

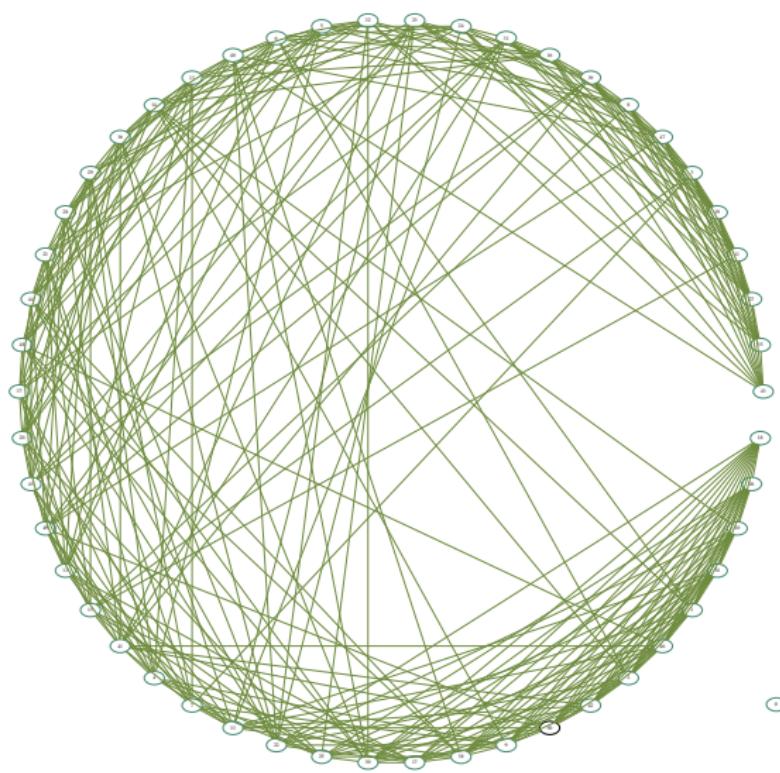


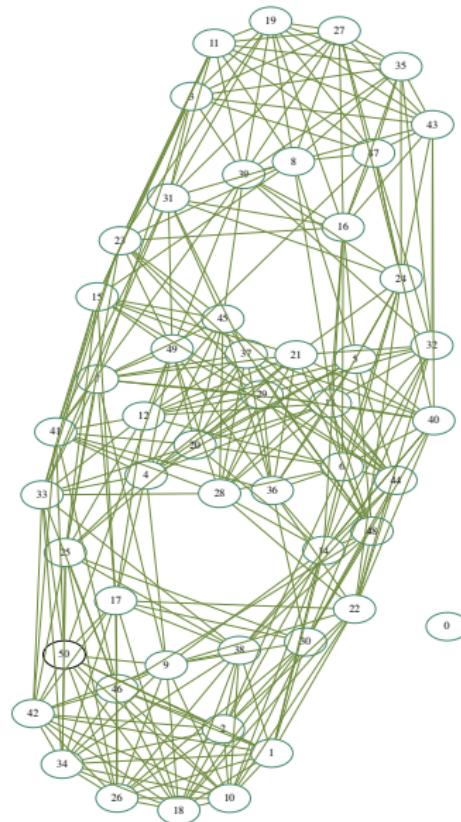
Algorithms, Matching

Part 1. Networks and Matchings

B9 - Algorithms Matching

M-ALG-102





...

└ Introduction

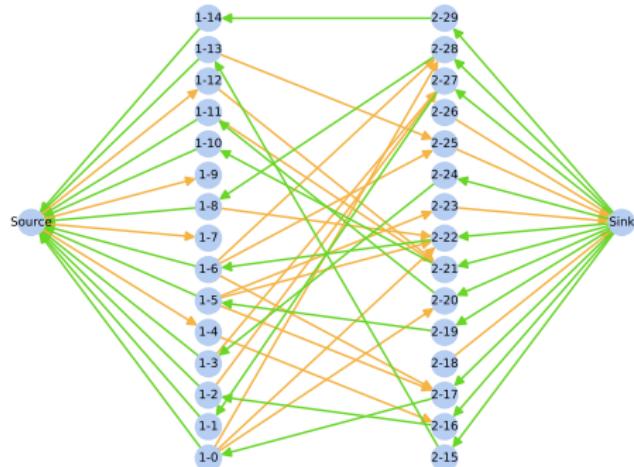
*Le réseau national
après déclassement*



...

└ Introduction

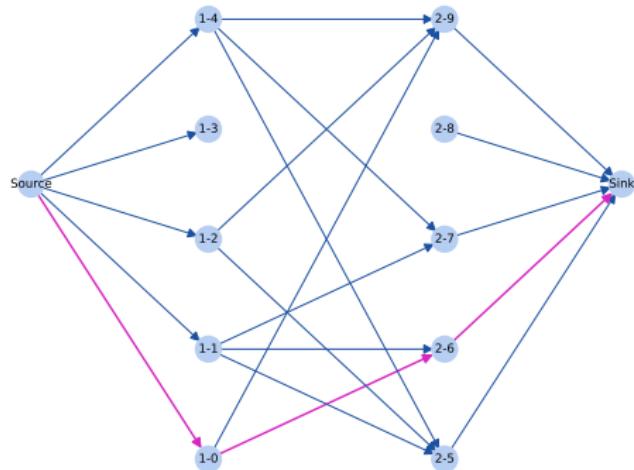
residual graph step 12

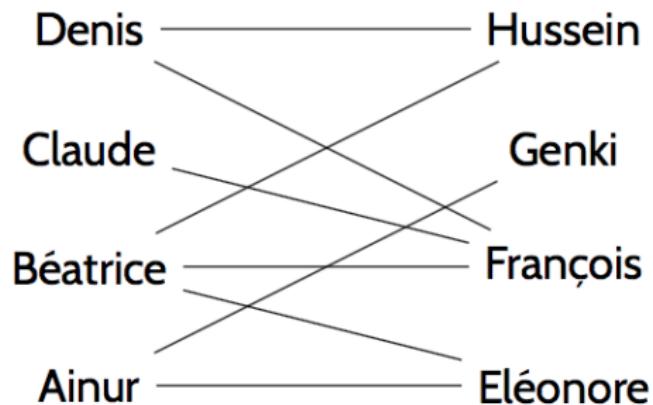


...

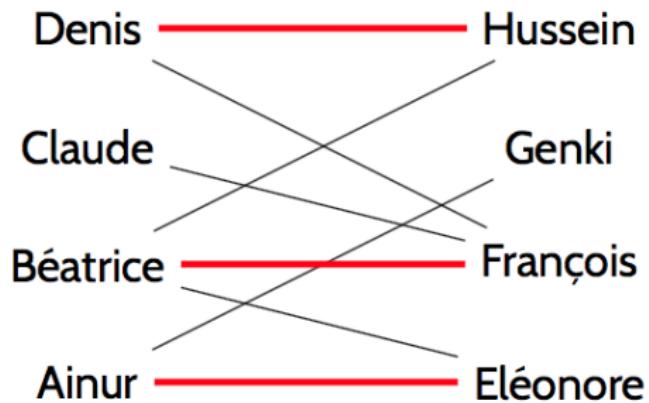
└ Introduction

augmenting path step 1

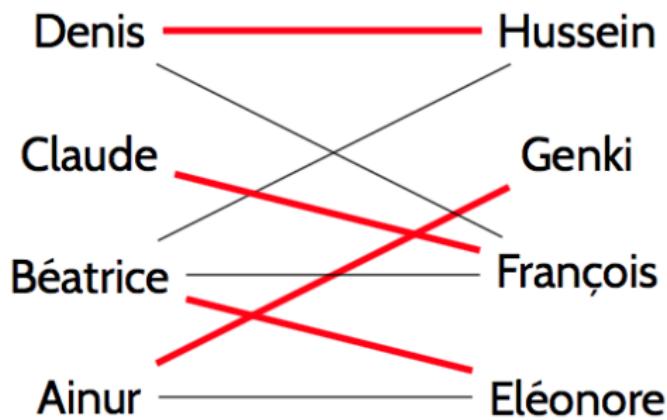


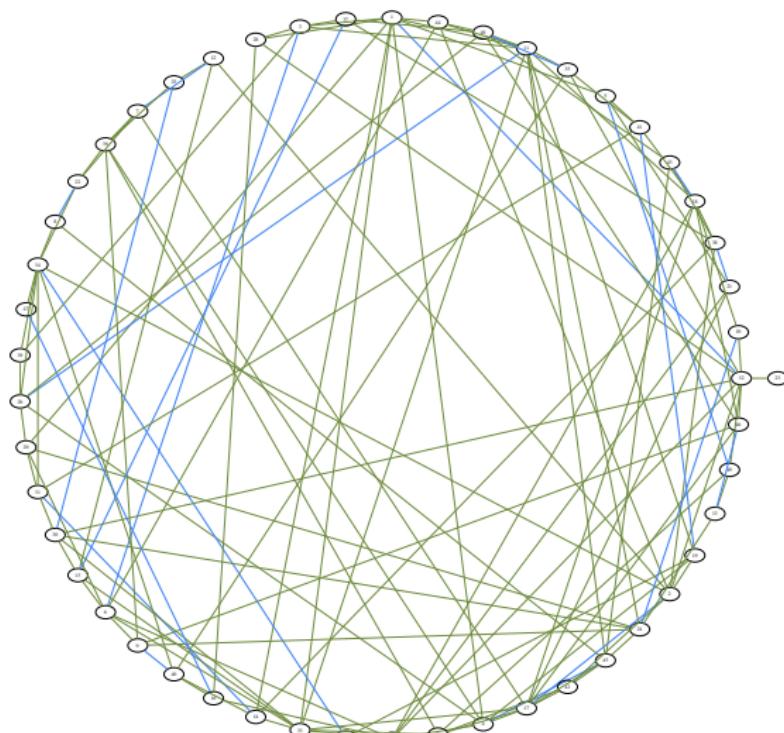


...

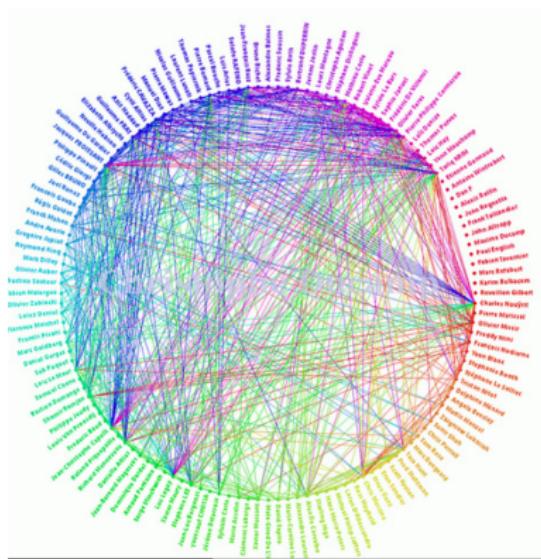


...



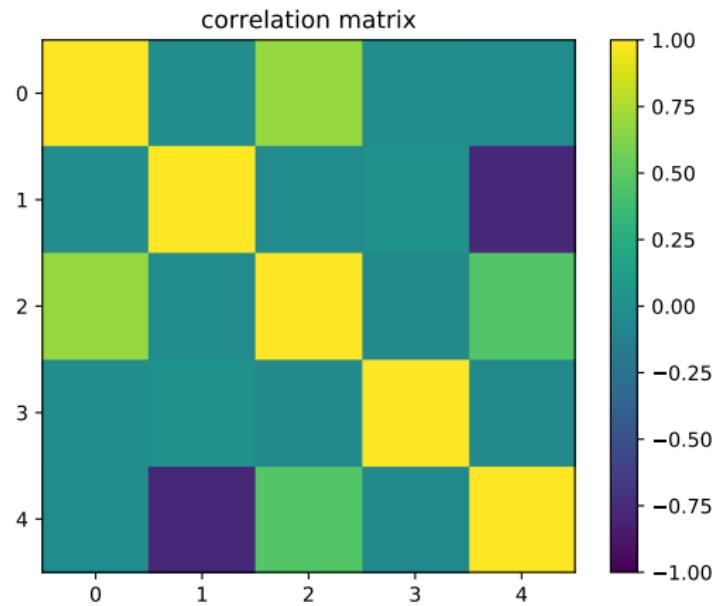


Matching size: 21
Algo step: 128
Nb nodes: 50



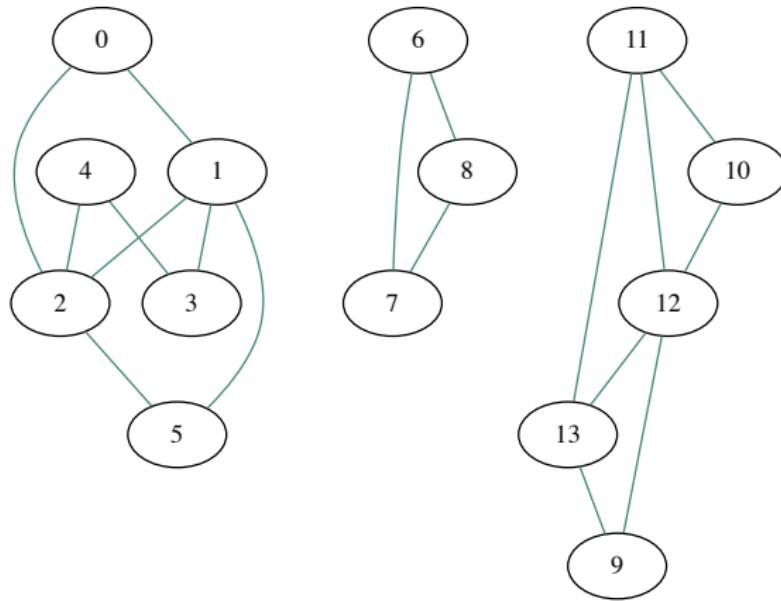
...

└ Introduction



...

└ Introduction



...

└ Introduction

- ▶ The content of the course will sometimes be mathematical.
- ▶ Don't hesitate to ask if you need more reminders.

...

└ Introduction

Overview of the module

Day 1 Networks, the matching problem and the maximum flow problem

Day 2 Data clustering and representation

Organisation of the module

- ▶ Course and exercises in python 3
- ▶ Small coding exercises, also paper + pen
- ▶ Project : explained tomorrow
- ▶ Please clone the following repository
<https://github.com/nlehir/ALG02>

...

└ Introduction

Libs

Day 1 networkx, numpy, matplotlib

Day 2 numpy, matplotlib, pandas, sklearn

Day 1

The matching problem

- Definition of the problem
- Experimental solutions
- Brute force algorithm
- Greedy algorithm

The Maximum flow problem

- Presentation of the problem
- Solution with the Ford-Fulkerson algorithm
- Connection with the matching problem
- More results on the two problems

Introductory example 1 : Max Flow

*Le réseau national
après déclassement*

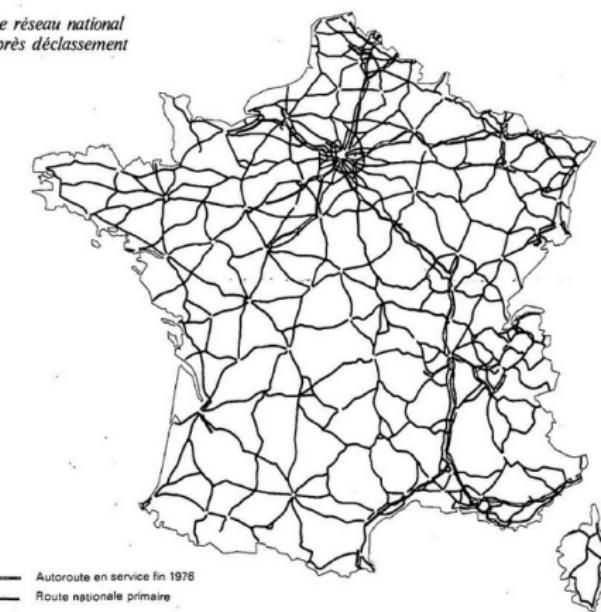


Figure: Problem 1 : transporting merchandise through a network

Introductory example 2 : Maximum matching (Optimal allocation)

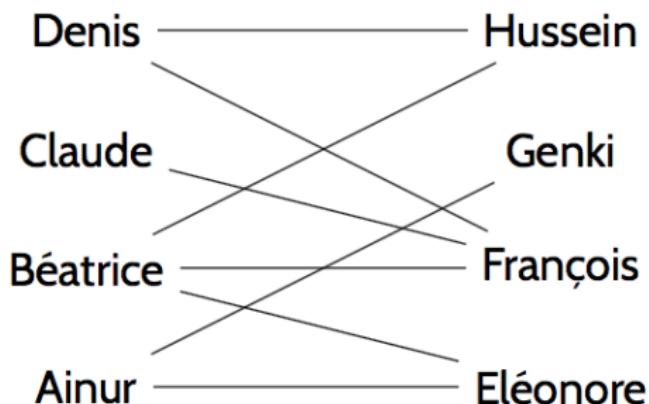


Figure: Problem 2 : Building the largest possible number of teams of 2 persons.

Introductory example 2

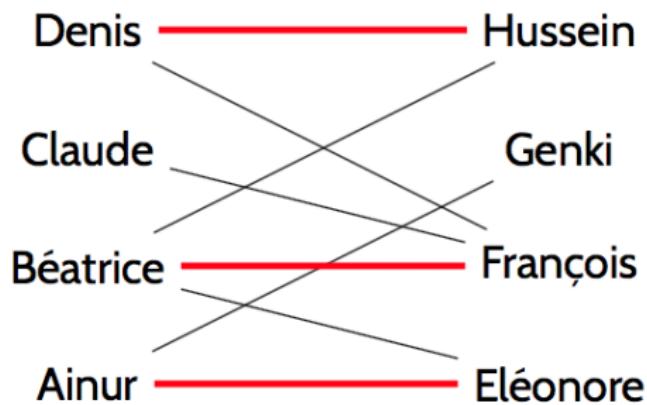


Figure: Problem 2 : not optimal allocation

Introductory example 2

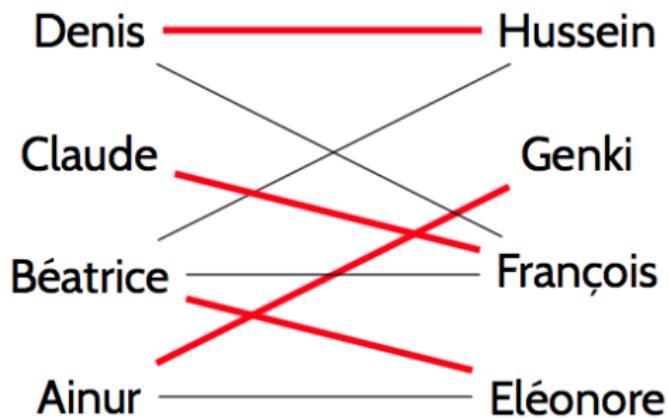


Figure: Problem 2 : optimal allocation

...

└ Introduction

Other examples

- ▶ Assigning students to internships

Other examples

- ▶ Assigning students to internships
- ▶ Assigning machines to a task

...

└ Introduction

Summary

- ▶ Today we will work on **connecting the two problems.**

...

