The following is the output of this program:

```
Visited nodes:
1
2
3
4
```

8  
5  
6  
7

### 4.1.2 Tutorial: Traverse a network in DFS

This tutorial shows how to traverse a network in DFS (Depth-First Search). For more information on graph algorithms available in LinkPred, consult Chapter 4 of the user guide.

1. In a file name `dfs.cpp` write the following code:

```
#include <linkpred.hpp>
#include <iostream>
using namespace LinkPred;
int main() {
    // Read network from file
    auto net = UNetwork<>::read("net-traversal.edges");
    // Create a DFS objec
    DFS<UNetwork<>, Counter<>> dfs(net);
    // We count nodes during traversal
    Counter<> counter;
    // We start traversal at node 1
    dfs.traverse(net->getID("1"), counter);
    // Print the number of visited nodes
    std::cout << "DFS visited " << counter.getCount() << "
        nodes" << std::endl;
    return 0;
}
```

**R** This code is available in: `tutorials/code/graphalg/traversal/dfs`

**R** `BFS` and `DFS` are class templates with two template parameters: the network (with default value `UNetwork<>`) and the node processor (with default value `Collector`). In this example, `DFS` is instantiated with `Counter` as the node processor instead of the default.

2. Compile your code:

```
$ mpiCC dfs.cpp -o dfs -fopenmp -lLinkPred
```

**R** Check Tutorial 1.2 if you face any compilation issues.

3. Run your code:

```
$ ./dfs
```

The following is the output of this program:

```
DFS visited 8 nodes
```

## 4.2 Shortest paths

This section shows how to use LinkPred classes to solve the shortest path problems. The class `Dijkstra` allows to find shortest paths between two nodes and compute shot-path distances from one node to all other nodes. The class `ESPDistCalculator` (exact shortest path distance calculator), which inherits from the abstract class facilitates memory management when computing shortest paths, a task that is crucial when dealing with very large networks. This section contains tutorials explaining the basic use scenarios of these classes. More details are presented in Section 4.2 of the user guide.

### 4.2.1 Tutorial: Finding the shortest path between two nodes

This tutorial shows how to find the shortest path between two nodes using the class `Dijkstra`. For more information on shortest path algorithms available in LinkPred, consult Section 4.2 of the user guide.

1. In a file name `dijkstra-two-nodes.cpp` write the following code:

```
#include <linkpred.hpp>
#include <iostream>
using namespace LinkPred;
int main() {
    // Read network from file
    auto net = UNetwork<>::read("net-sp.edges");
    // Create an edge length (weight) map
    auto length = net->template createEdgeMapSP<double>();
    // Assign a length to every edge
    int i = 1;
    for (auto it = net->edgesBegin(); it != net->edgesEnd(); ++
        it, i++) {
        (*length)[*it] = (13 * i) % 3 + 1;
    }
    // Create a Dijkstra object
    Dijkstra<> dijkstra(net);
    // Register length map
    auto lengthMapId = dijkstra.registerLengthMap(length);
    // Find shortest path between node 1 and 6
    auto res = dijkstra.getShortestPath(net->getID("1"), net->
        getID("6"), lengthMapId);
    // Print path and distance
    auto path = res.first;
    auto dist = res.second;
    std::cout << "Path:␣";
    for (auto it = path->begin(); it != path->end(); ++it) {
        std::cout << net->getLabel(*it) << "␣";
    }
    std::cout << "\nDistance:␣" << dist << std::endl;
    return 0;
}
```

 This code is available in: `tutorials/code/graphalg/sp/dijkstra-two-nodes`

2. Compile your code:

```
$ mpiCC dijkstra-two-nodes.cpp -o dijkstra-two-nodes -fopenmp
-lLinkPred
```

 Check Tutorial 1.2 if you face any compilation issues.

3. Run your code:

```
$ ./dijkstra-two-nodes
```

The following is the output of this program:

```
Path: 1 2 4 6
Distance: 5
```

### 4.2.2 Tutorial: Computing the distance from one node to all nodes

This tutorial shows how to find the distance from one node to all other nodes using the class `Dijkstra`. For more information on shortest path algorithms available in LinkPred, consult Section 4.2 of the user guide.

1. In a file name `dijkstra-one-to-all.cpp` write the following code:

```
#include <linkpred.hpp>
#include <iostream>
using namespace LinkPred;
int main() {
    // Read network from file
    auto net = UNetwork<>::read("net-sp.edges");
    // Create an edge length (weight) map
    auto length = net->template createEdgeMapSP<double>();
    // Assign a length to every edge
    int i = 1;
    for (auto it = net->edgesBegin(); it != net->edgesEnd(); ++
        it, i++) {
        (*length)[*it] = (13 * i) % 3 + 1;
    }
    // Create a Dijkstra object
    Dijkstra<> dijkstra(net);
    // Register length map
    auto lengthMapId = dijkstra.registerLengthMap(length);
    // Compute the distance from node 1 to all other nodes
    auto distMap = dijkstra.getDist(net->getID("1"),
        lengthMapId);
    // Print distances
    std::cout << "Target\tDist\tNumber_of_nodes_in_the_path" <<
        std::endl;
    for (auto it = net->nodesBegin(); it != net->nodesEnd(); ++
        it) {
        auto res = distMap->at(it->first);
        std::cout << it->second << "\t" << res.first << "\t" <<
            res.second << std::endl;
    }
    return 0;
}
```

 This code is available in: `tutorials/code/graphalg/sp/dijkstra-one-to-all`

2. Compile your code:

```
$ mpiCC dijkstra-one-to-all.cpp -o dijkstra-one-to-all -
    fopenmp -lLinkPred
```

 Check Tutorial 1.2 if you face any compilation issues.

3. Run your code:

```
$ ./dijkstra-one-to-all
```

The following is the output of this program:

Target	Dist	Number of nodes in the path
1	0	0
2	2	1
3	3	1
4	4	2
5	4	2
6	5	3
7	inf	18446744073709551615
8	inf	18446744073709551615

### 4.2.3 Tutorial: Memory management when computing distances

This tutorial shows how to use the class `ESPDistCalculator` (exact shortest path distance calculator), to facilitates memory management when using the class `Dijkstra`. For more information on shortest path algorithms available in LinkPred, consult Section 4.2 of the user guide.

1. In a file name `netdistcalc.cpp` write the following code:

```
#include <linkpred.hpp>
#include <iostream>
using namespace LinkPred;
int main() {
    // Read network from file
    auto net = UNetwork<>::read("net-sp.edges");
    // Create an edge length (weight) map
    auto length = net->template createEdgeMapSP<double>();
    // Assign a length to every edge
    int i = 1;
    for (auto it = net->edgesBegin(); it != net->edgesEnd(); ++
         it, i++) {
        (*length)[*it] = (13 * i) % 3 + 1;
    }
    // Create a Dijkstra object
    Dijkstra<> dijkstra(net);
    // Create a distance calculator. Here, we pass the option
    // NetworkCache, that is we cache all distances
    ESPDistCalculator<> calc(dijkstra, length, NetworkCache);
    // Print all distances
    std::cout << "i\tj\tDist" << std::endl;
    for (unsigned int i = 0; i < net->getNbNodes(); i++) {
        for (unsigned int j = 0; j < i; j++) {
            std::cout << net->getLabel(i) << "\t" << net->getLabel(
                j) << "\t" << calc.getDist(i, j).first << std::endl;
        }
    }
    return 0;
}
```

 This code is available in: `tutorials/code/graphalg/sp/netdistcalc`

2. Compile your code:

```
$ mpiCC netdistcalc.cpp -o netdistcalc -fopenmp -lLinkPred
```

 Check Tutorial 1.2 if you face any compilation issues.