└ Introduction

Summary

- ▶ Today we will work on **connecting the two problems**.
- ▶ Under some restrictions, the two problems **equivalent**.

...

└ The matching problem

└ Definition of the problem

Reminders on graphs

- ▶ A graph is defined by ?

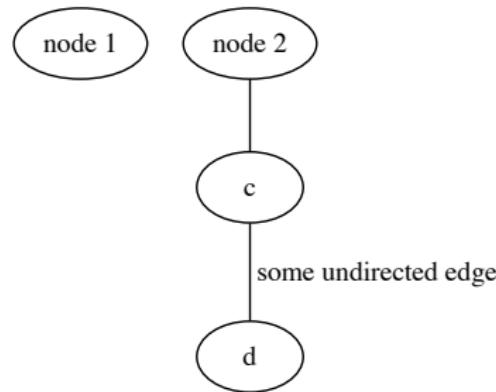
...

- └ The matching problem

- └ Definition of the problem

Reminders on graphs

- ▶ A graph is defined by set of **vertices** (or **nodes**) V and a set of **edges** E .



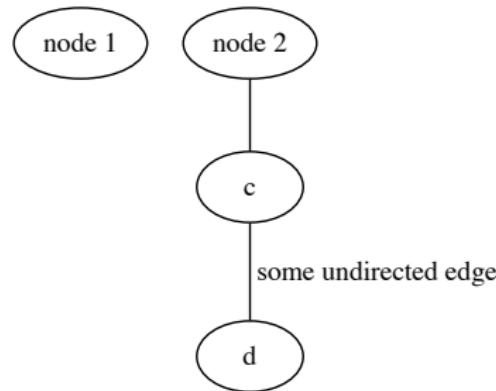
...

- └ The matching problem

- └ Definition of the problem

Reminders on graphs

- ▶ It can be **undirected**, as this one :



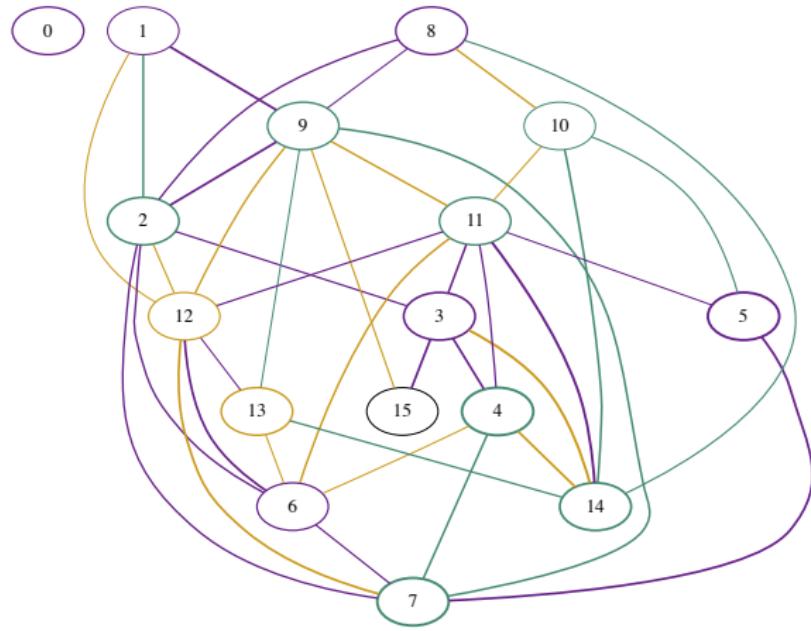
...

- The matching problem

- Definition of the problem

Reminders on graphs

Undirected graph



Reminders on graphs

- ▶ Or **directed**, as this one. (it is then called a **digraph**)

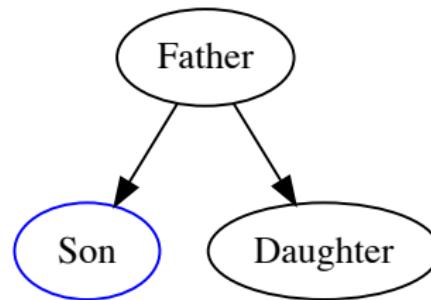


Figure: Digraph (graphviz demo)

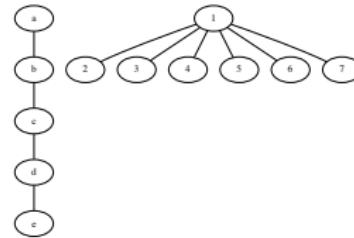
...

- └ The matching problem

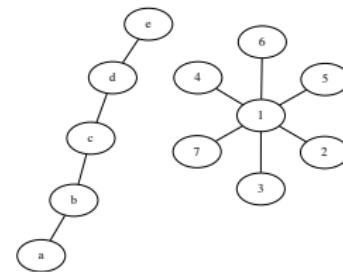
- └ Definition of the problem

Useful tool : graphviz

- ▶ A tool to visualize graphs
- ▶ Several **generator programs** : dot, neato



(a) Image generated with **dot**



(b) Image generated with **neato**

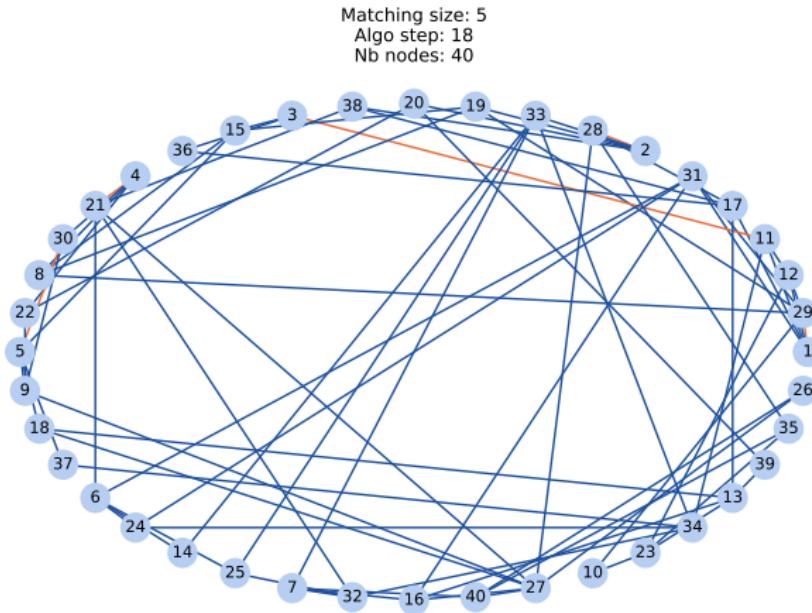
...

- └ The matching problem

- └ Definition of the problem

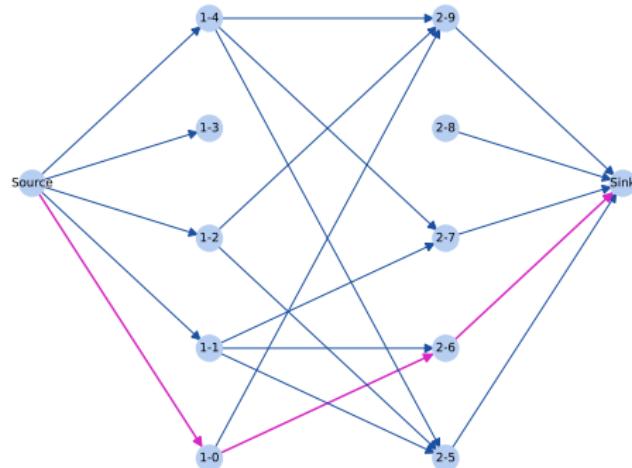
Networkx

We will use networkx.



Networkx

augmenting path step 1



simple/s

...

- └ The matching problem

- └ Definition of the problem

Warm up question

Given an **undirected** graph with n nodes, how many edges can we build ?

Notation of a graph : $G(V, E)$

- ▶ V : set of n vertices
- ▶ E : set of edges

...

└ The matching problem

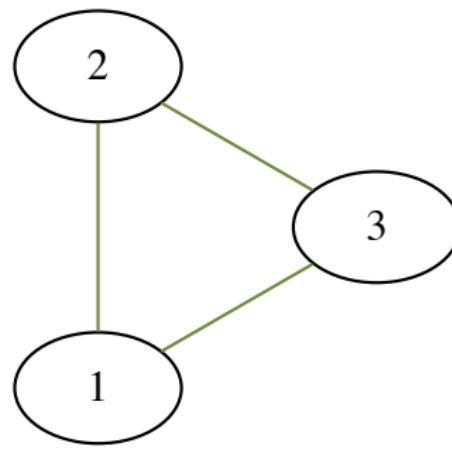
└ Definition of the problem



...

- └ The matching problem

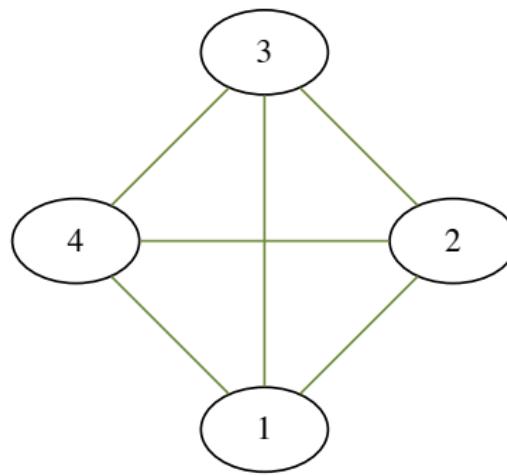
- └ Definition of the problem



...

- └ The matching problem

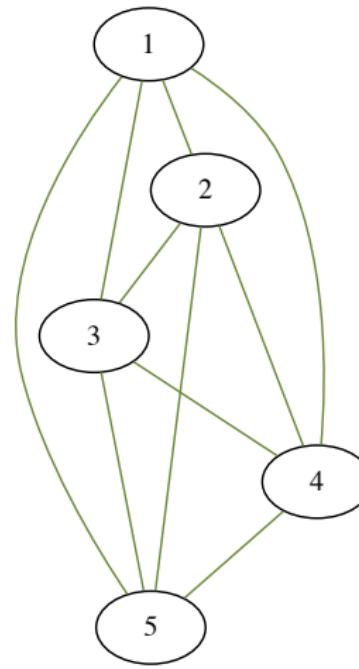
- └ Definition of the problem



...

- └ The matching problem

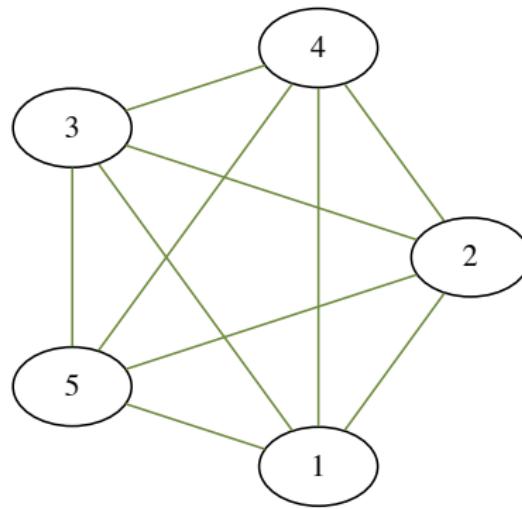
- └ Definition of the problem



...

- └ The matching problem

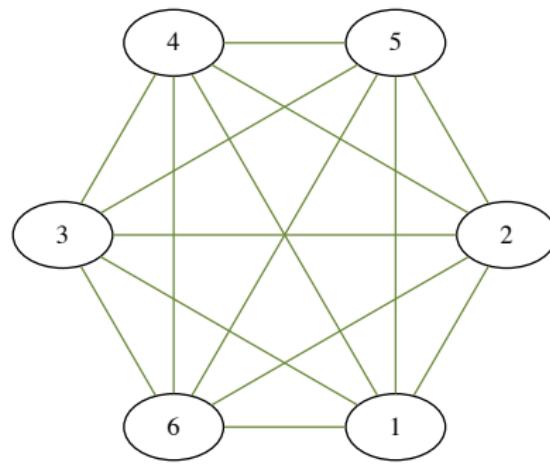
- └ Definition of the problem



...

- └ The matching problem

- └ Definition of the problem



...

- └ The matching problem

- └ Definition of the problem

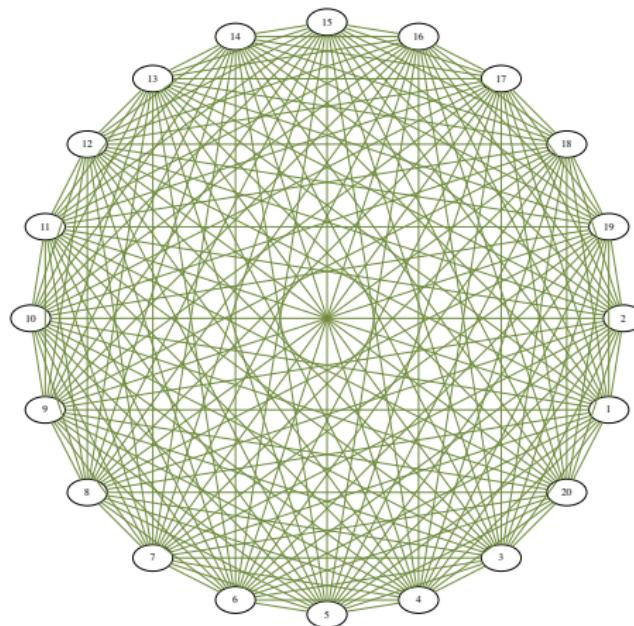


Figure: We cannot count anymore

...

- └ The matching problem

- └ Definition of the problem

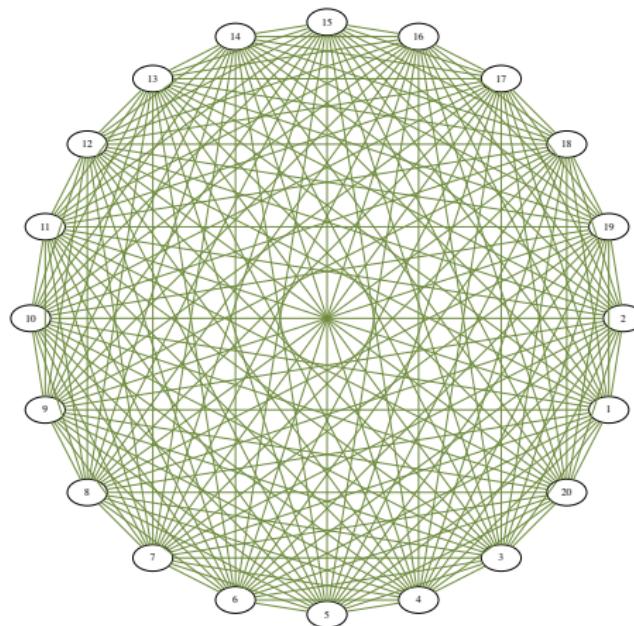


Figure: We cannot count anymore

...

└ The matching problem

└ Definition of the problem

What if the graph is directed ?

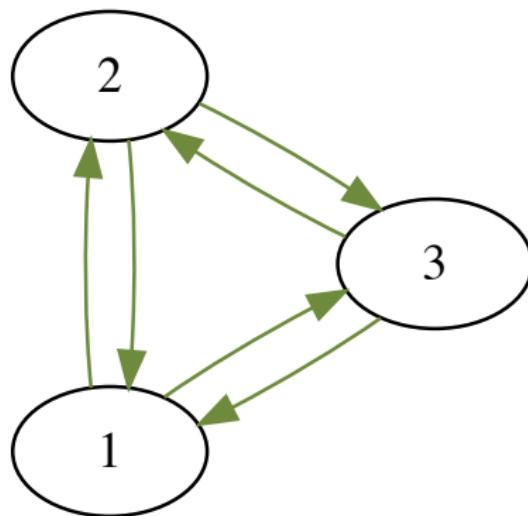


...

- └ The matching problem

- └ Definition of the problem

What if the graph is directed ?

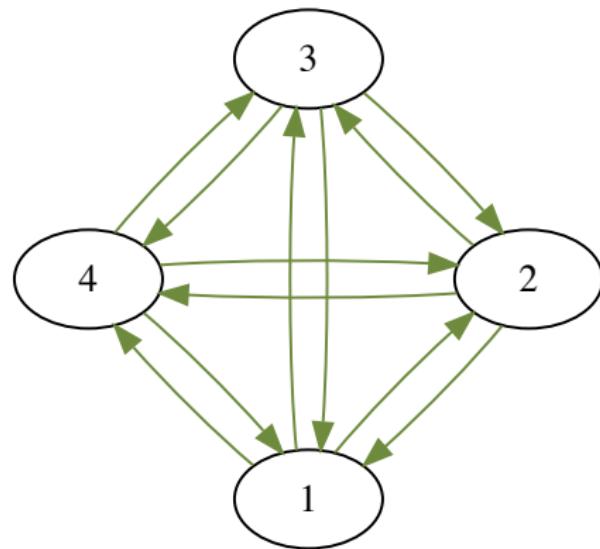


...

- └ The matching problem

- └ Definition of the problem

What if the graph is directed ?

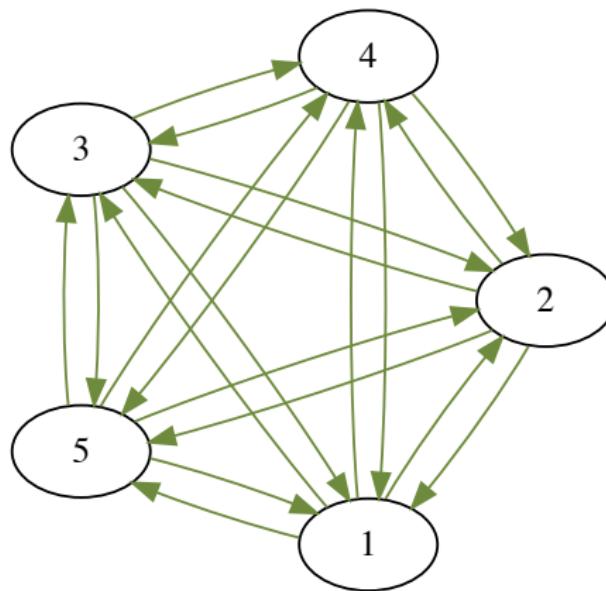


...

- └ The matching problem

- └ Definition of the problem

What if the graph is directed ?

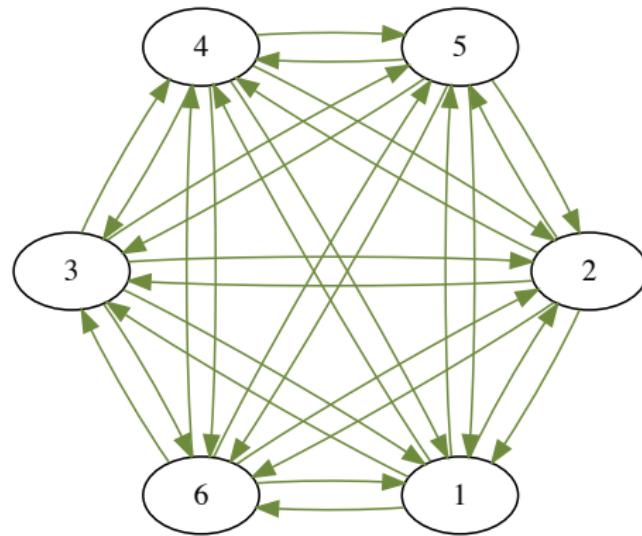


...

- └ The matching problem

- └ Definition of the problem

What if the graph is directed ?

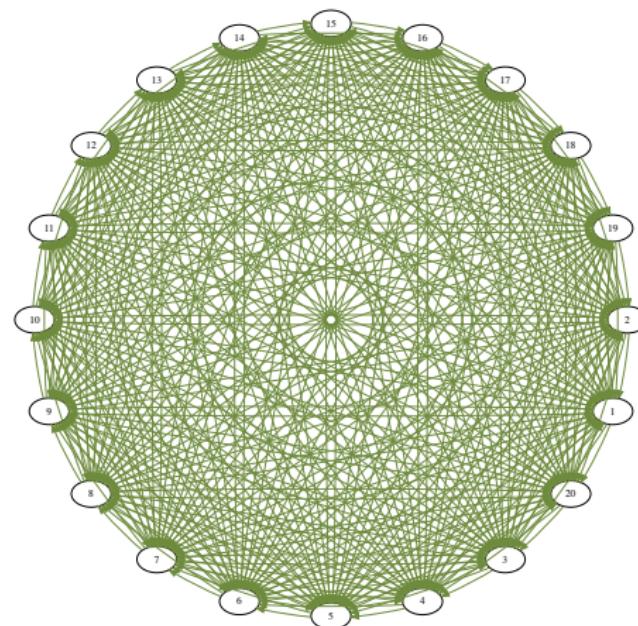


...

- └ The matching problem

- └ Definition of the problem

What if the graph is directed ?



...

└ The matching problem

└ Definition of the problem

Warm up question

Given an **directed** graph with n nodes, how many edges can we build ?

...

└ The matching problem

└ Definition of the problem

Warm up question

Given an **directed** graph with n nodes, how many edges can we build ?

$$n(n - 1) \quad (1)$$

Warm up question

Given an **directed** graph with n nodes, how many edges can we build ?

$$n(n - 1) \quad (2)$$

So if the graph is **undirected**, we can build :

$$\frac{n(n - 1)}{2} \quad (3)$$

edges.

...

- └ The matching problem

- └ Definition of the problem

Remark

$\frac{n(n-1)}{2}$ is also the number of subsets of size 2 in a set of size n .

$$\binom{n}{2} = \frac{n!}{2!(n-2)!} \quad (4)$$

...

└ The matching problem

 └ Definition of the problem

Famous graph problem

- ▶ Do you know some famous **graph problems** ?

...

└ The matching problem

└ Definition of the problem

Famous graph problem

- ▶ Do you know some famous **graph problems** ?
- ▶ Dominating set

...

└ The matching problem

└ Definition of the problem

Famous graph problem

- ▶ Do you know some famous **graph problems** ?
- ▶ Dominating set
- ▶ Maximum clique

...

└ The matching problem

 └ Definition of the problem

Famous graph problem

- ▶ Do you know some famous **graph problems** ?
- ▶ Dominating set
- ▶ Maximum clique
- ▶ Coloring

...

└ The matching problem

 └ Definition of the problem

Matching problem

Let us now focus on the **matching problem** (problme du **couplage**)

...

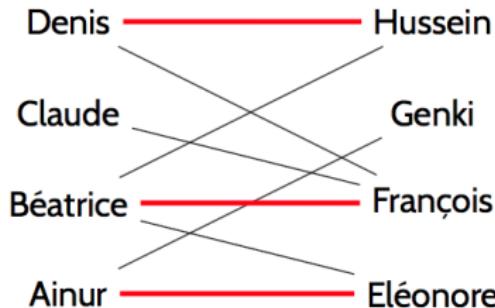
- The matching problem

- Definition of the problem

Back to our problem

Given a **undirected** graph $G = (V, E)$, we want a **matching** M , which means:

- ▶ A subset of edges $M \subset E$



...

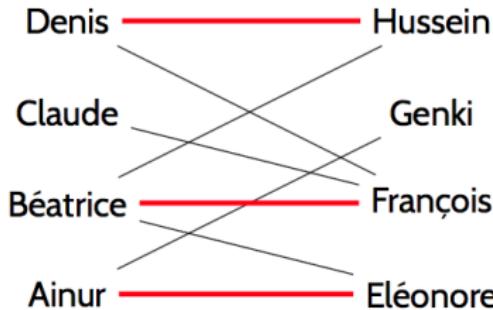
- The matching problem

- Definition of the problem

Back to our problem

Given a **undirected** graph $G = (V, E)$, we want a **matching**, which means:

- ▶ A subset of edges $M \subset E$
- ▶ Such that no pairs of edges of M are incident
- ▶ Equivalently, each node in the graph has **at most** one edge connected



...

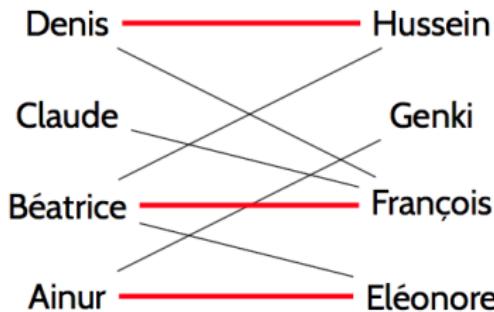
- The matching problem

- Definition of the problem

Back to our problem

Given **undirected** a graph $G = (V, E)$, we want a **matching**, which means:

- ▶ A subset of edges $M \subset E$
- ▶ Equivalently, each node in the graph has **at most** one edge connected
- ▶ Such that no pairs of edges of M are incident



...

└ The matching problem

 └ Definition of the problem

Maximum matching

- ▶ The **size** of a matching is the number of edges it contains.

...

└ The matching problem

 └ Definition of the problem

Maximum matching

- ▶ The **size** of a matching is the number of edges it contains.
- ▶ We want to find the matching of maximum size in a given graph.

...

- └ The matching problem

- └ Definition of the problem

Example 1

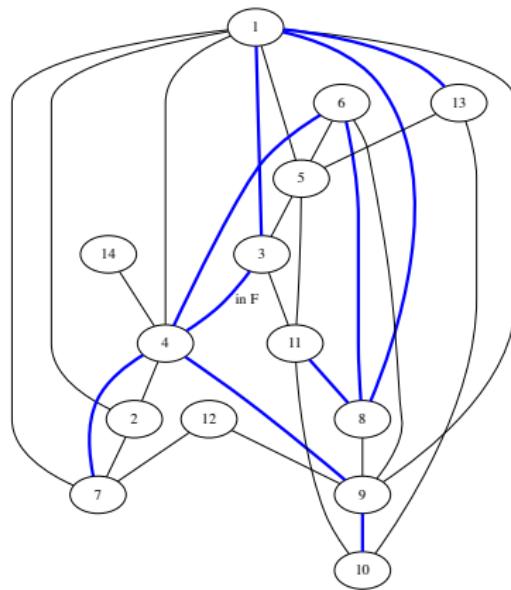


Figure: Is this a matching ?

...

- └ The matching problem

- └ Definition of the problem

Example 2

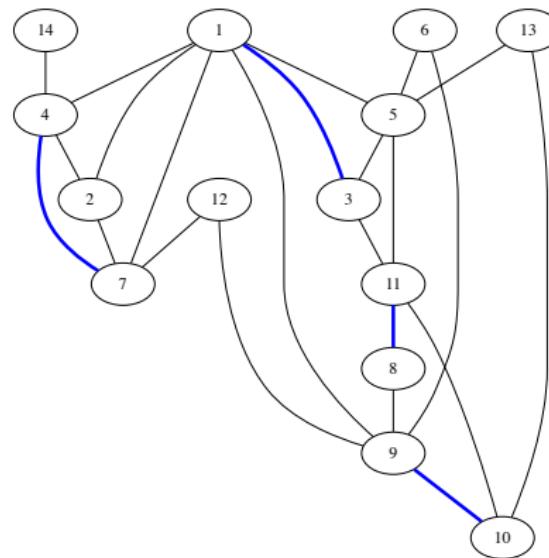


Figure: Is this a matching ?

...

- └ The matching problem

- └ Definition of the problem

Example 3

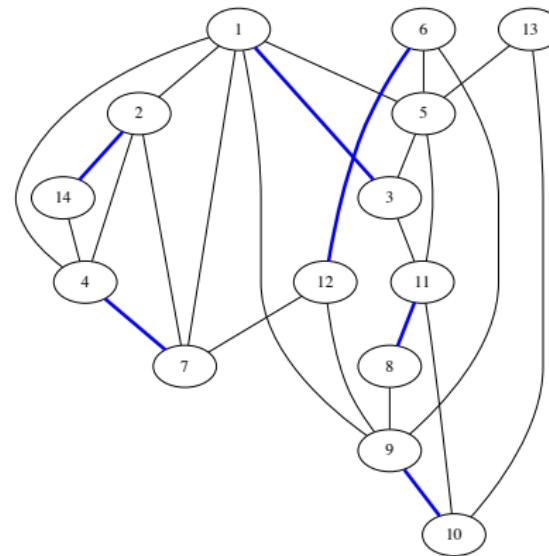


Figure: Is this an optimal matching ?

...

- └ The matching problem

- └ Definition of the problem

Example 4

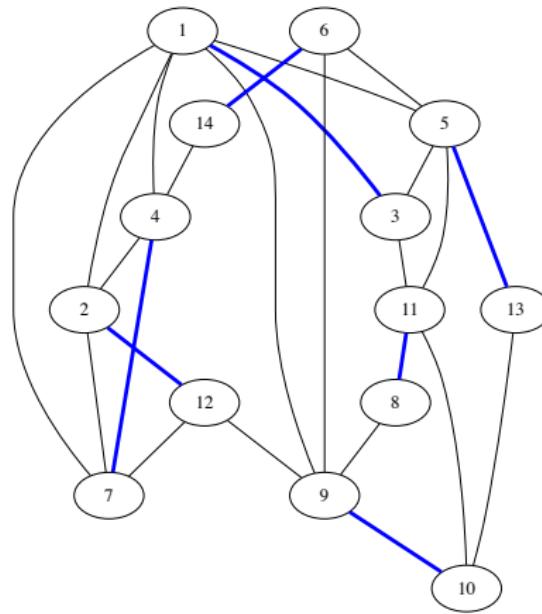


Figure: Is this an optimal matching ?

...

- └ The matching problem

- └ Definition of the problem

Example 5

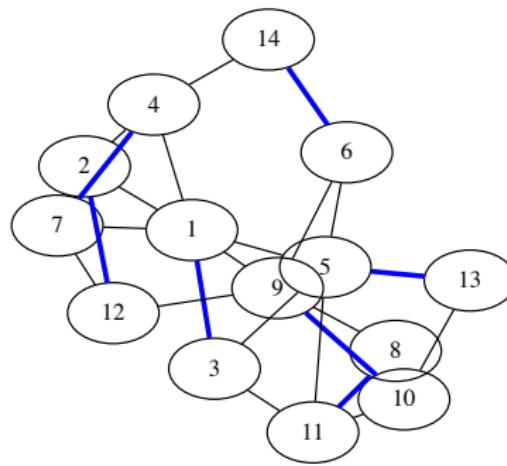


Figure: With neato

...

└ The matching problem

 └ Definition of the problem

Optimal matching

Exercice 1: Given a graph of size n , what is maximum size possible for a **matching** ?

...

- └ The matching problem

- └ Definition of the problem

Optimal matching

Exercice 1: Given a graph of size n , what is maximum size possible for a **matching** ?

- ▶ If n is even : $\frac{n}{2}$
- ▶ Else n is odd : $\frac{n-1}{2}$

...

└ The matching problem

 └ Definition of the problem

Optimal matching

Exercice 1: Can you think of a graph with n nodes that contains a matching of size $\frac{n}{2}$? (assuming n is even)

...

- └ The matching problem

- └ Definition of the problem

Optimal

Exercice 1: Can you think of a graph with n nodes that contains a matching of size $\frac{n}{2}$? (assuming n is even)

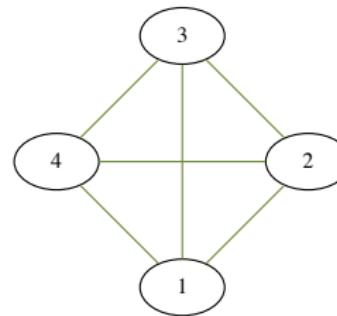


Figure: The complete graph works

...

└ The matching problem

 └ Definition of the problem

Optimal matching

Exercice 1: Can you think of a graph with n nodes that does **not** contains a matching of size $\frac{n}{2}$? (assuming n is even)

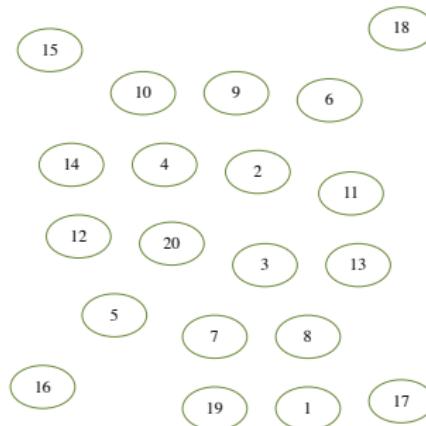
...

- └ The matching problem

- └ Definition of the problem

Optimal matching

Exercice 1: Can you think of a graph with n nodes that does **not** contains a matching of size $\frac{n}{2}$? (assuming n is even)



...

└ The matching problem

 └ Definition of the problem

Optimal matching

Exercice 1: Can you think of a **non trivial** graph that does **not** contains a matching of size n ? (assuming n is even)

...

- The matching problem

- Definition of the problem

Optimal matching

Exercice 2: Can you think of a **non trivial** graph that does **not** contains a matching of size n ? (assuming n is even)

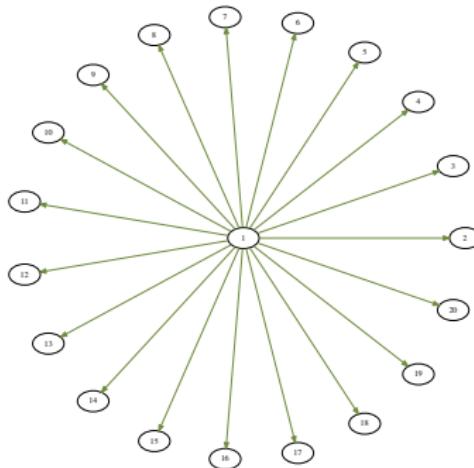


Figure: Star graph

...

- └ The matching problem
- └ Experimental solutions

Experiments

How would you code a graph ?

...

- └ The matching problem
- └ Experimental solutions

Experiments

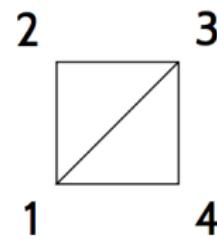
How would you code a graph ?

- ▶ list of sets of size 2 (for an undirected graph)
- ▶ a dictionary of successors (directed or undirected)

...

- └ The matching problem
- └ Experimental solutions

Coding a graph : as a list

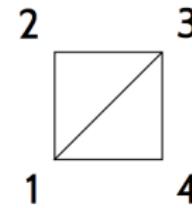


```
g1 = [{1,2},{1,3},{2,3},{3,4},{1,4}]
```

...

- └ The matching problem
- └ Experimental solutions

Coding a graph : as a dictionary



```
g1 = { 1:{2,3,4}, 2:{1,3}, 3:{1,2,4}, 4:{1,3} }
```

...

- └ The matching problem
- └ Experimental solutions

Random graph

Exercice 3: **cd other_graphs/** and please use
random_undirected_graph.py to build a graph with 20 vertices
and 50 edges.

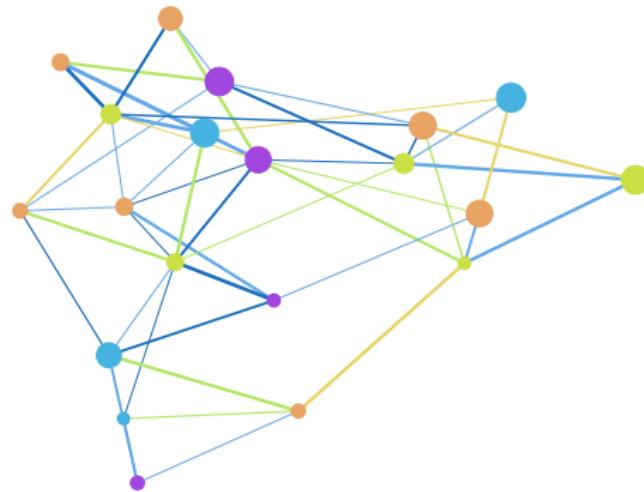
- ▶ You will need to install **networkx**

...

- └ The matching problem

- └ Experimental solutions

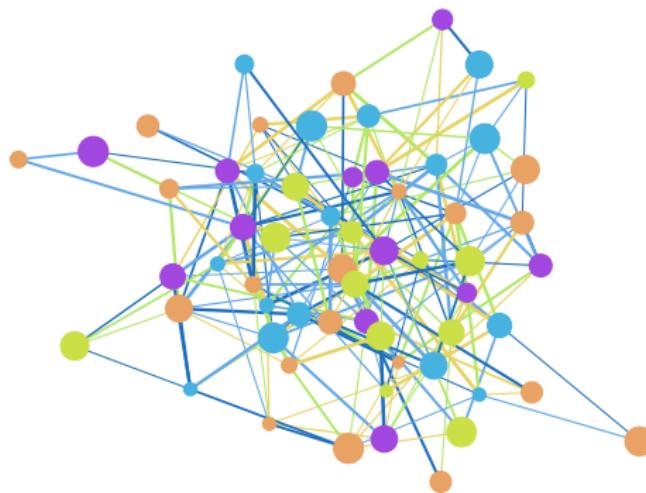
Example undirected graph obtained



...

- └ The matching problem
- └ Experimental solutions

Example undirected graph obtained



...

- └ The matching problem
- └ Experimental solutions

Example undirected graph obtained



...

- └ The matching problem
- └ Experimental solutions

Exercice 4 : Random directed graph.

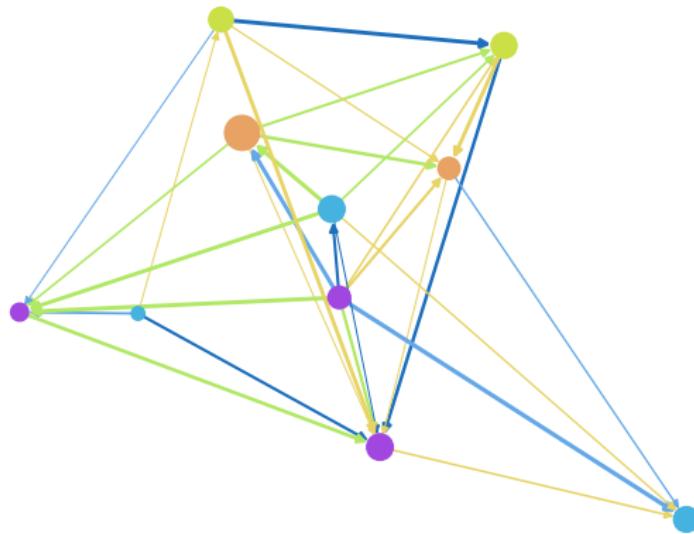
- ▶ Please use **random_directed_graph.py** to build a **directed** graph with a chosen number of vertices and **directed edges**.