3. Run your code:

```
$ ./netdistcalc
```

The following is the output of this program:

```
i      j      Dist
2      1      2
3      1      3
3      2      1
```

4	1	4
4	2	2
4	3	3
5	1	4
5	2	2
5	3	1
5	4	2
6	1	5
6	2	3
6	3	2
6	4	3
6	5	1
7	1	inf
7	2	inf
7	3	inf
7	4	inf
7	5	inf
7	6	inf
8	1	inf
8	2	inf
8	3	inf
8	4	inf
8	5	inf
8	6	inf
8	7	2

### 4.3 Network embedding

This section demonstrates the use of some of the graph embedding methods available in LinkPred. For more details, consult Section 4.3 of the user guide.

### 4.3.1 Tutorial: Embed a network using the HMSM encoder

This tutorial shows how to embed a network using the HMSM (Hidden Metric Space Model) encoder. For more information on graph embedding methods available in LinkPred, consult Section 4.3 of the user guide.

1. In a file name `hmsm.cpp` write the following code:

```
#include <linkpred.hpp>
#include <iostream>
using namespace LinkPred;
int main() {
    long int seed = 777;
    // Read network from file
    auto net = UNetwork<>::read("Zakarays_Karate_Club.edges");
    // Create a HMSM encoder
    HMSM<> encoder(net, seed);
    // Set encoding dimension
    encoder.setDim(3);
    // Initialize the encoder
    encoder.init();
    // Embed the network
    encoder.encode();
    // Print node codes
    for (std::size_t i = 0; i < net->getNbNodes(); i++) {
        auto v = encoder.getNodeCode(i);
        std::cout << net->getLabel(i) << "\t";
        for (int k = 0; k < v.size(); k++) {
            std::cout << std::fixed << std::setprecision(4) << v[k]
                << "\t";
        }
        std::cout << std::endl;
    }
    return 0;
}
```

 This code is available in: `tutorials/code/graphalg/encoder/hmsm`

2. Compile your code:

```
$ mpiCC hmsm.cpp -o hmsm -fopenmp -lLinkPred
```

 Check Tutorial 1.2 if you face any compilation issues.

3. Run your code:

```
$ ./hmsm
```

The following is a partial output of this program:

```
1      16.0000  9.5499  -8.1565
2       9.0000 19.0151 -7.9892
3     10.0000 20.9290 -7.7570
4       6.0000 19.9847 -8.3575
5       3.0000  0.3878 -13.0939
6       4.0000 -3.1152 -15.7564
7       4.0000 -3.1436 -16.0556
8       4.0000 19.4511 -8.8470
```

---

9	5.0000	-19.0161	-2.7566
11	3.0000	0.2081	-13.0402
...			

### 4.3.2 Tutorial: Embed a network using the LINE encoder

This tutorial shows how to embed a network using the LINE encoder. For more information on graph embedding methods available in LinkPred, consult Section 4.3 of the user guide.

1. In a file name `line.cpp` write the following code:

```
#include <linkpred.hpp>
#include <iostream>
using namespace LinkPred;
int main() {
    long int seed = 777;
    // Read network from file
    auto net = UNetwork<>::read("Zakarays_Karate_Club.edges");
    // Create a LINE encoder
    LINE<> encoder(net, seed);
    // Set encoding dimension
    encoder.setDim(3);
    // Initialize the encoder
    encoder.init();
    // Embed the network
    encoder.encode();
    // Print node codes
    for (std::size_t i = 0; i < net->getNbNodes(); i++) {
        auto v = encoder.getNodeCode(i);
        std::cout << net->getLabel(i) << "\t";
        for (int k = 0; k < v.size(); k++) {
            std::cout << std::fixed << std::setprecision(4) << v[k]
                << "\t";
        }
        std::cout << std::endl;
    }
    return 0;
}
```

 This code is available in: `tutorials/code/graphalg/encoder/line`

2. Compile your code:

```
$ mpiCC line.cpp -o line -fopenmp -lLinkPred
```

 Check Tutorial 1.2 if you face any compilation issues.

3. Run your code:

```
$ ./line
```

The following is a partial output of this program:

```
1      -0.1389 0.0465 0.0879
2      -0.1594 -0.0152 0.0996
3       0.0456 0.1431 -0.1103
4       0.0607 0.1393 -0.1405
5       0.0962 -0.1040 -0.0480
6      -0.0421 -0.0347 -0.0358
7      -0.0409 0.1416 -0.0189
8      -0.0325 0.0381 -0.0339
```

---

```
9      -0.0325 -0.1009 0.0468
11     -0.1361 0.0734 0.0281
... 
```

### 4.3.3 Tutorial: Embed a network using the Node2Vec encoder

This tutorial shows how to embed a network using the Node2Vec encoder. For more information on graph embedding methods available in LinkPred, consult Section 4.3 of the user guide.

1. In a file name `node2vec.cpp` write the following code:

```
#include <linkpred.hpp>
#include <iostream>
using namespace LinkPred;
int main() {
    long int seed = 777;
    // Read network from file
    auto net = UNetwork<>::read("Zakarays_Karate_Club.edges");
    // Create a Node2Vec encoder
    Node2Vec<> encoder(net, seed);
    // Set encoding dimension
    encoder.setDim(3);
    // Initialize the encoder
    encoder.init();
    // Embed the network
    encoder.encode();
    // Print node codes
    for (std::size_t i = 0; i < net->getNbNodes(); i++) {
        auto v = encoder.getNodeCode(i);
        std::cout << net->getLabel(i) << "\t";
        for (int k = 0; k < v.size(); k++) {
            std::cout << std::fixed << std::setprecision(4) << v[k]
                << "\t";
        }
        std::cout << std::endl;
    }
    return 0;
}
```

 This code is available in: `tutorials/code/graphalg/encoder/node2vec`

2. Compile your code:

```
$ mpiCC node2vec.cpp -o node2vec -fopenmp -lLinkPred
```

 Check Tutorial 1.2 if you face any compilation issues.

3. Run your code:

```
$ ./node2vec
```

The following is a partial output of this program:

```
1      -1.2866 0.8575  -0.0964
2      -1.6074 -0.1674  0.0551
3      -1.1292 -0.1409 -0.3301
4      -1.3907 0.3220  0.0459
5      -1.2650 1.7383  -0.3889
6      -1.5062 1.7597  -0.4098
7      -1.3218 2.0357  -0.3095
8      -1.2982 0.1699  -0.0778
```

```
9      -1.1241 -0.2370 -0.4324
11     -1.4957 1.8402 -0.2160
...
```



## 5. Predictors

This chapter contains tutorials on how to use the link prediction algorithms available in LinkPred.

## 5.1 Link prediction algorithms in undirected networks

This section describes how to use link prediction algorithms in undirected networks.

### 5.1.1 Tutorial: Computing all scores

This tutorial shows how to compute the scores of all non-existing edges in a network. For more information on link predictors in LinkPred, consult Chapter 5 of the user guide.

1. In a file name `pred-all.cpp` write the following code:

```
#include <linkpred.hpp>
#include <iostream>
using namespace LinkPred;
int main() {
    // Read network from file
    auto net = DNetwork<>::read("Zakarays_Karate_Club.edges");
    // Create an instance of the directed ADA predictor
    DADAPredictor<> p(net);
    // Initialize predictor
    p.init();
    // Train predictor
    p.learn();
    // Allocate memory for storing scores
    std::vector<double> scores(net->getNbNonEdges());
    // Predict the score of all non-existing edges
    auto its = p.predictNeg(scores.begin());
    // Print scores
    std::cout << "#Start\tEnd\tScore\n";
    int k = 0;
    for (auto it = its.first; it != its.second; ++it) {
        auto i = net->start(*it);
        auto j = net->end(*it);
        std::cout << net->getLabel(i) << "\t" << net->getLabel(j)
            << "\t" << scores[k++] << std::endl;
    }
    return 0;
}
```

 This code is available in: `tutorials/code/predictors/dnetwork/predAll`

2. Compile your code:

```
$ mpiCC predAll.cpp -o predAll -fopenmp -lLinkPred
```

 Check Tutorial 1.2 if you face any compilation issues.