...

- └ The matching problem

- └ Experimental solutions

Example directed graph

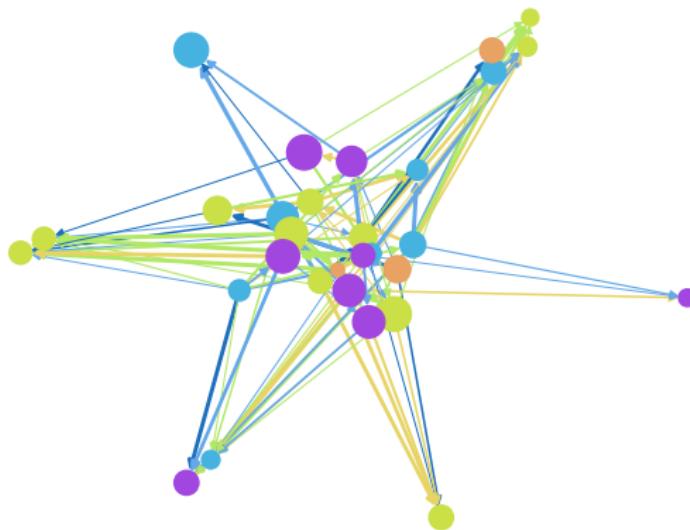


...

- └ The matching problem

- └ Experimental solutions

Example directed graph

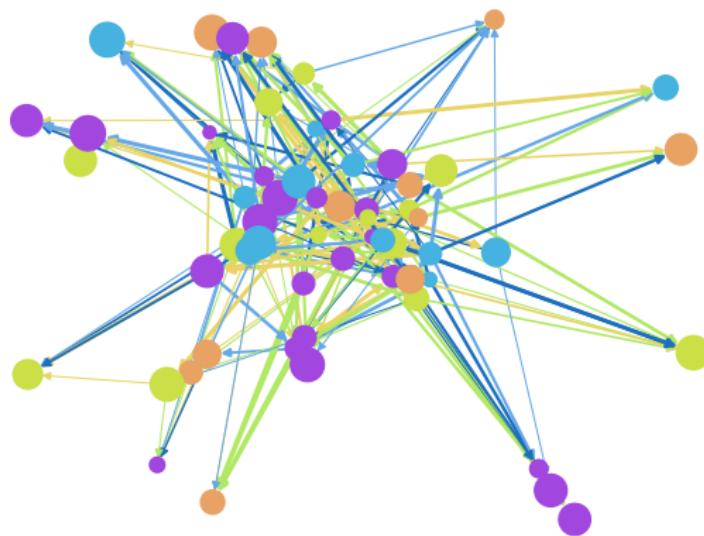


...

- └ The matching problem

- └ Experimental solutions

Example directed graph

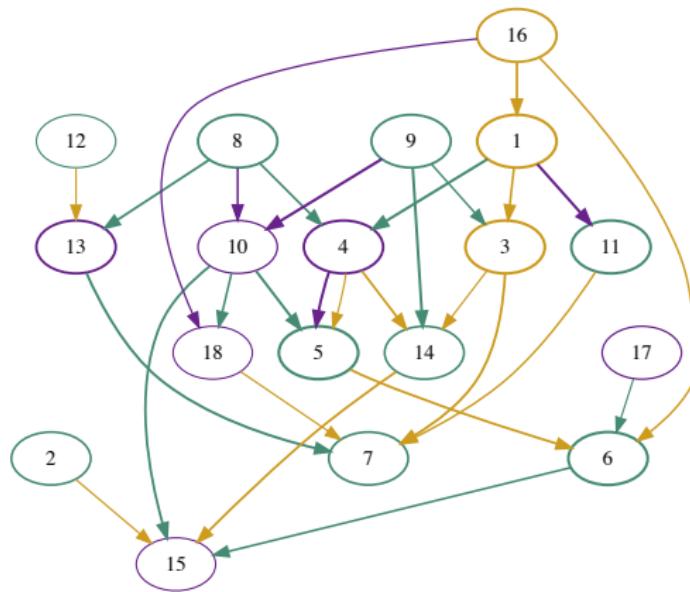


...

- The matching problem

- Experimental solutions

Example directed graph



...

- └ The matching problem
- └ Experimental solutions

Manual matching

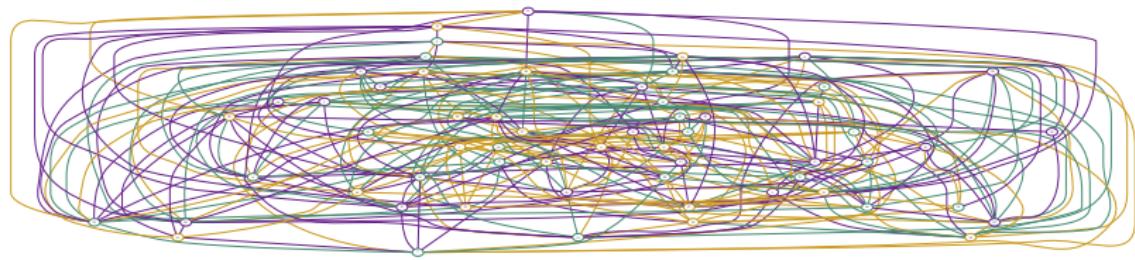
Exercice 5 : Please manually find an **optimal matching** in your **undirected** graph.

...

- └ The matching problem
- └ Experimental solutions

Big graph

We could not manually find an optimal matching in this graph :



...

- └ The matching problem
 - └ Brute force algorithm

Summary

- ▶ We have defined the matching problem.
- ▶ When the size of the problem is large, we can not manually find an optimal matching.

...

- └ The matching problem
 - └ Brute force algorithm

Brute force approach

Exercice 6 : Enumeration

- ▶ Given a graph, what would a brute force approach on the matching problem be ?

Brute force approach

Exercice 6 : Exhaustive search

- ▶ Given a graph what would a brute force approach on the matching problem be ?
 - ▶ 1) Enumerate all possible subsets in the set of the edges.
 - ▶ 2) Check if each subset is a matching.
 - ▶ 3) Return the biggest one obtained.

Brute force approach

Exercice 6 : Exhaustive search

- ▶ Given a graph what would a brute force approach on the matching problem be ?
 - ▶ 1) Enumerate all possible subsets in the set of the edges.
 - ▶ 2) Check if each subset is a matching.
 - ▶ 3) Return the biggest one obtained.

If the graph contains n nodes, and given a subset of edges, what if the number of computations needed to perform step 2 ?

Brute force approach

Exercice 6 : Exhaustive search

- ▶ Given a graph what would a brute force approach on the matching problem be ?
 - ▶ 1) Enumerate all possible subsets in the set of the edges.
 - ▶ 2) Check if each subset is a matching.
 - ▶ 3) Return the biggest one obtained.

If the graph contains n nodes, and given a subset of edges, what if the number of computations needed to perform step 2 ?

You can give a rough approximation.

Brute force approach

Exercice 6 : Exhaustive search

- ▶ Given a graph what would a brute force approach on the matching problem be ?
 - ▶ 1) Enumerate all possible subsets in the set of the edges.
 - ▶ 2) Check if each subset is a matching.
 - ▶ 3) Return the biggest one obtained.

If the graph contains n nodes, and given a subset of edges, what if the number of computations needed to perform step 2 ?

It is a **polynomial** number of computations : so it is ok.

...

- └ The matching problem
 - └ Brute force algorithm

Notion of complexity

- ▶ The **time complexity** of an algorithm is a measure of the **number of elementary** operations needed for the algorithm to terminate with respect to the input size.

...

- └ The matching problem
 - └ Brute force algorithm

Brute force search

Exercice 7 : Complexity of brute force

- ▶ 1) Enumerate all possible subsets in the set of the edges.
- ▶ 2) Check if each subset is a matching.
- ▶ 3) Return the biggest one obtained.

What is the complexity of step 1 ?

Brute force search

Exercice 7 : Complexity of brute force

- ▶ 1) Enumerate all possible subsets in the set of the edges.
- ▶ 2) Check if each subset is a matching.
- ▶ 3) Return the biggest one obtained.

What is the complexity of step 1 ?

The number of subsets is $2^{\frac{n(n-1)}{2}}$ (in the worst case), which is exponential.

...

- └ The matching problem
 - └ Brute force algorithm

Brute force search

Exercice 7: Complexity of brute force Assume that checking a subset requires 1 microsecond. How long should we wait in order to check all possible matching in a graph with 100 nodes ?

...

- └ The matching problem
 - └ Brute force algorithm

Other example of complexities

- ▶ linear search
- ▶ dichotomic search

...

└ The matching problem

 └ Greedy algorithm

Summary II

- ▶ For the matching problem on a large graph, we can neither
 - ▶ manually find an optimal matching
 - ▶ perform the exhaustive search (brute force algorithm)

...

└ The matching problem

 └ Greedy algorithm

Algorithms

- ▶ Hence, we need different algorithms to solve the problem.

...

└ The matching problem

 └ Greedy algorithm

Algorithms

- ▶ Hence, we need different algorithms to solve the problem.
- ▶ Let us first introduce some theoretical notions.

...

- └ The matching problem
 - └ Greedy algorithm

Notion of maximal and maximum matching

We will say that a matching M of cardinality (number of elements) $|M|$ is:

- ▶ **Maximum** if it has the maximum possible number of edges (it is thus optimal)

...

- └ The matching problem

- └ Greedy algorithm

Notion of maximal and maximum matching

We will say that a matching M of cardinality $|M|$ is:

- ▶ **Maximum** if it has the maximum possible number of edges (it is thus optimal)
- ▶ **Maximal** if the set of edges obtained by adding any edge to it is **not a matching**. This means that $M \cup \{e\}$ is not a matching for any e not in M .
- ▶ \cup means union of sets.

...

└ The matching problem

└ Greedy algorithm

is being a **maximal** matching the same thing as beeing a
maximum matching ?

...

└ The matching problem

 └ Greedy algorithm

Maximum implies maximal

Let us show that a maximum matching is maximal.

...

└ The matching problem

 └ Greedy algorithm

Counter Example

However, a matching that is maximal is **not necessarily Maximum**.

...

└ The matching problem

 └ Greedy algorithm

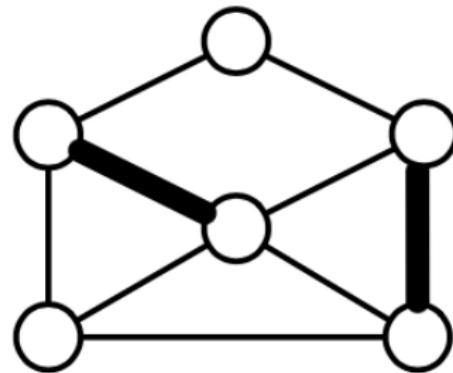
Counter Example

However, a matching that is maximal is **not necessary Maximum**.
Can you find an example ?

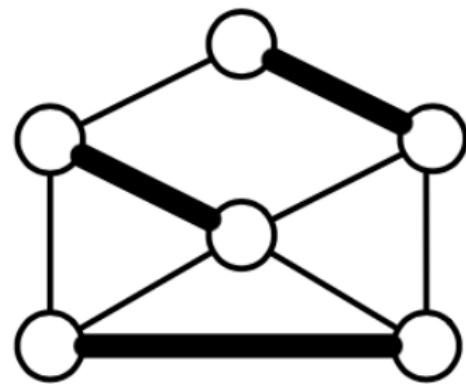
...

- └ The matching problem

- └ Greedy algorithm



(a) A maximal matching not maximum



(b) A maximum matching

...

└ The matching problem

 └ Greedy algorithm

Greedy algorithm

Can you propose a greedy algorithm to address the maximum matching problem ?

Greedy algorithm

Result: Matching M

$M \leftarrow \emptyset;$

for $e \in E$ **do**

if $M \cup \{e\}$ is a matching **then**

$M \leftarrow M \cup \{e\}$

end

end

return M

Algorithm 0: Greedy algorithm to find a matching

...

- └ The matching problem
 - └ Greedy algorithm

Greedy algorithm

- ▶ What is the type of matching algorithm returned by this algorithm ?
- ▶ What is the complexity of this algorithm ? (as a function of the number of nodes n of the graph)

...

- └ The matching problem

- └ Greedy algorithm

Greedy algorithm

- ▶ The greedy algorithm returns a **maximal** matching (proof)
- ▶ Its complexity is **quadratic** : $\mathcal{O}(n^2)$

...

└ The matching problem

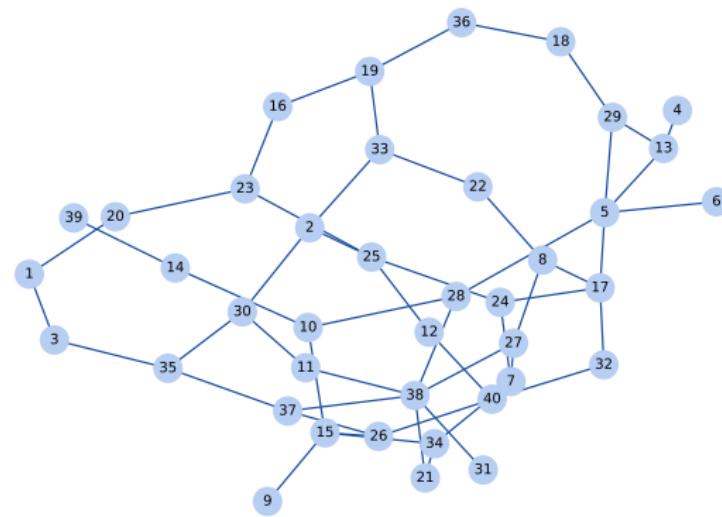
 └ Greedy algorithm

Greedy algorithm

- ▶ We will implement the greedy algorithm to find a maximal matching.

Exercice 8: `cd matching_greedy/` and use `generate_graph.py` to build a graph with at least 30 nodes. The images are stored in `images/`, data stored in `data/`

initial graph



Implementing the greedy algorithm

Exercice 8 : Implement the greedy algorithm on this graph.

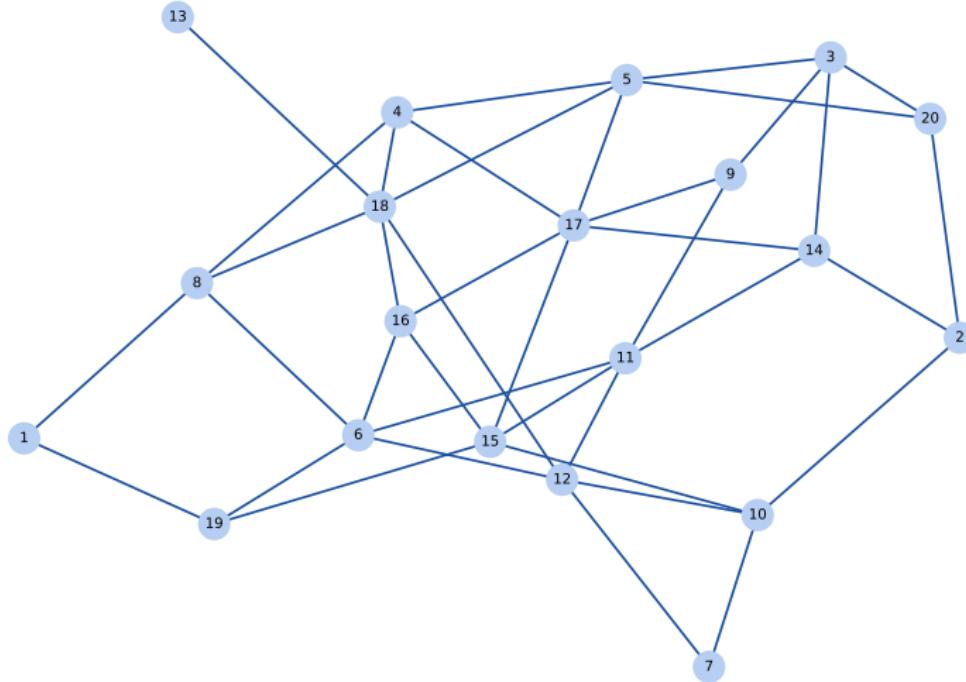
- ▶ Use the functions in **matching_functions.py** and call them from **apply_matching_algorithm.py**
- ▶ More details in the file.

...

- └ The matching problem

- └ Greedy algorithm

initial graph

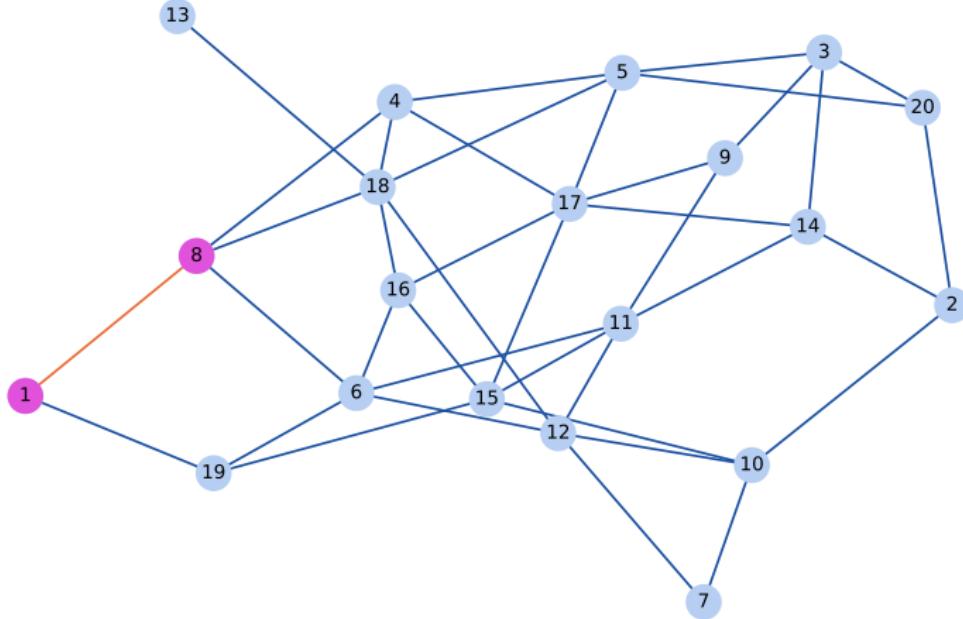


...

- The matching problem

- └ Greedy algorithm

Matching size: 1
Algo step: 1
Nb nodes: 20



...