3. Run your code:

```
$ ./predAll
```

The first few lines of this programs' output are as follows:

```
#Start  End    Score
1      31     0.780271
1      10     0.333808
1      28     0.333808
1      29     0.736238
1      33     1.17053
1      17     0.961797
1      34     1.82913
```

1	15	0
1	16	0
...		

### 5.1.2 Tutorial: Computing scores of specific edges

This tutorial shows how to compute the scores of specific edges in a network. For more information on link predictors in LinkPred, consult Chapter 5 of the user guide.

There are two ways to predict the scores of specific edges: using the method `score`, which computes the score of a single edges, and the method `predict`, which computes the score for a range of edges. This tutorials give an example to each of these methods.

1. In a file name `pred-score.cpp` write the following code:

```
#include <linkpred.hpp>
#include <iostream>
using namespace LinkPred;
int main() {
    // Read network from file
    auto net = UNetwork<>::read("Zakarays_Karate_Club.edges");
    // Create an instance of the KAB predictor
    UKABPredictor<> p(net);
    // Initialize predictor
    p.init();
    // Train predictor
    p.learn();
    // Compute the score for the two edges (1, 34) and (26,34)
    double sc = p.score(net->makeEdge(net->getID("1"), net->
        getID("34")));
    std::cout << "1\t34\t" << sc << std::endl;
    sc = p.score(net->makeEdge(net->getID("26"), net->getID("34
        ")));
    std::cout << "26\t34\t" << sc << std::endl;
    return 0;
}
```

 This code is available in: `tutorials/code/predictors/unetwork/pred`

 For performance reasons, the edges to be predicted are passed using the nodes' IDs and not their labels.

2. Compile your code:

```
$ mpiCC pred-score.cpp -o pred-score -fopenmp -lLinkPred
```

 Check Tutorial 1.2 if you face any compilation issues.

3. Run your code:

```
$ ./pred-score
```

The output of this program is as follows:

```
1      34      0.54199
26     34      0.468782
```

4. In a file name `pred-predict.cpp` write the following code:

```
#include <linkpred.hpp>
#include <iostream>
using namespace LinkPred;
```

```

int main() {
    // Read network from file
    auto net = UNetwork<>::read("Zakarays_Karate_Club.edges");
    // Create an instance of the KAB predictor
    UKABPredictor<> p(net);
    // Initialize predictor
    p.init();
    // Train predictor
    p.learn();
    // Create a vector to store edges
    std::vector<typename UNetwork<>::Edge> ev;
    // Push the two edges (1, 34) and (26, 34)
    ev.push_back(net->makeEdge(net->getID("1"), net->getID("34"
    )));
    ev.push_back(net->makeEdge(net->getID("26"), net->getID("34"
    )));
    // Allocate memory for storing scores
    std::vector<double> scores(2);
    // Predict the scores
    p.predict(ev.begin(), ev.end(), scores.begin());
    // Print scores
    std::cout << "#Start\tEnd\tScore\n";
    int k = 0;
    for (auto it = ev.begin(); it != ev.end(); ++it) {
        auto i = net->start(*it);
        auto j = net->end(*it);
        std::cout << net->getLabel(i) << "\t" << net->getLabel(j)
            << "\t" << scores[k++] << std::endl;
    }

    return 0;
}

```

 This code is available in: `tutorials/code/predictors/unetwork/pred`

##### 5. Compile your code:

```
$ mpiCC pred-predict.cpp -o pred-predict -fopenmp -lLinkPred
```

##### 6. Run your code:

```
$ ./pred-predict
```

The output of this program is as follows:

#Start	End	Score
1	34	0.54199
26	34	0.468782

### 5.1.3 Tutorial: Computing top scores

This tutorial shows how to compute the top edge scores. For more information on link predictors in LinkPred, consult Chapter 5 of the user guide.

1. In a file name `predTop.cpp` write the following code:

```
#include <linkpred.hpp>
#include <iostream>
using namespace LinkPred;
int main() {
    int k = 10; // Find top 10
    // Read network from file
    auto net = UNetwork<>::read("Zakarays_Karate_Club.edges");
    // Create an instance of the KAB predictor
    UKABPredictor<> p(net);
    // Initialize predictor
    p.init();
    // Train predictor
    p.learn();
    // Allocate memory for storing scores
    std::vector<double> scores(k);
    // Create a vector to store edges
    std::vector<typename UNetwork<>::Edge> ev(k);
    // Predict top scores
    k = p.top(k, ev.begin(), scores.begin());
    for (int l = 0; l < k; l++) {
        auto i = net->start(ev[l]);
        auto j = net->end(ev[l]);
        std::cout << net->getLabel(i) << "\t" << net->getLabel(j)
                  << "\t" << scores[l] << std::endl;
    }
    return 0;
}
```

 This code is available in: `tutorials/code/predictors/unetwork/predTop`

2. Compile your code:

```
$ mpiCC predTop.cpp -o predTop -fopenmp -lLinkPred
```

 Check Tutorial 1.2 if you face any compilation issues.

3. Run your code:

```
$ ./predTop
```

The output of this program is as follows:

```
1      33      0.495478
1      17      0.540224
1      34      0.54199
2      34      0.505588
3      34      0.589745
5       6      0.465234
7      11      0.465234
34     26      0.468782
```

---

34	25	0.483836
24	25	0.454449

### 5.1.4 Tutorial: Encoder-classifier prediction

This tutorial shows how to predict links using an encoder-classifier predictor. For more information on link predictors in LinkPred, consult Chapter 5 of the user guide.

1. In a file named `ec1.cpp` write the following code:

```
#include <linkpred.hpp>
#include <iostream>
using namespace LinkPred;
int main() {
    int k = 10;
    // Read network from file
    auto net = UNetwork<>::read("Zakarays_Karate_Club.edges");
    // Create a N2V encoder
    auto encoder = std::make_shared<Node2Vec<>>(net, 777);
    // Create a logistic regresser
    auto classifier = std::make_shared<LogisticRegressor
        <>>(0.001, 888);
    // Create an instance of the ECL predictor
    UECLPredictor<> p(net, encoder, classifier, 999);
    // Initialize predictor
    p.init();
    // Train predictor
    p.learn();
    // Allocate memory for storing scores
    std::vector<double> scores(k);
    // Create a vector to store edges
    std::vector<typename UNetwork<>::Edge> ev(k);
    // Predict top scores
    k = p.top(k, ev.begin(), scores.begin());
    for (int l = 0; l < k; l++) {
        auto i = net->start(ev[l]);
        auto j = net->end(ev[l]);
        std::cout << net->getLabel(i) << "\t" << net->getLabel(j)
            << "\t" << scores[l] << std::endl;
    }
    return 0;
}
```

 This code is available in: `tutorials/code/predictors/unetwork/ec1`

 For the names of available encoders and classifiers, consult the library reference manual.

2. Compile your code:

```
$ mpiCC ec1.cpp -o ec1 -fopenmp -lLinkPred
```

 Check Tutorial 1.2 if you face any compilation issues.

3. Run your code:

```
$ ./ec1
```

The output of this program is as follows:

1	10	0.506023
1	34	0.741211
2	5	0.521754
3	5	0.561345
3	13	0.501856
32	31	0.527168
32	10	0.616398
33	17	0.710924
34	26	0.584236
34	25	0.607985

### 5.1.5 Tutorial: Encoder-similarity prediction

This tutorial shows how to predict links using an encoder-similarity predictor. For more information on link predictors in LinkPred, consult Chapter 5 of the user guide.