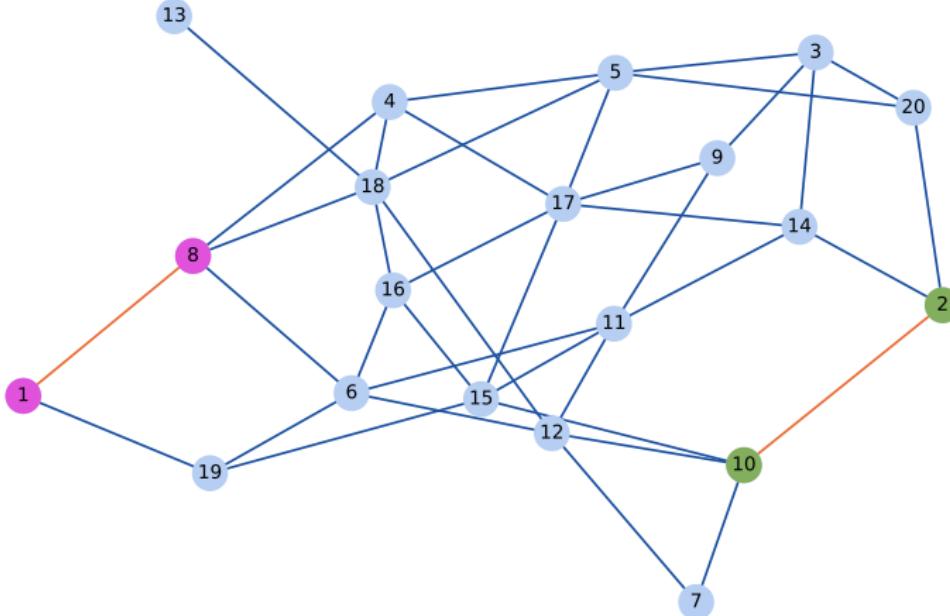
- The matching problem

- Greedy algorithm

Matching size: 2

Algo step: 3

Nb nodes: 20



...

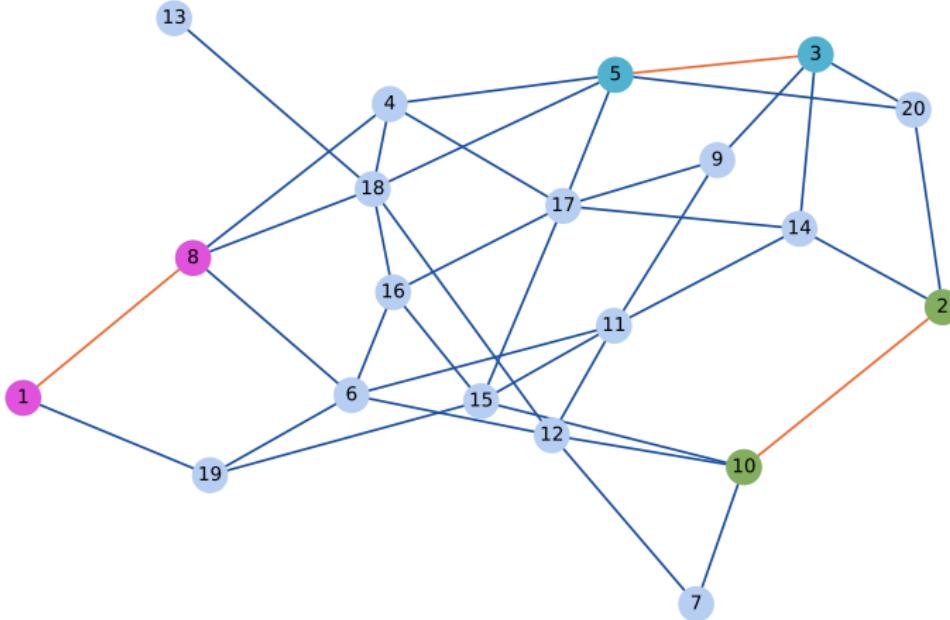
- The matching problem

- Greedy algorithm

Matching size: 3

Algo step: 6

Nb nodes: 20



...

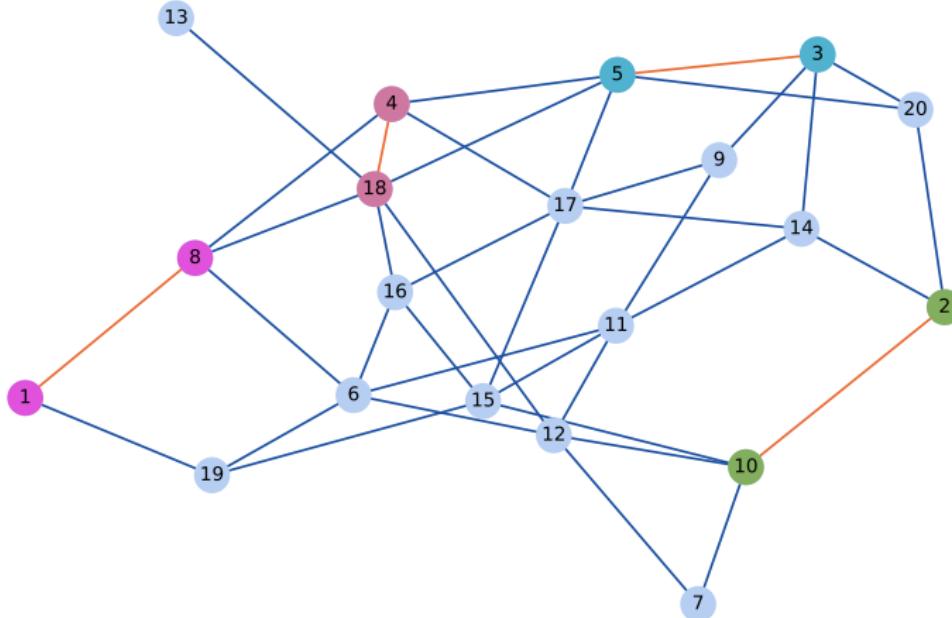
- The matching problem

- Greedy algorithm

Matching size: 4

Algo step: 11

Nb nodes: 20



...

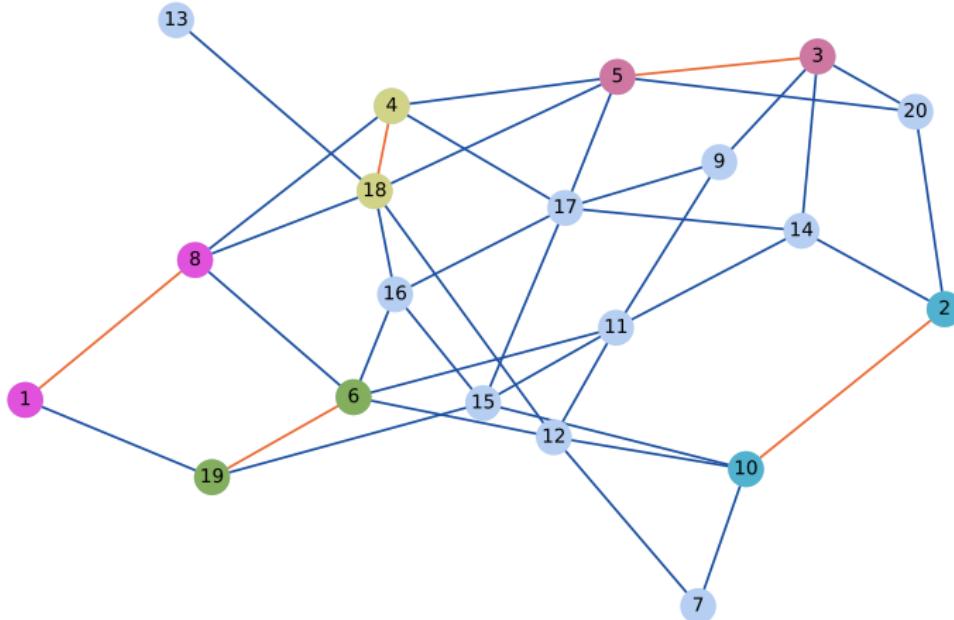
- The matching problem

- Greedy algorithm

Matching size: 5

Algo step: 17

Nb nodes: 20



...

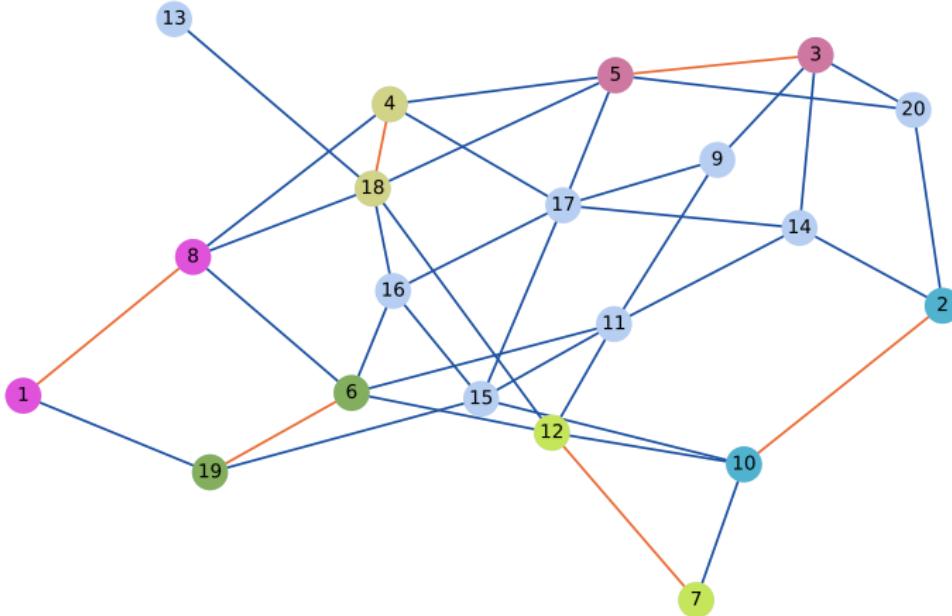
- The matching problem

- Greedy algorithm

Matching size: 6

Algo step: 22

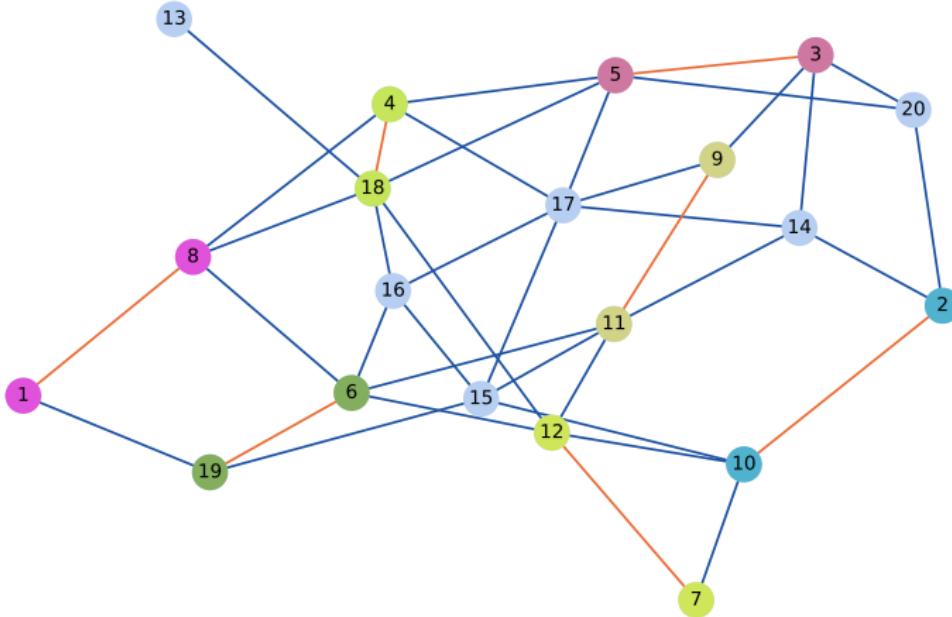
Nb nodes: 20



Matching size: 7

Algo step: 25

Nb nodes: 20



...

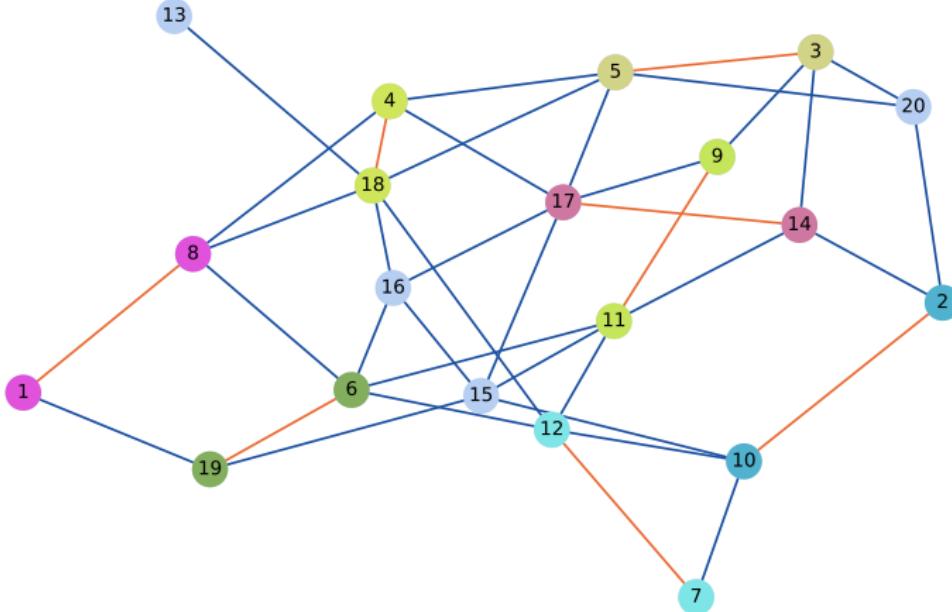
- The matching problem

- Greedy algorithm

Matching size: 8

Algo step: 34

Nb nodes: 20



...

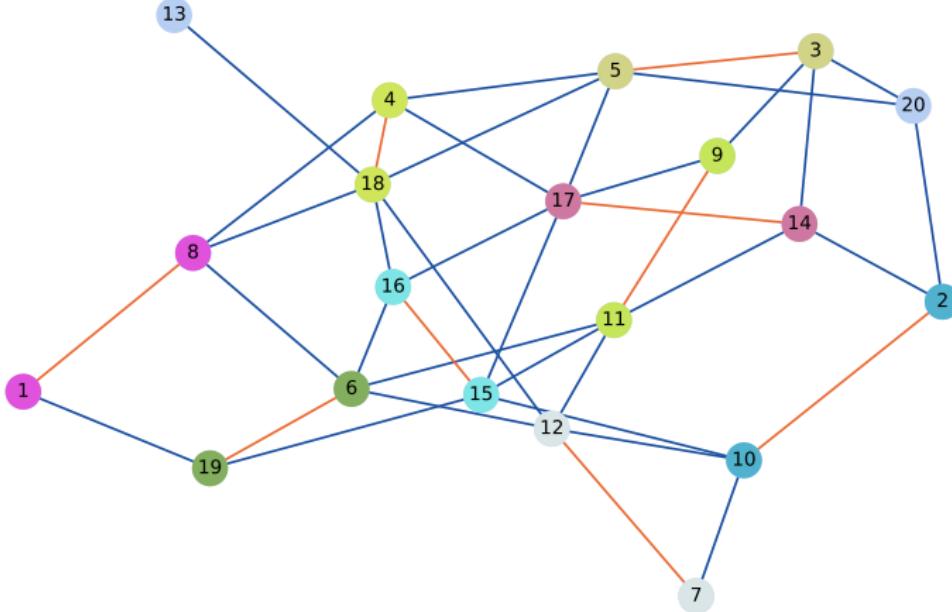
- The matching problem

- Greedy algorithm

Matching size: 9

Algo step: 36

Nb nodes: 20

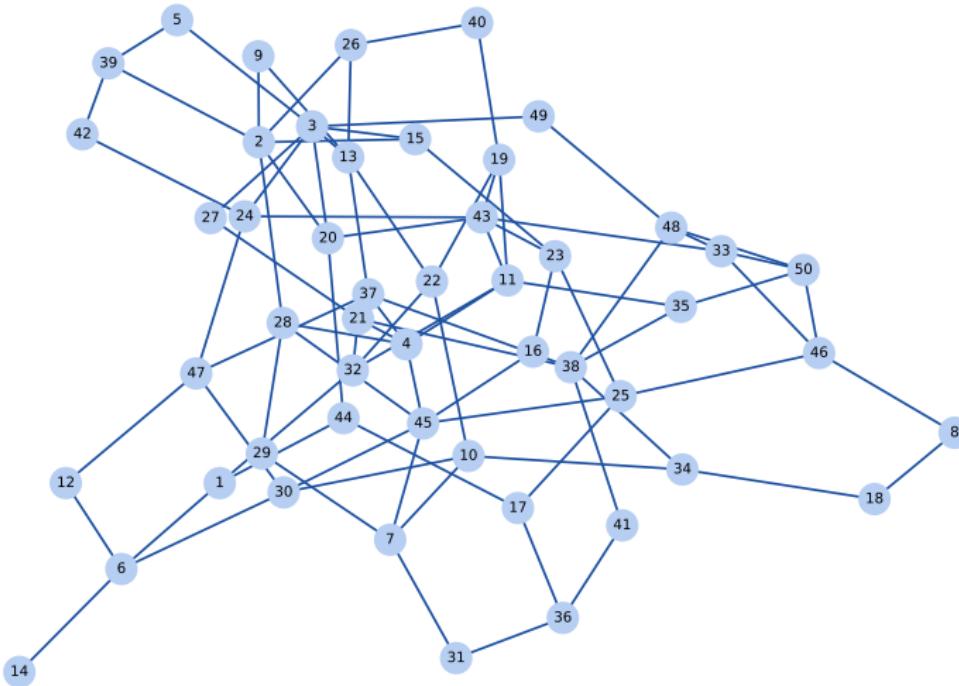


...

- The matching problem

- Greedy algorithm

initial graph

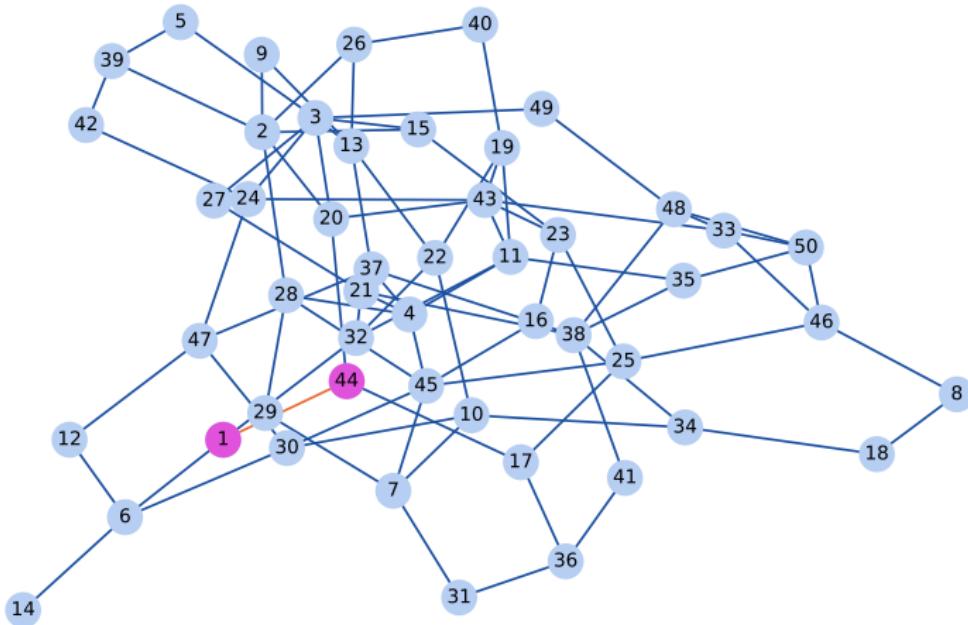


...