1. In a file name `esm.cpp` write the following code:

```
#include <linkpred.hpp>
#include <iostream>
using namespace LinkPred;
int main() {
    int k = 10;
    // Read network from file
    auto net = UNetwork<>::read("Zakarays_Karate_Club.edges");
    // Create a LIN encoder
    auto encoder = std::make_shared<LINE<>>(net, 777);
    // Create an L2 similarity object
    auto simMeasure = std::make_shared<L2Sim>();
    // Create an instance of the ESM predictor
    UESMPredictor<> p(net, encoder, simMeasure);
    // Initialize predictor
    p.init();
    // Train predictor
    p.learn();
    // Allocate memory for storing scores
    std::vector<double> scores(k);
    // Create a vector to store edges
    std::vector<typename UNetwork<>::Edge> ev(k);
    // Predict top scores
    k = p.top(k, ev.begin(), scores.begin());
    for (int l = 0; l < k; l++) {
        auto i = net->start(ev[l]);
        auto j = net->end(ev[l]);
        std::cout << net->getLabel(i) << "\t" << net->getLabel(j)
            << "\t" << scores[l] << std::endl;
    }
    return 0;
}
```

 This code is available in: `tutorials/code/predictors/unetwork/esm`

 For the names of available encoders and similarity measures, consult the library reference manual.

2. Compile your code:

```
$ mpiCC esm.cpp -o esm -fopenmp -lLinkPred
```

 Check Tutorial 1.2 if you face any compilation issues.

3. Run your code:

```
$ ./esm
```

The output of this program is as follows:

1	23	-0.0658803
4	19	-0.0623656
5	6	-0.0687798
6	29	-0.0682746
6	30	-0.0713388
11	31	-0.0725597
12	28	-0.0607567
12	16	-0.0715096
28	23	-0.0699596
29	30	-0.051615

## 5.2 Link prediction algorithms in directed networks

This section describes how to use link prediction algorithms in directed networks.

### 5.2.1 Tutorial: Computing all scores

This tutorial shows how to compute the scores of all non-existing edges in a network. For more information on link predictors in LinkPred, consult Chapter 5 of the user guide.

1. In a file name `pred-all.cpp` write the following code:

```
#include <linkpred.hpp>
#include <iostream>
using namespace LinkPred;
int main() {
    // Read network from file
    auto net = UNetwork<>::read("Zakarays_Karate_Club.edges");
    // Create an instance of the KAB predictor
    UKABPredictor<> p(net);
    // Initialize predictor
    p.init();
    // Train predictor
    p.learn();
    // Allocate memory for storing scores
    std::vector<double> scores(net->getNbNonEdges());
    // Predict the score of all non-existing edges
    auto its = p.predictNeg(scores.begin());
    // Print scores
    std::cout << "#Start\tEnd\tScore\n";
    int k = 0;
    for (auto it = its.first; it != its.second; ++it) {
        auto i = net->start(*it);
        auto j = net->end(*it);
        std::cout << net->getLabel(i) << "\t" << net->getLabel(j)
            << "\t" << scores[k++] << std::endl;
    }
    return 0;
}
```

 This code is available in: `tutorials/code/predictors/unetwork/predAll`

2. Compile your code:

```
$ mpiCC predAll.cpp -o predAll -fopenmp -lLinkPred
```

 Check Tutorial 1.2 if you face any compilation issues.

3. Run your code:

```
$ ./predAll
```

The first few lines of this programs' output are as follows:

```
#Start  End    Score
1      31     0.392467
1      10     0.268335
1      28     0.280569
1      29     0.358308
1      33     0.495478
1      17     0.540224
1      34     0.54199
```

1	15	0
1	16	0
...		

### 5.2.2 Tutorial: Computing scores of specific edges

This tutorial shows how to compute the scores of specific edges in a network. For more information on link predictors in LinkPred, consult Chapter 5 of the user guide.

There are two ways to predict the scores of specific edges: using the method `score`, which computes the score of a single edges, and the method `predict`, which computes the score for a range of edges. This tutorials give an example to each of these methods.

1. In a file name `pred-score.cpp` write the following code:

```
#include <linkpred.hpp>
#include <iostream>
using namespace LinkPred;
int main() {
    // Read network from file
    auto net = DNetwork<>::read("Zakarays_Karate_Club.edges");
    // Create an instance of the directed ADA predictor
    DADAPredictor<> p(net);
    // Initialize predictor
    p.init();
    // Train predictor
    p.learn();
    // Compute the score for the two edges (1, 34) and (26,34)
    double sc = p.score(net->makeEdge(net->getID("1"), net->
        getID("34")));
    std::cout << "1\t34\t" << sc << std::endl;
    sc = p.score(net->makeEdge(net->getID("26"), net->getID("34
        ")));
    std::cout << "26\t34\t" << sc << std::endl;
    return 0;
}
```

 This code is available in: `tutorials/code/predictors/dnetwork/pred`

 For performance reasons, the edges to be predicted are passed using the nodes' IDs and not their labels.

2. Compile your code:

```
$ mpiCC pred-score.cpp -o pred-score -fopenmp -lLinkPred
```

 Check Tutorial 1.2 if you face any compilation issues.

3. Run your code:

```
$ ./pred-score
```

The output of this program is as follows:

```
1      34      1.82913
26     34      0.836724
```

4. In a file name `pred-predict.cpp` write the following code:

```
#include <linkpred.hpp>
#include <iostream>
using namespace LinkPred;
```

```

int main() {
    // Read network from file
    auto net = DNetwork<>::read("Zakarays_Karate_Club.edges");
    // Create an instance of the directed CNE predictor
    DCNEPredictor<> p(net);
    // Initialize predictor
    p.init();
    // Train predictor
    p.learn();
    // Create a vector to store edges
    std::vector<typename UNetwork<>::Edge> ev;
    // Push the two edges (1, 34) and (26, 34)
    ev.push_back(net->makeEdge(net->getID("1"), net->getID("34"
    )));
    ev.push_back(net->makeEdge(net->getID("26"), net->getID("34"
    )));
    // Allocate memory for storing scores
    std::vector<double> scores(2);
    // Predict the scores
    p.predict(ev.begin(), ev.end(), scores.begin());
    // Print scores
    std::cout << "#Start\tEnd\tScore\n";
    int k = 0;
    for (auto it = ev.begin(); it != ev.end(); ++it) {
        auto i = net->start(*it);
        auto j = net->end(*it);
        std::cout << net->getLabel(i) << "\t" << net->getLabel(j)
            << "\t" << scores[k++] << std::endl;
    }

    return 0;
}

```

 This code is available in: tutorials/code/predictors/dnetwork/pred

#### 5. Compile your code:

```
$ mpiCC pred-predict.cpp -o pred-predict -fopenmp -lLinkPred
```

#### 6. Run your code:

```
$ ./pred-predict
```

The output of this program is as follows:

```

#Start  End    Score
1      34     4
26     34     2

```

### 5.2.3 Tutorial: Computing top scores

This tutorial shows how to compute the top edge scores. For more information on link predictors in LinkPred, consult Chapter 5 of the user guide.

1. In a file name `predTop.cpp` write the following code:

```
#include <linkpred.hpp>
#include <iostream>
using namespace LinkPred;
int main() {
    int k = 10; // Find top 10
    // Read network from file
    auto net = DNetwork<>::read("Zakarays_Karate_Club.edges");
    // Create an instance of the directed CNE predictor
    DCNEPredictor<> p(net);
    // Initialize predictor
    p.init();
    // Train predictor
    p.learn();
    // Allocate memory for storing scores
    std::vector<double> scores(k);
    // Create a vector to store edges
    std::vector<typename UNetwork<>::Edge> ev(k);
    // Predict top scores
    k = p.top(k, ev.begin(), scores.begin());
    for (int l = 0; l < k; l++) {
        auto i = net->start(ev[l]);
        auto j = net->end(ev[l]);
        std::cout << net->getLabel(i) << "\t" << net->getLabel(j)
                  << "\t" << scores[l] << std::endl;
    }
    return 0;
}
```

 This code is available in: `tutorials/code/predictors/dnetwork/predTop`

2. Compile your code:

```
$ mpiCC predTop.cpp -o predTop -fopenmp -lLinkPred
```

 Check Tutorial 1.2 if you face any compilation issues.

3. Run your code:

```
$ ./predTop
```

The output of this program is as follows:

```
1      1      16
2      2       9
3      3      10
3     34       6
4      4       6
32     32       6
33     33      12
34     3       6
```

---

34	34	16
24	24	5





## 6. Performance Evaluation

This chapter covers the topic of test data setup and performance evaluation.

## 6.1 Data setup

This section describes the data setup process for performance evaluation, including, creating test data by removing and adding edges, and loading test data from file.

- Ⓡ LinkPred provides various methods to generate test data that offer flexibility and fit different use scenario, in particular with very large networks. This sections contains basic use scenarios, for more advanced options, the readers is invited to consult the user guide and reference manual.

### 6.1.1 Tutorial: Creating test data by removing edges

This tutorial shows how to create test data by removing edges from a ground-truth network. For more information on performance evaluation routines in LinkPred and the associated terminology, consult Chapter 6 of the user guide.

1. In a file named `create-rem.cpp` write the following code:

```
#include <linkpred.hpp>
#include <iostream>
using namespace LinkPred;
int main() {
    // Remove 20% of the edges
    double remRatio = 0.2;
    long int seed = 777;
    // Read network from file
    auto net = UNetwork<>::read("net.edges");
    // Create the test data
    auto testData = NetworkManipulator<>::createTestDataRem(net
        , remRatio, seed);
    std::cout << "Reference_network:\n";
    testData.getRefNet()->print();
    std::cout << "Observed_network:\n";
    testData.getObsNet()->print();
    std::cout << "Positive_examples_(removed_edges):" << std::
        endl;
    for (auto it = testData.posBegin(); it != testData.posEnd()
        ; ++it) {
        auto i = net->start(*it);
        auto j = net->end(*it);
        std::cout << net->getLabel(i) << "\t" << net->getLabel(j)
            << std::endl;
    }
    std::cout << "Negative_examples:" << std::endl;
    for (auto it = testData.negBegin(); it != testData.negEnd()
        ; ++it) {
        auto i = net->start(*it);
        auto j = net->end(*it);
        std::cout << net->getLabel(i) << "\t" << net->getLabel(j)
            << std::endl;
    }
    return 0;
}
```

 This code is available in: `tutorials/code/performance/data-setup/create-rem`

The input reference network contained in `net.edges` is:

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

```
1      3
3      5
5      7
7      1
```

## 2. Compile your code:

```
$ mpiCC create-rem.cpp -o create-rem -fopenmp -lLinkPred
```

**R** Check Tutorial 1.2 if you face any compilation issues.

## 3. Run your code:

```
$ ./create-rem
```

The output of this program is as follows:

```
Reference network:
1      2
1      3
1      7
1      8
2      3
3      4
3      5
4      5
5      6
5      7
6      7
7      8
Observed network:
1      2
1      3
1      7
1      8
2      3
3      4
3      5
5      7
6      7
7      8
Positive examples (removed edges):
4      5
5      6
Negative examples:
1      4
1      5
1      6
2      4
2      5
2      6
2      7
2      8
3      6
3      7
3      8
4      6
```

---

4	7
4	8
5	8
6	8

### 6.1.2 Tutorial: Creating test data by adding edges

This tutorial shows how to create test data by adding edges to a ground-truth network. For more information on performance evaluation routines in LinkPred and the associated terminology, consult Chapter 6 of the user guide.

1. In a file named `create-add.cpp` write the following code:

```
#include <linkpred.hpp>
#include <iostream>
using namespace LinkPred;
int main() {
    // Add 20% of the edges
    double addRatio = 0.2;
    long int seed = 888;
    // Read network from file
    auto net = UNetwork<>::read("net.edges");
    // Create the test data
    auto testData = NetworkManipulator<>::createTestDataAdd(net
        , addRatio, seed);
    std::cout << "Reference_network:\n";
    testData.getRefNet()->print();
    std::cout << "Observed_network:\n";
    testData.getObsNet()->print();
    std::cout << "Positive_examples:" << std::endl;
    for (auto it = testData.posBegin(); it != testData.posEnd()
        ; ++it) {
        auto i = net->start(*it);
        auto j = net->end(*it);
        std::cout << net->getLabel(i) << "\t" << net->getLabel(j)
            << std::endl;
    }
    std::cout << "Negative_examples_(added_edges):" << std::
        endl;
    for (auto it = testData.negBegin(); it != testData.negEnd()
        ; ++it) {
        auto i = net->start(*it);
        auto j = net->end(*it);
        std::cout << net->getLabel(i) << "\t" << net->getLabel(j)
            << std::endl;
    }
    return 0;
}
```

 This code is available in: `tutorials/code/performance/data-setup/create-add`

The input reference network contained in `net.edges` is:

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

```
1    3
3    5
5    7
7    1
```

## 2. Compile your code:

```
$ mpiCC create-add.cpp -o create-add -fopenmp -lLinkPred
```

 Check Tutorial 1.2 if you face any compilation issues.

## 3. Run your code:

```
$ ./create-add
```

The output of this program is as follows:

Reference network:

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

Observed network:

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

Positive examples:

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

```
7      8
Negative examples (added edges):
1      6
2      4
```

### 6.1.3 Tutorial: Loading test data obtained by removing edges

This tutorial shows how to load from file test data obtained by removing edges from a ground-truth network. For more information on performance evaluation routines in LinkPred and the associated terminology, consult Chapter 6 of the user guide.

1. In a file named `load-rem.cpp` write the following code:

```
#include <linkpred.hpp>
#include <iostream>
using namespace LinkPred;
int main() {
    // Load test data
    auto testData = NetworkManipulator<>::loadTestDataRem("net-obs.edges", "net-rem.edges");
    std::cout << "Reference_network:\n";
    auto refNet = testData.getRefNet();
    refNet->print();
    std::cout << "Observed_network:\n";
    auto obsNet = testData.getObsNet();
    obsNet->print();
    std::cout << "Positive_examples_(removed_edges):" << std::endl;
    for (auto it = testData.posBegin(); it != testData.posEnd(); ++it) {
        auto i = refNet->start(*it);
        auto j = refNet->end(*it);
        std::cout << refNet->getLabel(i) << "\t" << refNet->getLabel(j) << std::endl;
    }
    std::cout << "Negative_examples:" << std::endl;
    for (auto it = testData.negBegin(); it != testData.negEnd(); ++it) {
        auto i = refNet->start(*it);
        auto j = refNet->end(*it);
        std::cout << refNet->getLabel(i) << "\t" << refNet->getLabel(j) << std::endl;
    }
    return 0;
}
```

 This code is available in: `tutorials/code/performance/data-setup/load-rem`

The file `net-obs.edges` contains the set of observed edges:

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

The file `net-rem.edges` contains the set of removed edges:

```
4      5
5      6
```

## 2. Compile your code:

```
$ mpiCC load-rem.cpp -o load-rem -fopenmp -lLinkPred
```

**R** Check Tutorial 1.2 if you face any compilation issues.

## 3. Run your code:

```
$ ./load-rem
```

The output of this program is as follows:

```
Reference network:
1      2
1      3
1      7
1      8
2      3
3      4
3      5
7      8
7      5
7      6
4      5
5      6
Observed network:
1      2
1      3
1      7
1      8
2      3
3      4
3      5
7      8
7      5
7      6
Positive examples (removed edges):
4      5
5      6
Negative examples:
1      4
1      5
1      6
2      7
2      8
2      4
2      5
2      6
3      7
3      8
3      6
7      4
8      4
8      5
```

---

8	6
4	6

### 6.1.4 Tutorial: Loading test data obtained by adding edges

This tutorial shows how to load from file test data obtained by adding edges to a ground-truth network. For more information on performance evaluation routines in LinkPred and the associated terminology, consult Chapter 6 of the user guide.