The matching problem

Greedy algorithm

Matching size: 1
Algo step: 1
Nb nodes: 50



...

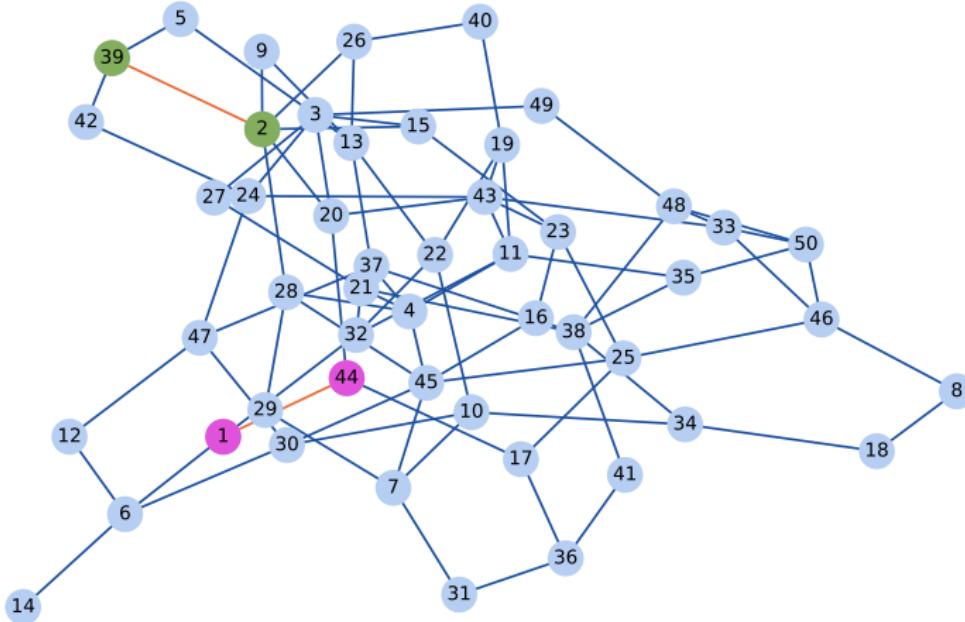
The matching problem

Greedy algorithm

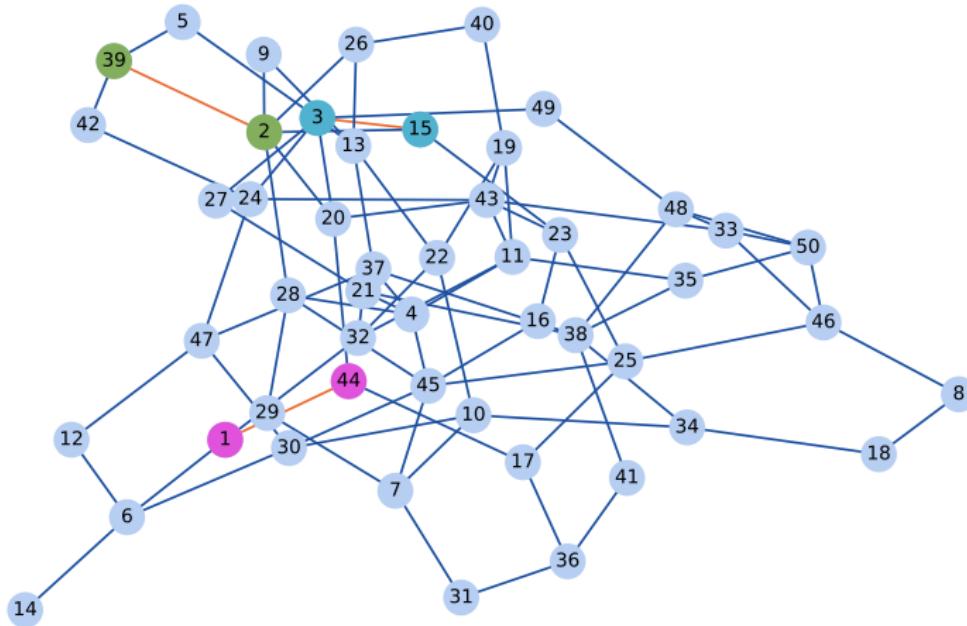
Matching size: 2

Algo step: 4

Nb nodes: 50



Matching size: 3
Algo step: 10
Nb nodes: 50

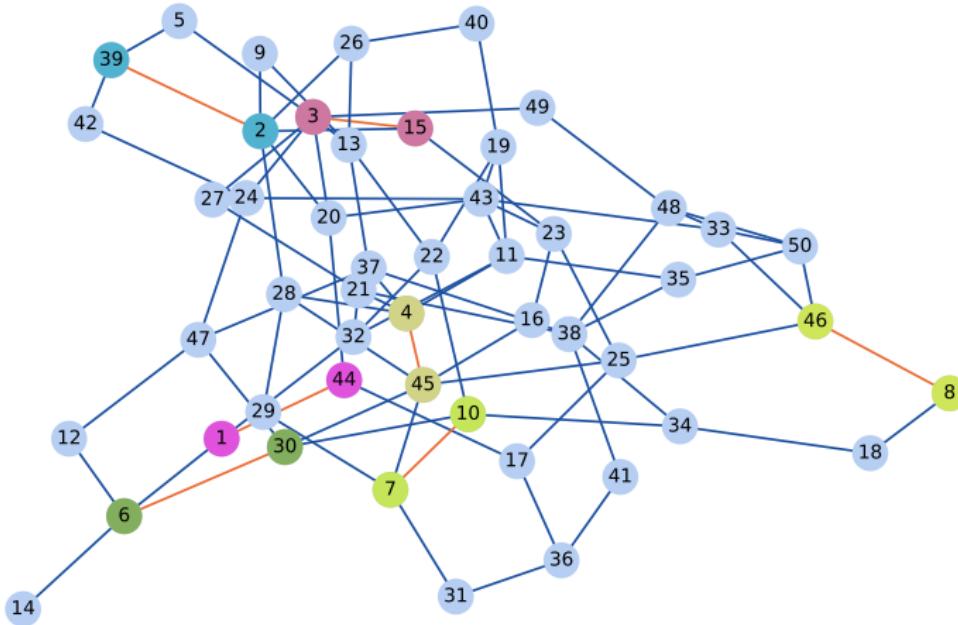


...

- The matching problem

- Greedy algorithm

Matching size: 7
Algo step: 30
Nb nodes: 50



...

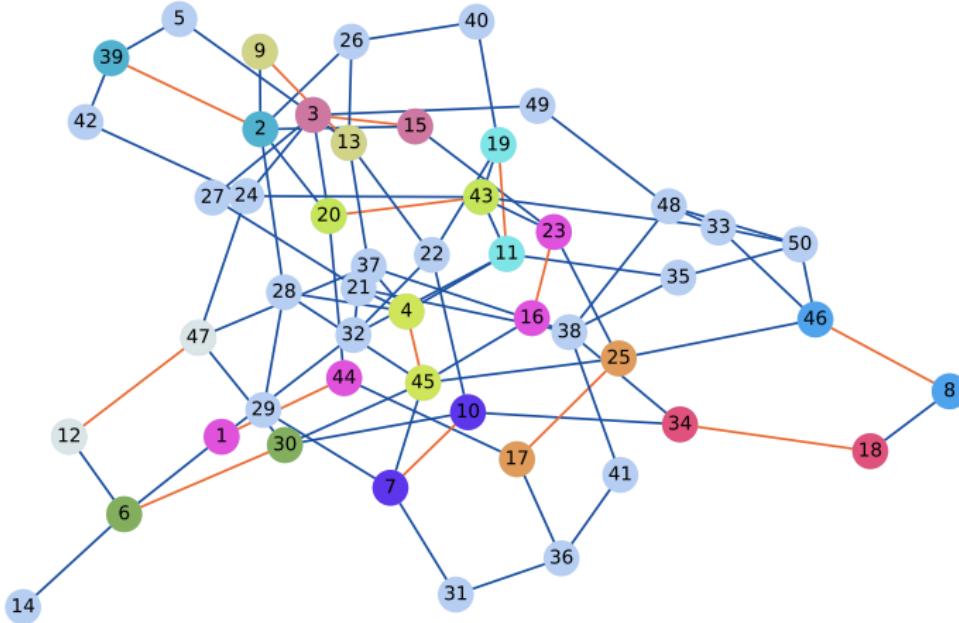
- The matching problem

- Greedy algorithm

Matching size: 14

Algo step: 54

Nb nodes: 50

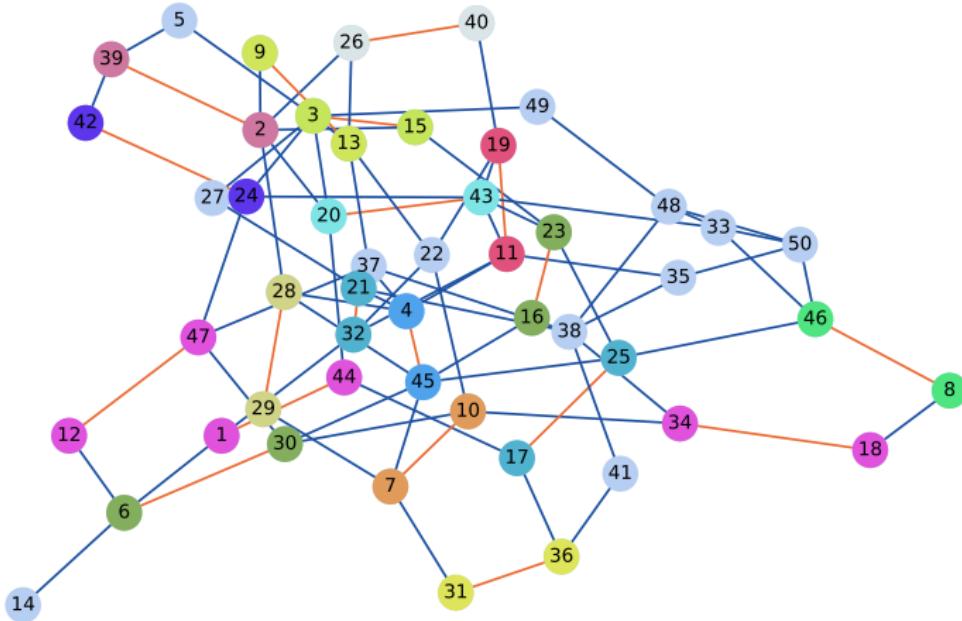


...

- The matching problem

- Greedy algorithm

Matching size: 19
Algo step: 72
Nb nodes: 50



...

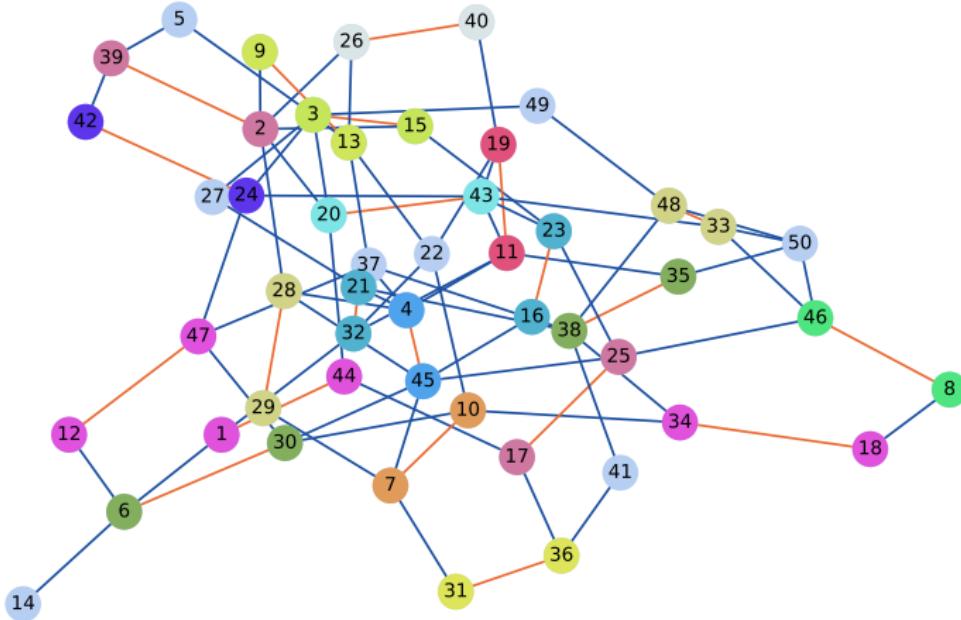
- The matching problem

- Greedy algorithm

Matching size: 21

Algo step: 78

Nb nodes: 50

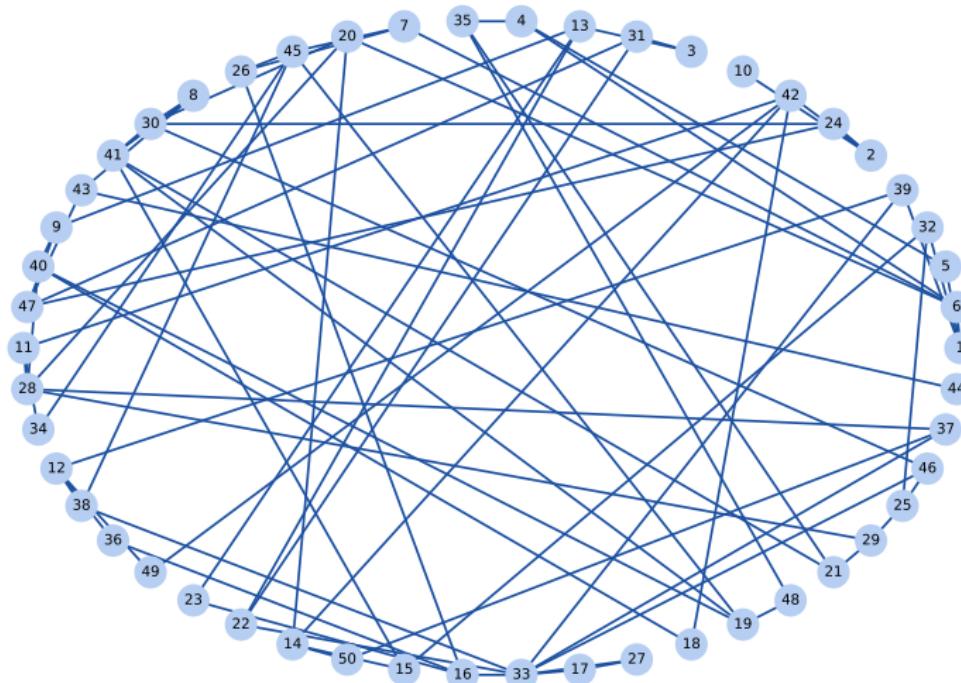


...

The matching problem

Greedy algorithm

initial graph



...

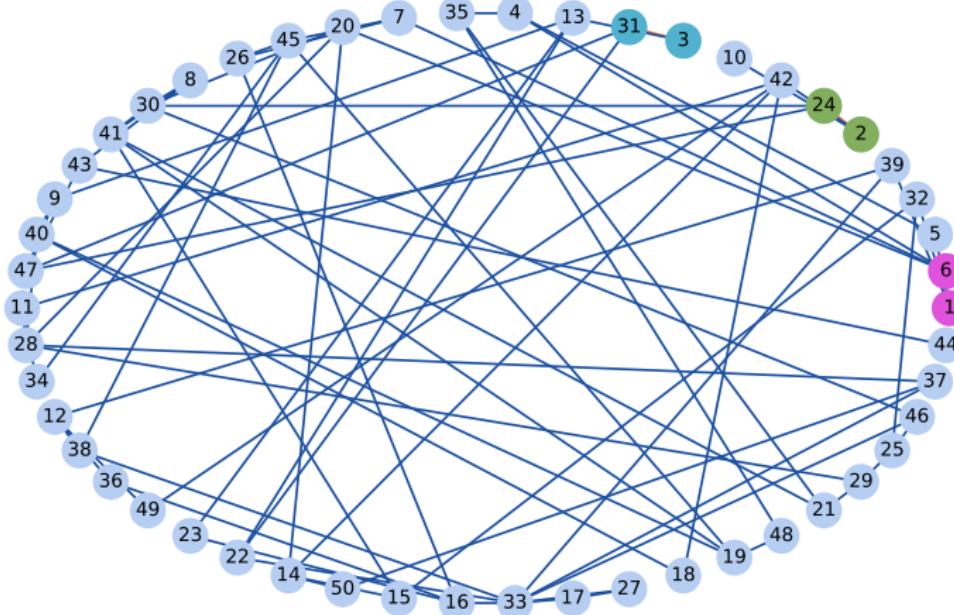
The matching problem

Greedy algorithm

Matching size: 3

Algo step: 8

Nb nodes: 50



...