1. In a file named `load-add.cpp` write the following code:

```
#include <linkpred.hpp>
#include <iostream>
using namespace LinkPred;
int main() {
    // Load test data
    auto testData = NetworkManipulator<>::loadTestDataAdd("net-
        obs.edges", "net-add.edges");
    std::cout << "Reference_network:\n";
    auto refNet = testData.getRefNet();
    refNet->print();
    std::cout << "Observed_network:\n";
    auto obsNet = testData.getObsNet();
    obsNet->print();
    std::cout << "Positive_examples:" << std::endl;
    for (auto it = testData.posBegin(); it != testData.posEnd()
        ; ++it) {
        auto i = refNet->start(*it);
        auto j = refNet->end(*it);
        std::cout << refNet->getLabel(i) << "\t" << refNet->
            getLabel(j) << std::endl;
    }
    std::cout << "Negative_examples_(added_edges):" << std::
        endl;
    for (auto it = testData.negBegin(); it != testData.negEnd()
        ; ++it) {
        auto i = refNet->start(*it);
        auto j = refNet->end(*it);
        std::cout << refNet->getLabel(i) << "\t" << refNet->
            getLabel(j) << std::endl;
    }
    return 0;
}
```

 This code is available in: `tutorials/code/performance/data-setup/load-add`

The file `net-obs.edges` contains the set of observed edges:

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

```
5      7
6      7
7      8
```

The file `net-add.edges` contains the set of added edges:

```
1      6
2      4
```

## 2. Compile your code:

```
$ mpiCC load-add.cpp -o load-add -fopenmp -lLinkPred
```

 Check Tutorial 1.2 if you face any compilation issues.

## 3. Run your code:

```
$ ./load-add
```

The output of this program is as follows:

Reference network:

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

Observed network:

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

Positive examples:

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

6 5

7 8

7 5

4 5

Negative examples (added edges):

1 6

2 4

## 6.2 Performance evaluation

This section describes the classes used for performance evaluation.

### 6.2.1 Tutorial: Using performance measures

This tutorial shows how to use performance measures to evaluate the performance of a link prediction algorithm. For more information on performance evaluation routines in LinkPred and the associated terminology, consult Chapter 6 of the user guide.

1. In a file named `perfmeasures.cpp` write the following code:

```
#include <linkpred.hpp>
#include <iostream>
using namespace LinkPred;
int main() {
    // Remove 10% of the edges
    double remRatio = 0.1;
    long int seed = 888;
    // Read network from file
    auto refNet = UNetwork<>::read("Zakarays_Karate_Club.edges"
    );
    // Create the test data
    auto testData = NetworkManipulator<>::createTestDataRem(
        refNet, remRatio, seed);
    // Lock test data
    testData.lock();
    // Create an instance of the KAB predictor
    auto p = std::make_shared<UKABPredictor<>>(testData.
        getObsNet());
    // Initialize predictor
    p->init();
    // Train predictor
    p->learn();
    // Create a prediction result object
    auto predResults = std::make_shared<PredResults<>>(testData
        , p);
    // A map to store prediction results
    PerfResults res;
    // Create a ROC object
    ROC<> roc;
    // Compute ROCAUC
    roc.eval(predResults, res);
    std::cout << "ROCAUC:␣" << res.at(roc.getName()) << std::
        endl;
    // Create a PR object
    PR<> pr;
    // Compute PRAUC
    pr.eval(predResults, res);
    std::cout << "PRAUC:␣" << res.at(pr.getName()) << std::endl
        ;
    // Create a TPR object
    TPR<> tpr(testData.getNbPos());
    // Compute TPR
    tpr.eval(predResults, res);
    std::cout << "TPR:␣" << res.at(tpr.getName()) << std::endl;
    return 0;
}
```

 This code is available in: `tutorials/code/performance/perfeval/perfmeasures`

### 2. Compile your code:

```
$ mpiCC perfmeasures.cpp -o perfmeasures -fopenmp -lLinkPred
```

 Check Tutorial 1.2 if you face any compilation issues.

### 3. Run your code:

```
$ ./perfmeasures
```

The output of this program is as follows:

```
ROCAUC: 0.712215  
PRAUC: 0.224628  
TPR: 0.25
```

### 6.2.2 Tutorial: Using the class `PerfEvaluator` for performance evaluation

This tutorial shows how to use the class `PerfEvaluator` to evaluate the performance of several link predictors based on several performance measures. For more information on performance evaluation routines in `LinkPred` and the associated terminology, consult Chapter 6 of the user guide.

1. In a file named `perfevaluator.cpp` write the following code:

```
#include <linkpred.hpp>
#include <iostream>
using namespace LinkPred;
int main() {
    // Remove 10% of the edges
    double remRatio = 0.1;
    long int seed = 888;
    // Read network from file
    auto refNet = UNetwork<>::read("Zakarays_Karate_Club.edges"
    );
    // Create the test data
    auto testData = NetworkManipulator<>::createTestDataRem(
        refNet, remRatio, seed);
    // Lock test data
    testData.lock();
    auto obsNet = testData.getObsNet();
    // Create an evaluator object
    PerfEvaluator<> perf(testData);
    // Create an ADA predictor
    auto ada = std::make_shared<UADAPredictor<>>(obsNet);
    // Add it to the evaluator
    perf.addPredictor(ada);
    // Create a CNE predictor
    auto cne = std::make_shared<UCNEPredictor<>>(obsNet);
    // Add it to the evaluator
    perf.addPredictor(cne);
    // Create a ROC object
    auto roc = std::make_shared<ROC<>>();
    // Add it to the evaluator
    perf.addPerfMeasure(roc);
    // Create a PR object
    auto pr = std::make_shared<PR<>>();
    // Add it to the evaluator
    perf.addPerfMeasure(pr);
    // Run evaluation
    perf.eval();
    // Print results
    for (auto it = perf.resultsBegin(); it != perf.resultsEnd()
        ; ++it) {
        std::cout << it->first << "\t" << it->second << std::endl
        ;
    }
    return 0;
}
```

 This code is available in: `tutorials/code/performance/perfeval/perfevaluator`

- R** This code executes one test run. To execute multiple test runs, it is possible to enclose the relevant parts in a for loop or use the class `PerfEvalExp` as described in the next tutorial.

## 2. Compile your code:

```
$ mpiCC perfevaluator.cpp -o perfevaluator -fopenmp -  
lLinkPred
```

- R** Check Tutorial 1.2 if you face any compilation issues.

## 3. Run your code:

```
$ ./perfevaluator
```

The output of this program is as follows:

```
PRADA 0.207284  
PRCNE 0.183308  
ROCAD 0.695135  
ROCCNE 0.664467
```

### 6.2.3 Tutorial: Using the class `PerfEvalExp` for performance evaluation

This tutorial shows how to use the class `PerfEvalExp` to evaluate the performance of several link predictors based on several performance measures on multiple test runs. For more information on performance evaluation routines in `LinkPred` and the associated terminology, consult Chapter 6 of the user guide.

1. In a file named `perfevalexp.cpp` write the following code:

```
#include <linkpred.hpp>
#include <iostream>
using namespace LinkPred;
// This is a factory to create predictors and performance
// measures
class Factory: public PEFactory<> {
public:
    // This method creates predictors
    virtual std::vector<std::shared_ptr<ULPredictor<>>>
        getPredictors(std::shared_ptr<UNetwork<> const> obsNet)
        {
            std::vector<std::shared_ptr<ULPredictor<>>> prs;
            // Add ADA
            prs.push_back(std::make_shared<URALPredictor<>>(obsNet));
            // Add KAB
            prs.push_back(std::make_shared<UKABPredictor<>>(obsNet));
            return prs;
        }
    // This method creates performance measures
    virtual std::vector<std::shared_ptr<PerfMeasure<>>>
        getPerfMeasures(TestData<> const & testData) {
            std::vector<std::shared_ptr<PerfMeasure<>>> pms;
            // Add PR
            pms.push_back(std::make_shared<PR<>>());
            // Add ROC
            pms.push_back(std::make_shared<ROC<>>());
            return pms;
        }
    virtual ~Factory() = default;
};
int main() {
    // Remove 10% of the edges
    double remRatio = 0.1;
    long int seed = 888;
    // Read network from file
    auto refNet = UNetwork<>::read("Zakarays_Karate_Club.edges"
        );
    // The parameters of our experiment
    PerfEvalExpDescp<> ped;
    // Set the reference network
    ped.refNet = refNet;
    // We run 10 tests
    ped.nbTestRuns = 10;
    ped.seed = 777;
    // Create the factory
    auto factory = std::make_shared<Factory>();
    // Create the experiment object
    PerfEvalExp<> exp(ped, factory);
```

```
// Run the experiment
exp.run();
return 0;
}
```

 This code is available in: `tutorials/code/performance/perfeval/perfevalexp`

## 2. Compile your code:

```
$ mpiCC perfevalexp.cpp -o perfevalexp -fopenmp -lLinkPred
```

 Check Tutorial 1.2 if you face any compilation issues.

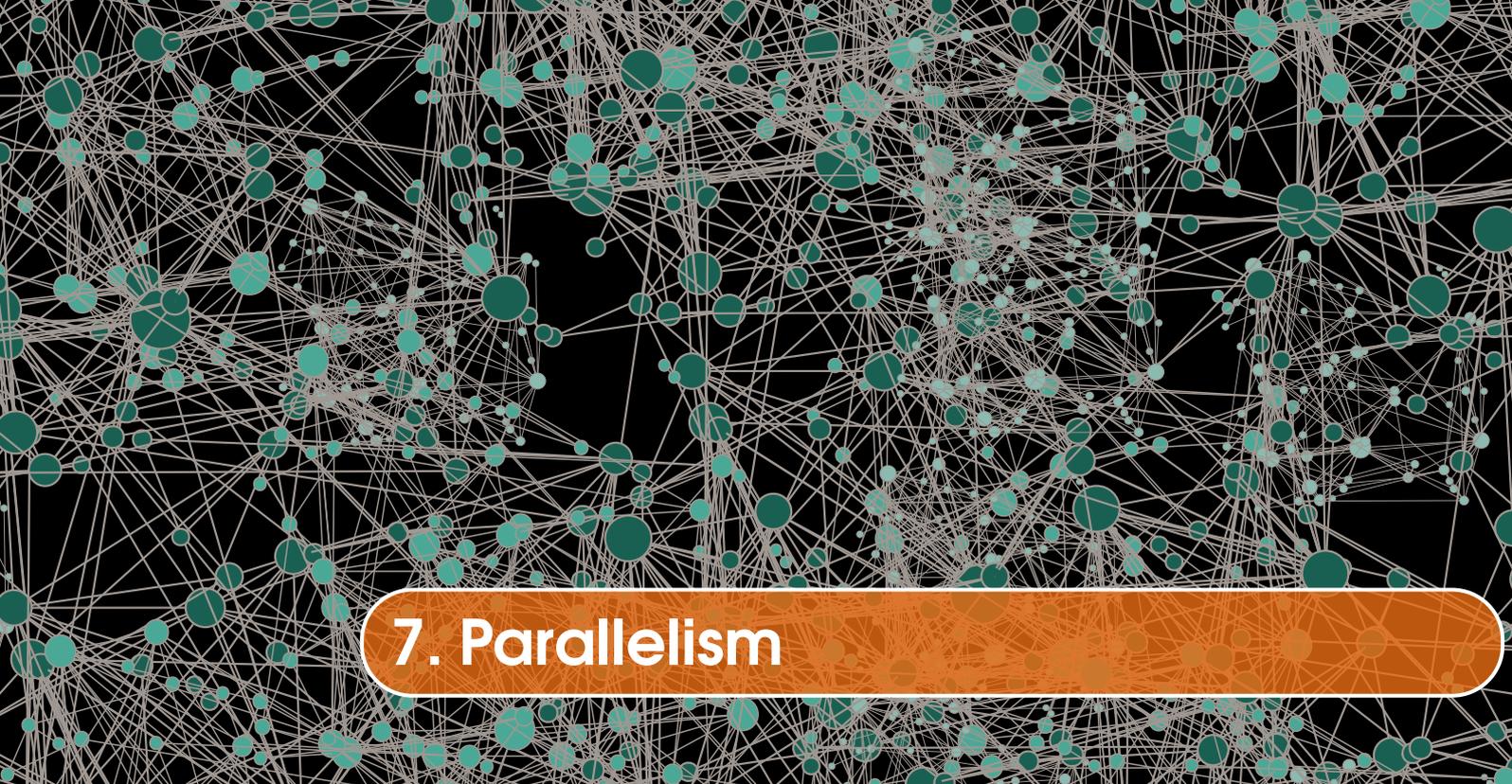
## 3. Run your code:

```
$ ./perfevalexp
```

The output of this program is as follows:

```
# n: 34 m: 78
#ratio PRKAB PRRAL ROCKAB ROCRAL
0.10 0.1159 0.0744 0.8615 0.8028
0.10 0.2231 0.1001 0.7943 0.7823
0.10 0.0398 0.0334 0.6945 0.6712
0.10 0.1787 0.1617 0.6417 0.6219
0.10 0.0196 0.0170 0.5817 0.5487
0.10 0.2072 0.1867 0.8527 0.8386
0.10 0.0198 0.0159 0.5705 0.5167
0.10 0.0901 0.0712 0.8834 0.8359
0.10 0.1207 0.0841 0.8962 0.8617
0.10 0.2244 0.1221 0.7650 0.7433
#Time: 64.3621 ms
```





## 7. Parallelism

This chapter shows how to run LinkPred algorithms on shared and distributed memory architectures. Most link prediction algorithms included in LinkPred support shared memory parallelism, and many of them (especially local predictors) also support distributed memory parallelism, which allows the library to handle very large networks.

## 7.1 Shared memory parallelism

This section shows how to run LinkPred in parallel on shared memory architectures. Shared memory parallelism in LinkPred is implemented using OpenMP. Parallelism is controlled at the object level by calling the method `setParallel`. For example, in a link predictor, this is achieved by:

```
predictor->setParallel(true);
```

The same applies for parallel measures:

```
measure->setParallel(true);
```

- R** When applicable, use the environment variable `OMP_NUM_THREADS` to control the number of threads, for instance:

```
$ export OMP_NUM_THREADS=4
```

### 7.1.1 Tutorial: Computing the score of all negative links in parallel

This tutorial shows how to compute the scores for all negative links of a network in parallel. For more information on parallelism in LinkPred, consult Chapter 7 of the user guide.