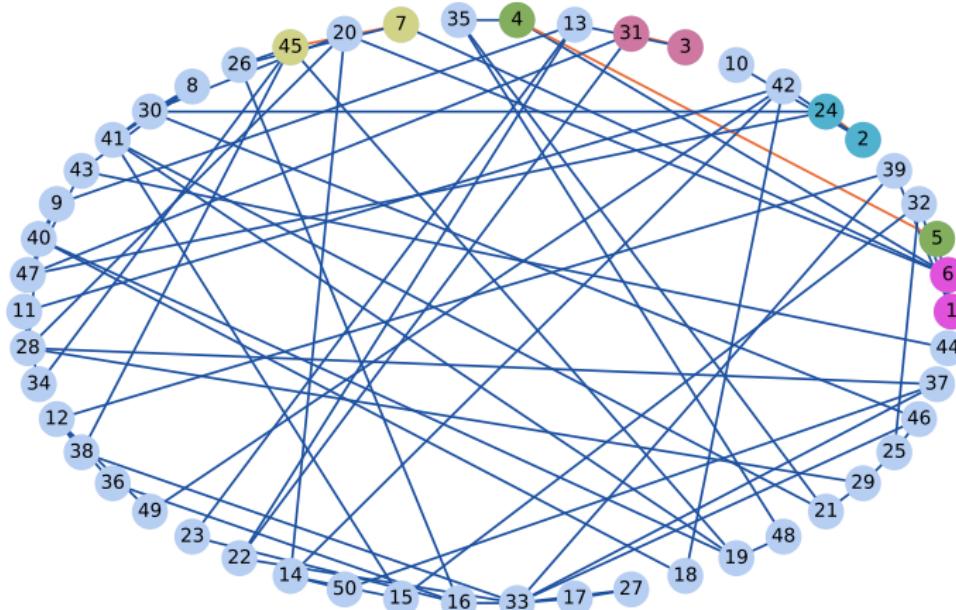
- The matching problem

- Greedy algorithm

Matching size: 5

Algo step: 15

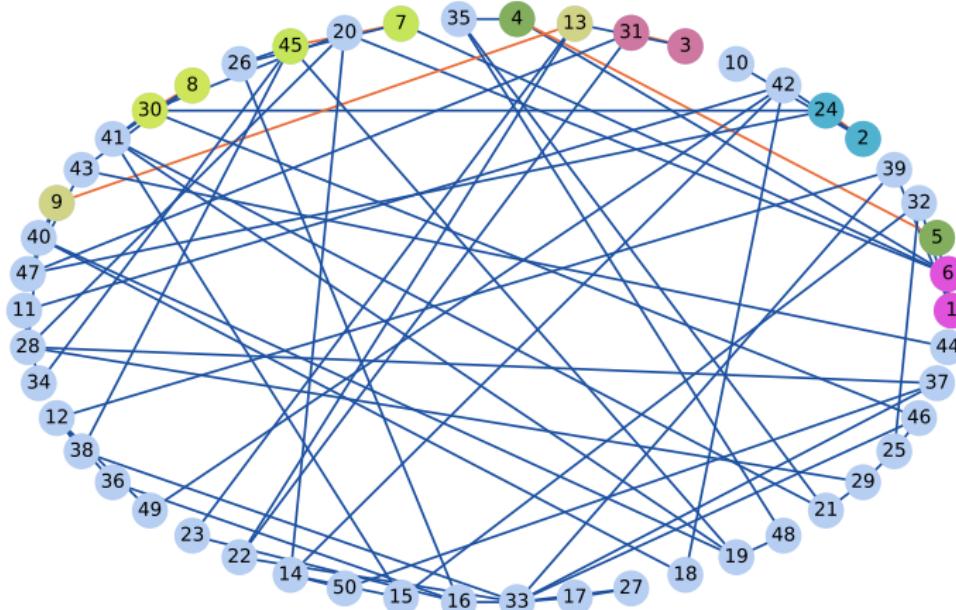
Nb nodes: 50



Matching size: 7

Algo step: 20

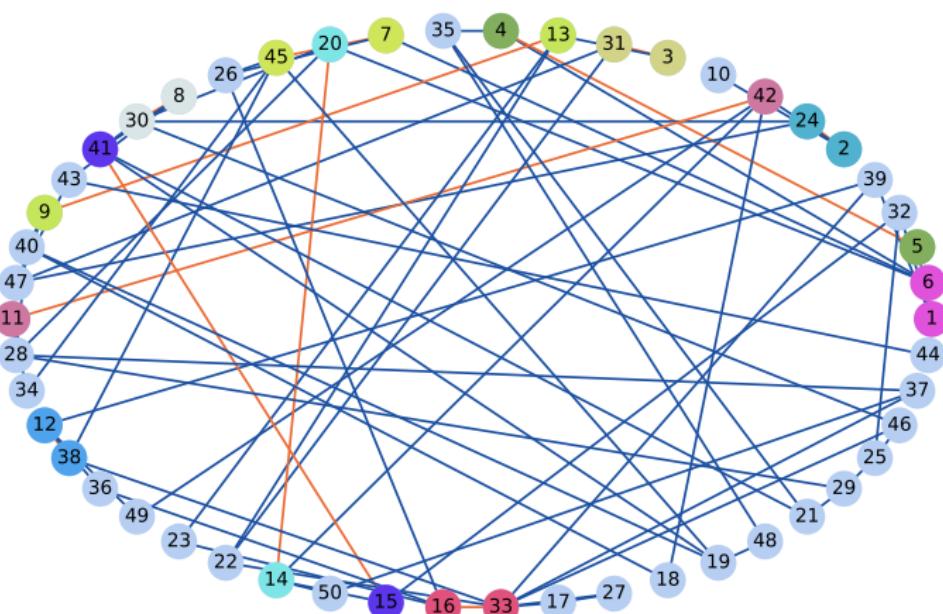
Nb nodes: 50



Matching size: 12

Algo step: 38

Nb nodes: 50



...

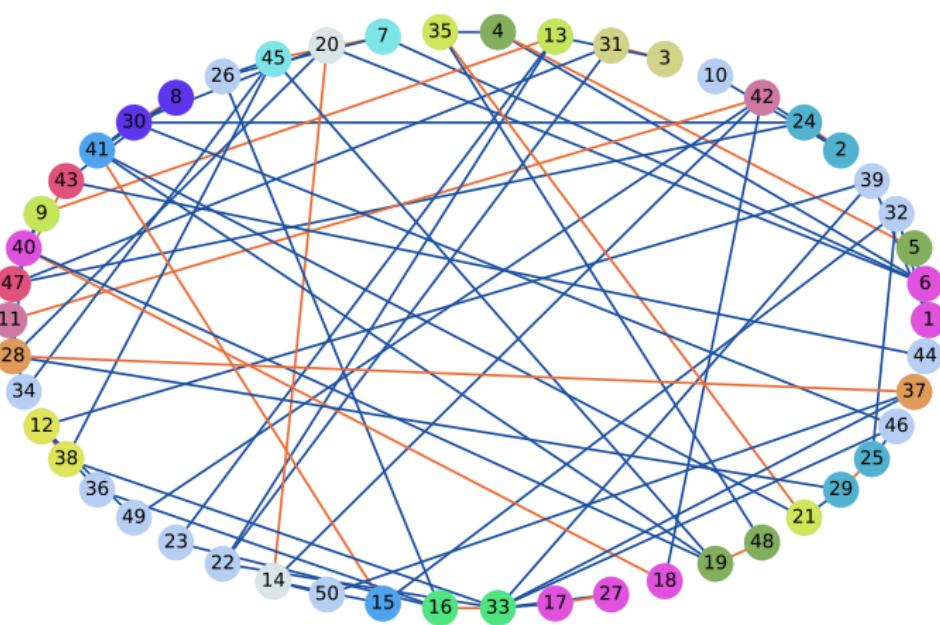
The matching problem

Greedy algorithm

Matching size: 19

Algo step: 79

Nb nodes: 50



Example

Exercice 9: Can you think of an example where the greedy algorithm gives a **bad** matching, e.g. of the size **half** the size of an optimal matching ?

...

- └ The matching problem

- └ Greedy algorithm

Example

Exercice 10: Can you think of an example where the greedy algorithm gives a **bad** matching, e.g. of the size **half** the size of an optimal matching ?



...

- └ The matching problem

- └ Greedy algorithm

Greedy matching

However, is $|M|$ is the cardinality of a matching returned by the greedy algorithm, and if $|M^*|$ is the cardinal of the real optimal matching, we have :

$$|M| \geq \frac{|M^*|}{2} \quad (5)$$

...

└ The Maximum flow problem

Changing the problem (for now)

We temporarily leave the maximum matching problem to focus on another problem : the **Maximum flow problem**

...

- └ The Maximum flow problem
- └ Presentation of the problem

Max flow



Figure: Optimizing the quantity of something transported from one place to another, under constraints

The Maximum flow problem

└ Presentation of the problem

Example

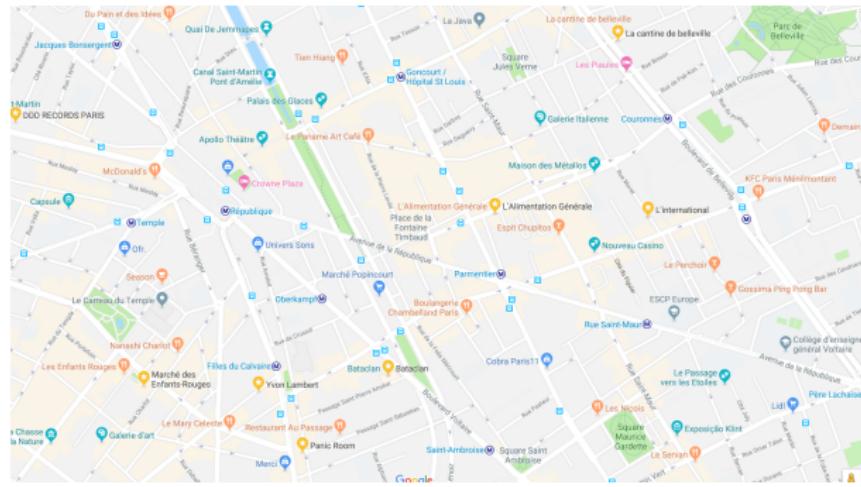


Figure: Optimizing the quantity of something transported from one place to another, under constraints

...

- └ The Maximum flow problem
- └ Presentation of the problem

Formalizing the problem

We introduce the concept of **flow network (reseau de flot)**.

...

- └ The Maximum flow problem
 - └ Presentation of the problem

Formalizing the problem

- ▶ A **Directed graph** $G = (E, V)$

...

- The Maximum flow problem

- Presentation of the problem

Formalizing the problem

We introduce the concept of **flow network (reseau de flot)**.

- ▶ A **Directed graph** $G = (E, V)$
- ▶ Each edge (u, v) must have a **capacity** $c(u, v) \geq 0$

...

- └ The Maximum flow problem
 - └ Presentation of the problem

Formalizing the problem

We introduce the concept of **flow network (reseau de flot)**.

- ▶ A **Directed graph** $G = (E, V)$
- ▶ Each edge (u, v) must have a **capacity** $c(u, v) \geq 0$
- ▶ We define two special nodes : a **source** E and a **sink** S .

Formalizing the problem

We introduce the concept of **flow network (reseau de flot)**.

- ▶ A **Directed graph** $G = (E, V)$
- ▶ Each edge (u, v) must have a **capacity** $c(u, v) \geq 0$
- ▶ We define two special nodes : a **source** E and a **sink** S .

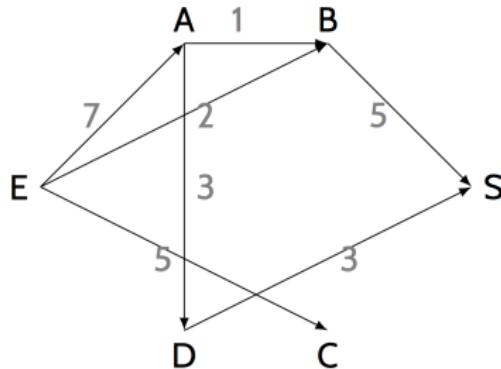


Figure: A **flow network (reseau de flot)** with capacities

...

- The Maximum flow problem

- Presentation of the problem

Formalizing the problem

We introduce the concept of **flow network (reseau de flot)**.

- ▶ A **Directed graph** $G = (E, V)$
- ▶ Each edge (u, v) must have a **capacity** $c(u, v) \geq 0$
- ▶ We define two special nodes : a **source** E and a **sink** S .
- ▶ A **flow** f is a function $f(u, v) \leq c(u, v)$ (+ additional constraints)

...

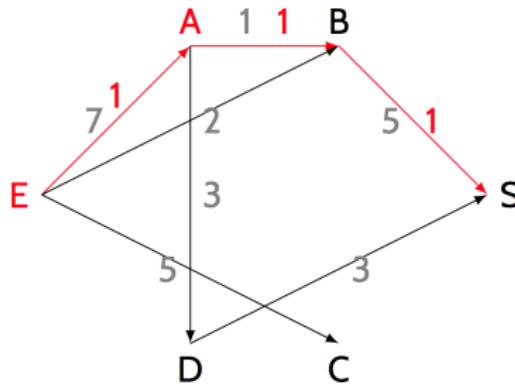
- The Maximum flow problem

- Presentation of the problem

Formalizing the problem

We introduce the concept of **flow network (reseau de flot)**.

- ▶ Each edge (u, v) must have a **capacity** $c(u, v) \geq 0$
- ▶ A **flow** f is a function $f(u, v) \leq c(u, v)$ (+ additional constraints)



...

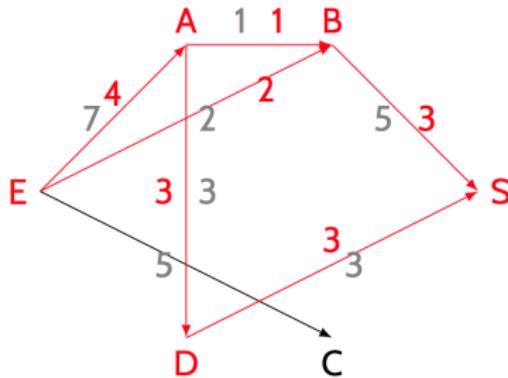
- The Maximum flow problem

- Presentation of the problem

Formalizing the problem

We introduce the concept of **flow network (reseau de flot)**.

- ▶ Each edge (u, v) must have a **capacity** $c(u, v) \geq 0$
- ▶ A flow f is a function $f(u, v) \leq c(u, v)$ (+ additional constraints)



...

└ The Maximum flow problem

 └ Presentation of the problem

Conservation of the flow

We must have :

- ▶ antisymmetry : $f(v, u) = -f(u, v)$
- ▶ flow conservation

...

- └ The Maximum flow problem

- └ Presentation of the problem

conservation of the flow

we must have :

- ▶ antisymmetry : $f(v, u) = -f(u, v)$
- ▶ flow conservation : $\sum_{w \in V} f(u, w) = 0$ for $u \notin \{e, s\}$

...

- └ The Maximum flow problem

- └ Presentation of the problem

Other formulation of the flow conservation

Let us show that for a flow f :

$$\sum_{f(u,v)>0} f(u,v) = \sum_{f(v,u)>0} f(v,u) \quad (6)$$

...

- The Maximum flow problem

- Presentation of the problem

Maximum flow

- The **value of the flow**, noted $|f|$, is $\sum_{v \in S} f(E, v)$
- The problem is that of finding a flow with **maximum value**

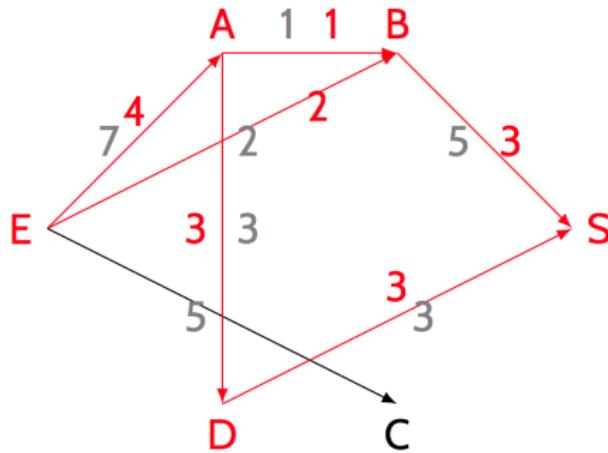


Figure: Max flow

Ford Fulkerson algorithm

We will introduce an algorithm to solve the problem. This algorithm :

- ▶ terminates
- ▶ is correct
- ▶ is polynomial

Ford Fulkerson algorithm

We will introduce an algorithm to solve the problem. This algorithm :

- ▶ terminates
- ▶ is correct
- ▶ is polynomial

So it is a good algorithm.

Ford Fulkerson algorithm

We will introduce an algorithm to solve the problem. This algorithm :

- ▶ terminates
- ▶ is correct
- ▶ is polynomial

So it a good algorithm. **This section is going to be a little bit technical.**

...

└ The Maximum flow problem

 └ Solution with the Ford-Fulkerson algorithm

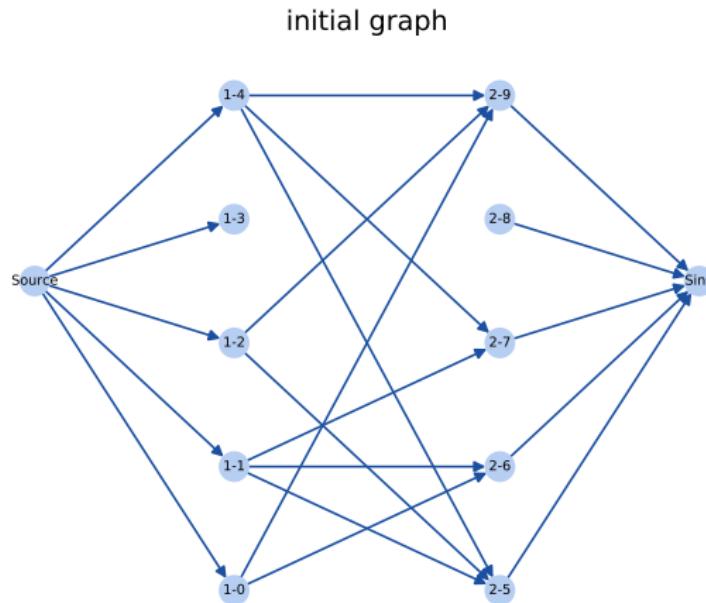
Residual graph

- ▶ Given a graph with capacities $c(u, v)$ and a flow $f(u, v)$, we will define its **residual graph** that has a capacity $c_r(u, v)$:

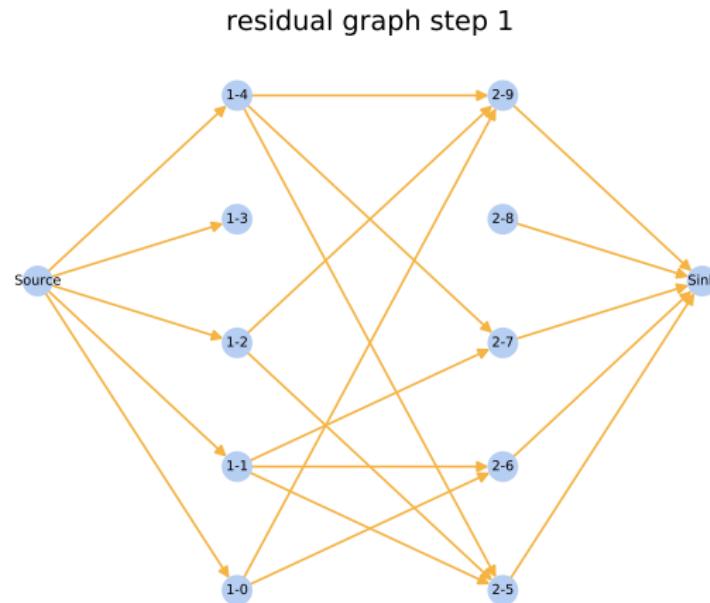
$$c_r(u, v) = c(u, v) - f(u, v) \quad (7)$$