1. In a file named `cnepar.cpp` write the following code:

```
#include <linkpred.hpp>
#include <iostream>
using namespace LinkPred;
int main() {
    // Enable nested parallelism
    omp_set_nested(1);
    // Read network from file
    auto net = UNetwork<>::read("Infectious.edges");
    // Create a CNE predictor
    UCNEPredictor<> p(net);
    // Enable parallelism
    p.setParallel(true);
    // Initialize predictor
    p.init();
    // Train predictor
    p.learn();
    // Allocate memory for storing scores
    std::vector<double> scores(net->getNbNonEdges());
    // Predict the score of all non-existing edges
    auto its = p.predictNeg(scores.begin());
    // Print scores
    std::cout << "#Start\tEnd\tScore\n";
    int k = 0;
    for (auto it = its.first; it != its.second; ++it) {
        auto i = net->start(*it);
        auto j = net->end(*it);
        std::cout << net->getLabel(i) << "\t" << net->getLabel(j)
            << "\t" << scores[k++] << std::endl;
    }
    return 0;
}
```

 This code is available in: `tutorials/code/parallel/shared/cnepar`

2. Compile your code:

```
$ mpiCC cnepar.cpp -o cnepar -fopenmp -lLinkPred
```

 Check Tutorial 1.2 if you face any compilation issues.

3. Run your code:

```
$ ./cnepar
```

A partial output of this program is as follows:

```
#Start  End    Score
100    10     0
100    11     0
100    113    7
```

---

100	12	0
100	13	0
100	14	0
100	15	0
100	16	0
100	107	10
...		

### 7.1.2 Tutorial: Computing the top edge scores in parallel

This tutorial shows how to compute the top edge scores in parallel. For more information on parallelism in LinkPred, consult Chapter 7 of the user guide.

1. In a file named `kabpar.cpp` write the following code:

```
#include <linkpred.hpp>
#include <iostream>
using namespace LinkPred;
int main() {
    int k = 10; // Find top 10
    // Read network from file
    auto net = UNetwork<>::read("Infectious.edges");
    // Create an instance of the KAB predictor
    UKABPredictor<> p(net);
    // Enable parallelism
    p.setParallel(true);
    // Initialize predictor
    p.init();
    // Train predictor
    p.learn();
    // Allocate memory for storing scores
    std::vector<double> scores(k);
    // Create a vector to store edges
    std::vector<typename UNetwork<>::Edge> ev(k);
    // Predict top scores
    k = p.top(k, ev.begin(), scores.begin());
    for (int l = 0; l < k; l++) {
        auto i = net->start(ev[l]);
        auto j = net->end(ev[l]);
        std::cout << net->getLabel(i) << "\t" << net->getLabel(j)
                  << "\t" << scores[l] << std::endl;
    }
    return 0;
}
```

 This code is available in: `tutorials/code/parallel/shared/kabpar`

2. Compile your code:

```
$ mpiCC kabpar.cpp -o kabpar -fopenmp -lLinkPred
```

 Check Tutorial 1.2 if you face any compilation issues.

3. Run your code:

```
$ ./kabpar
```

A partial output of this program is as follows:

```
102    109    0.698612
109    91     0.701562
12     19     0.726582
169    178    0.702122
164    155    0.698949
154    181    0.695083
51     39     0.708767
```

---

272	309	0.704433
30	44	0.713792
389	367	0.715296

## 7.2 Distributed memory parallelism

This section shows how to run LinkPred in parallel on distributed memory architectures. Distributed memory parallelism in LinkPred is implemented using MPI and is controlled at the object level by calling the method `setDistributed`. For example, in a link predictor, this is achieved by:

```
predictor->setDistributed(true);
```

The same applies for parallel measures:

```
measure->setDistributed(true);
```

### 7.2.1 Tutorial: Computing the top edge scores distributively

This tutorial shows how to compute the scores for all negative links of a network distributively. For more information on parallelism in LinkPred, consult Chapter 7 of the user guide.

1. In a file named `raldist.cpp` write the following code:

```
#include <linkpred.hpp>
#include <iostream>
using namespace LinkPred;
int main(int argc, char*argv[]) {
    // Initialize MPI
    MPI_Init(&argc, &argv);
    std::size_t k = 10;
    // Read network from file
    auto net = UNetwork<>::read("Infectious.edges");
    // Create an RAL predictor
    URALPredictor<> p(net);
    // Enable distributed processing
    p.setDistributed(true);
    // Initialize predictor
    p.init();
    // Train predictor
    p.learn();
    // Allocate memory to store results
    std::vector<typename UNetwork<>::Edge> edges(k);
    std::vector<double> scores(k);
    // Find top k edges
    k = p.top(k, edges.begin(), scores.begin());
    int procID;
    // Get local process ID
    MPI_Comm_rank(MPI_COMM_WORLD, &procID);
    // Print the results
    if (procID == 0) {
        std::cout << "#Start\tEnd\tScore\n";
    }
    for (std::size_t i = 0; i < k; i++) {
        std::cout << net->getLabel(net->start(edges[i])) << "\t"
            << net->getLabel(net->end(edges[i])) << "\t" << scores
            [i] << std::endl;
    }
    // Finalize MPI
    MPI_Finalize();
    return 0;
}
```

 This code is available in: `tutorials/code/parallel/distributed/raldist`

2. Compile your code:

```
$ mpiCC raldist.cpp -o raldist -fopenmp -lLinkPred
```

 Check Tutorial 1.2 if you face any compilation issues.

3. Run your code (here we are running the code on 4 nodes):

```
$ mpirun -n 4 ./raldist
```

A partial output of this program is as follows:

#Start	End	Score
169	178	0.912642
144	142	0.886008
51	39	0.985052
265	297	0.811915
300	295	0.806431
197	237	0.836456
257	299	0.864928
257	294	0.887479
261	292	0.973033
389	367	0.965622

## 7.2.2 Tutorial: Computing the area under the ROC curve distributively

This tutorial shows how to compute the area under the ROC curve distributively. For more information on parallelism in LinkPred, consult Chapter 7 of the user guide.

1. In a file named `rocstrmdist.cpp` write the following code:

```
#include <linkpred.hpp>
#include <iostream>
using namespace LinkPred;
int main(int argc, char*argv[]) {
    double remRatio = 0.1;
    long int seed = 777;
    // Initialize MPI
    MPI_Init(&argc, &argv);
    int procID = 0;
    // Get local process ID
    MPI_Comm_rank(MPI_COMM_WORLD, &procID);
    // Read network from file
    auto net = UNetwork<>::read("Infectious.edges");
    // Create the test data
    auto testData = NetworkManipulator<>::createTestDataRem(net
        , remRatio, seed, false);
    testData.lock();
    // Create an ADA predictor
    auto p = std::make_shared<UADAPredictor<>>(testData.
        getObsNet());
    // Initialize predictor
    p->init();
    // Train predictor
    p->learn();
    // Create object to store prediction results
    auto predResults = std::make_shared<PredResults<>>(testData
        , p);
    // Create a ROC object
    auto roc = std::make_shared<ROC<>>("ROC");
    // Set options
    roc->setParallel(true);
    roc->setDistributed(true);
    roc->setStrmEnabled(true);
    // Create object to store results
    PerfResults res;
    // Evaluate performance
    roc->eval(predResults, res);
    // Print results
    if (procID == 0) {
        std::cout << "#ROCAUC_␣(streaming):_␣" << res.at(roc->
            getName()) << std::endl;
    }
    // Finalize MPI
    MPI_Finalize();
    return 0;
}
```

 This code is available in: `tutorials/code/parallel/distributed/rocstrmdist`

2. Compile your code:

```
$ mpiCC rocstrmdist.cpp -o rocstrmdist -fopenmp -lLinkPred
```

**R** Check Tutorial 1.2 if you face any compilation issues.

3. Run your code (here we are running the code on 4 nodes):

```
$ mpirun -n 4 ./rocstrmdist
```

The output of this program is as follows:

```
#ROCAUC (streaming): 0.922352
```