- ...
└ The Maximum flow problem
 └ Solution with the Ford-Fulkerson algorithm

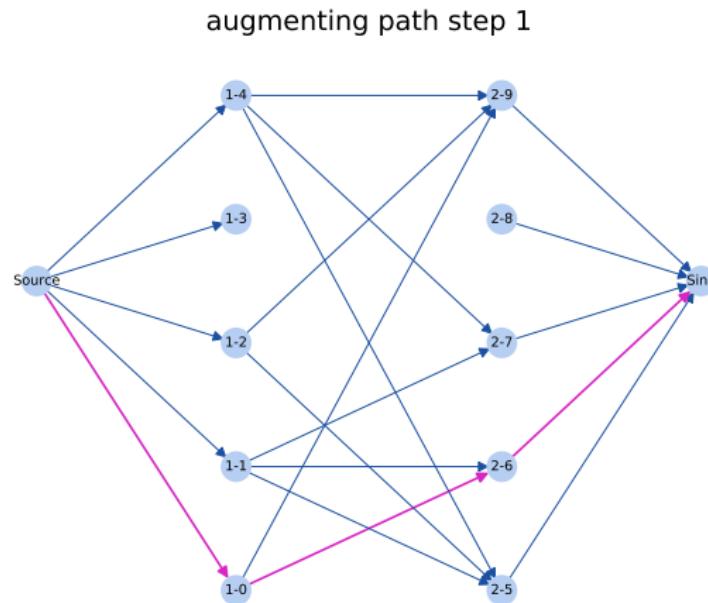
Example of residual graph



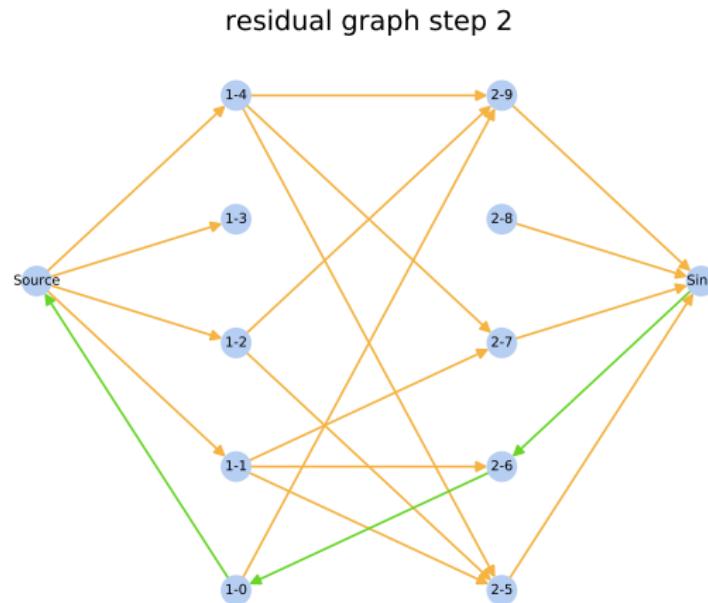
Example of residual graph



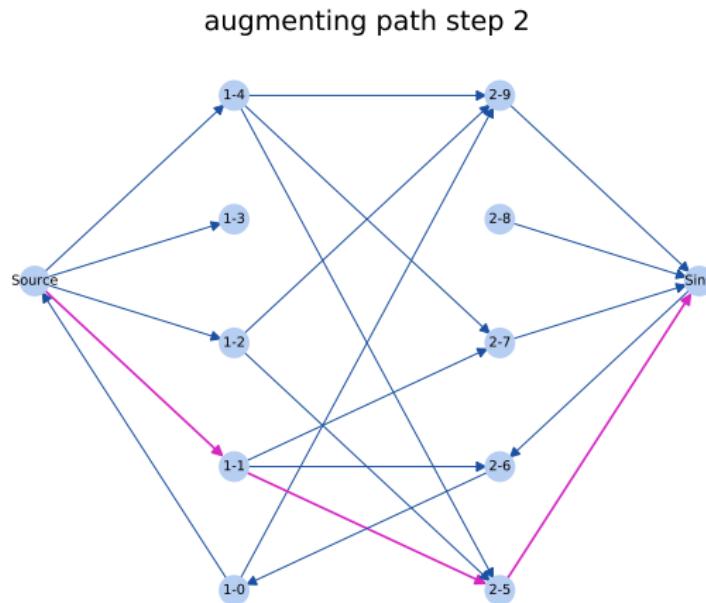
Example of residual graph



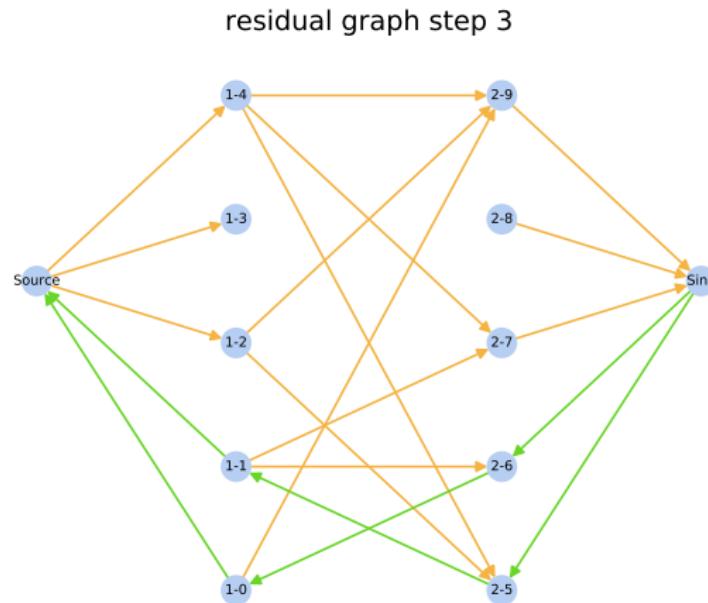
Example of residual graph



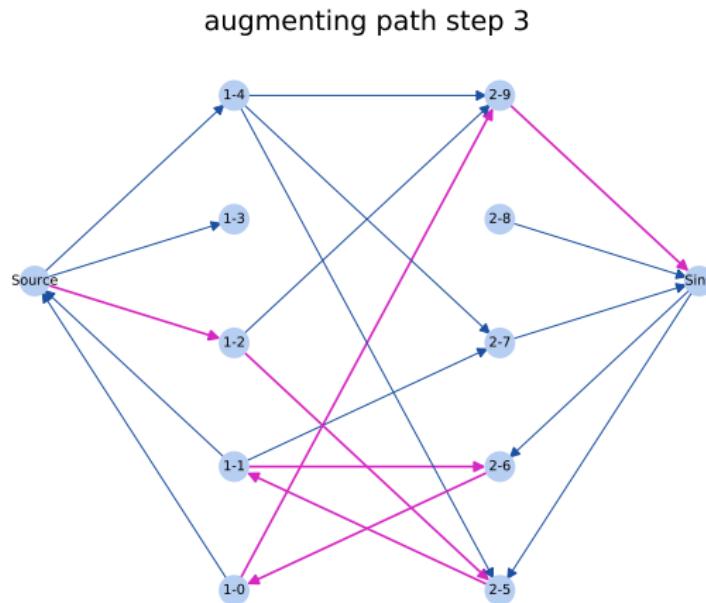
Example of residual graph



Example of residual graph



Example of residual graph



Residual graph

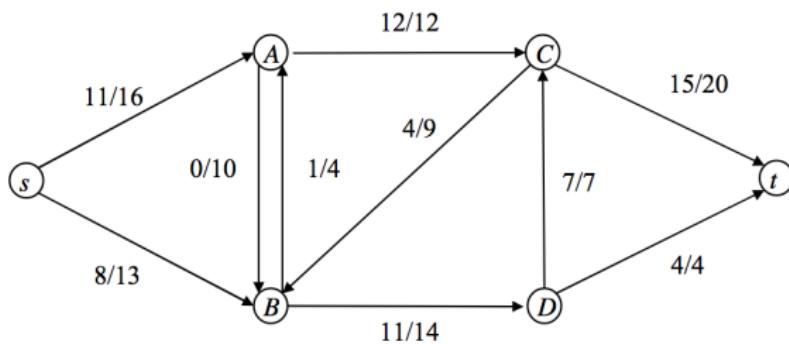


Figure: Another flow network

Residual graph

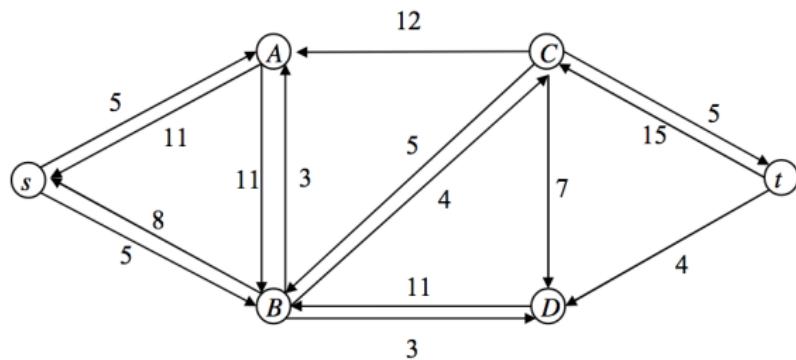


Figure: Residual graph

...

└ The Maximum flow problem

└ Solution with the Ford-Fulkerson algorithm

Augmenting path

An augmenting path is a path in the **residual graph** from the source to the sink with capacities > 0 .

Augmenting path

An augmenting path is a path in the **residual graph** from the source to the sink with capacities > 0 .

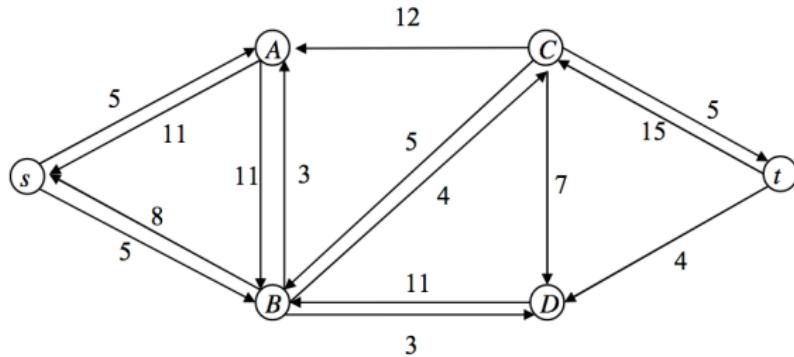


Figure: Residual graph

Augmenting path

An augmenting path is a path from the source to the sink with capacities > 0 .

The Ford-Fulkerson algorithm uses augmenting paths until there are no more augmenting paths.

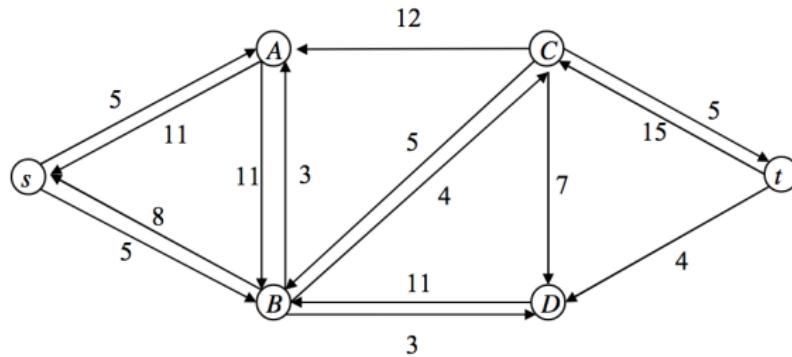


Figure: Residual graph

...

└ The Maximum flow problem

└ Solution with the Ford-Fulkerson algorithm

Ford Fulkerson algorithm

Can you deduce the algorithm from the previous remarks ?

Ford Fulkerson algorithm

Result: Flow f

for $(u, v) \in E$ **do**

 | $f(u, v) = 0$

end

while $\exists \rho$ augmenting path **do**

 | augment f with ρ

end

return f

Algorithm 1: Ford Fulkerson algorithm

...

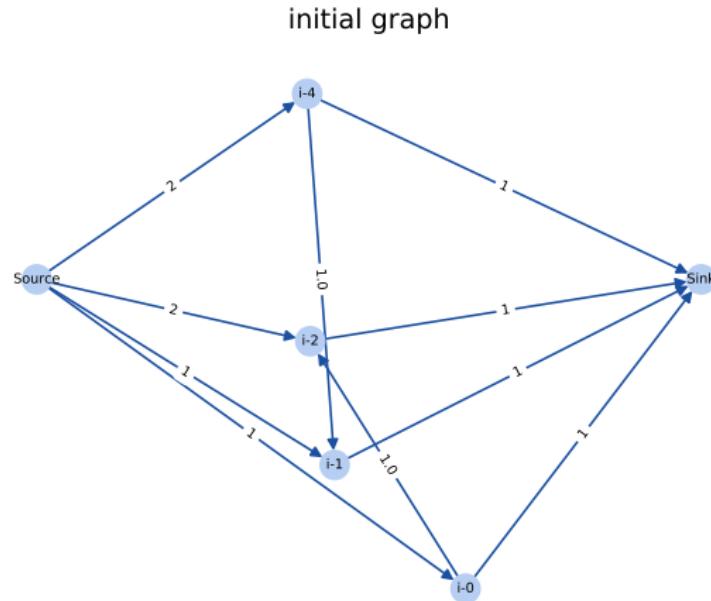
└ The Maximum flow problem

 └ Solution with the Ford-Fulkerson algorithm

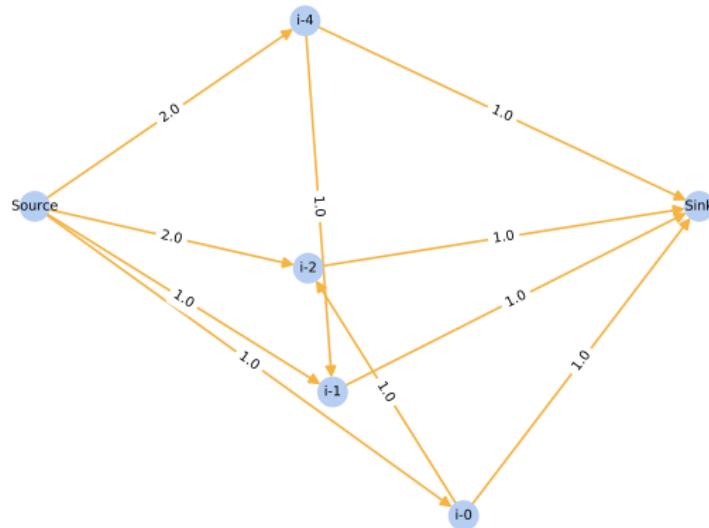
Ford-Fulkerson algorithm

Let us some complete instances of the algorithm:

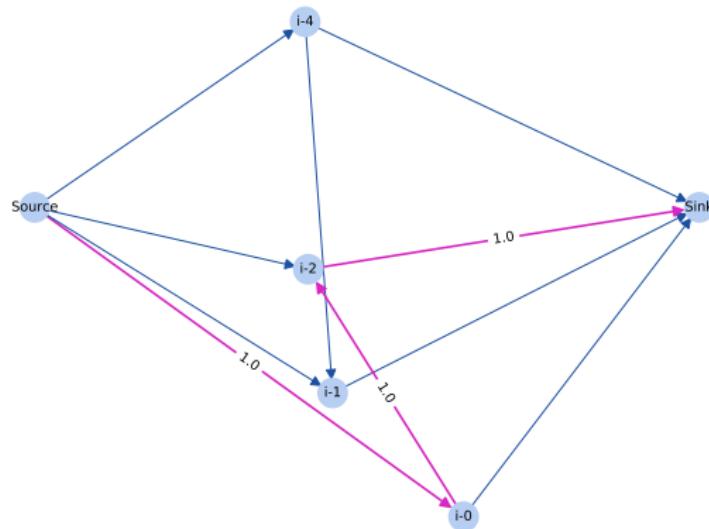
- ...
└ The Maximum flow problem
└ Solution with the Ford-Fulkerson algorithm



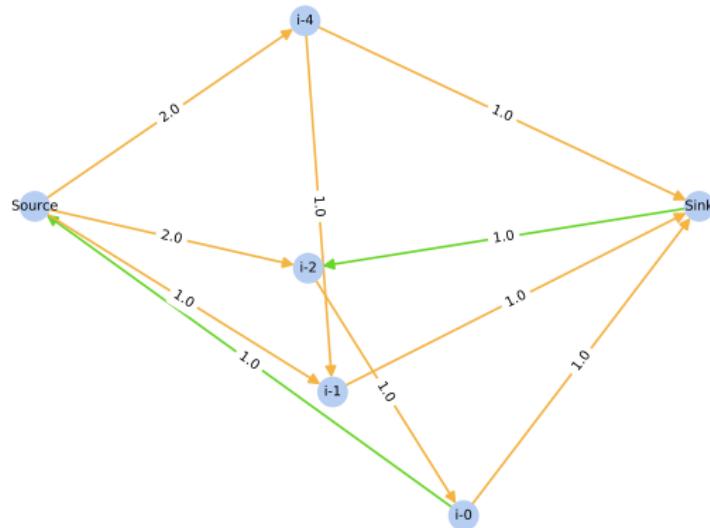
residual graph step 1



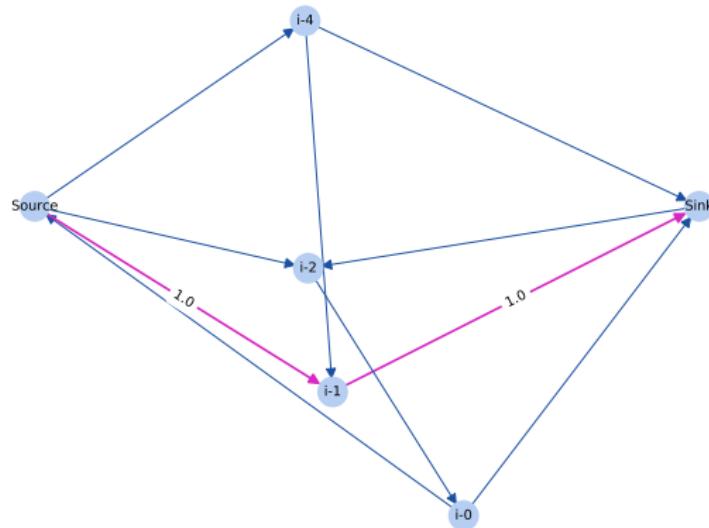
augmenting path step 1



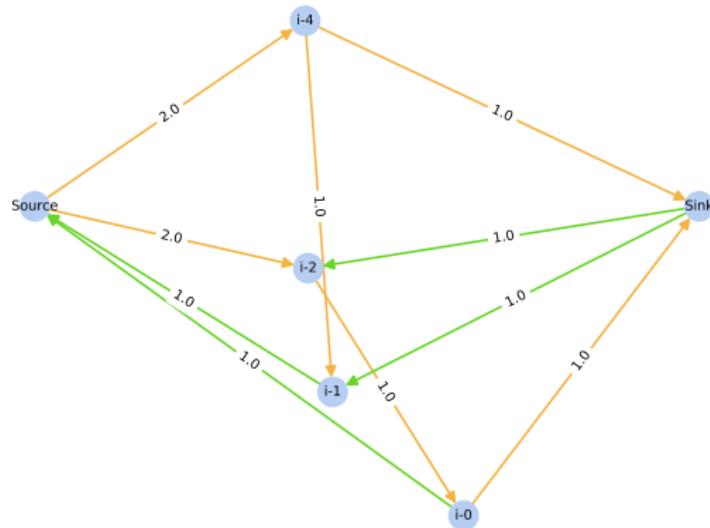
residual graph step 2



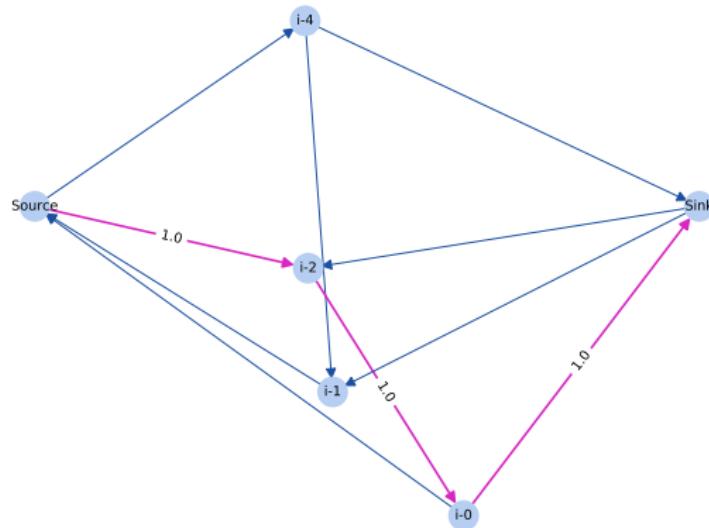
augmenting path step 2



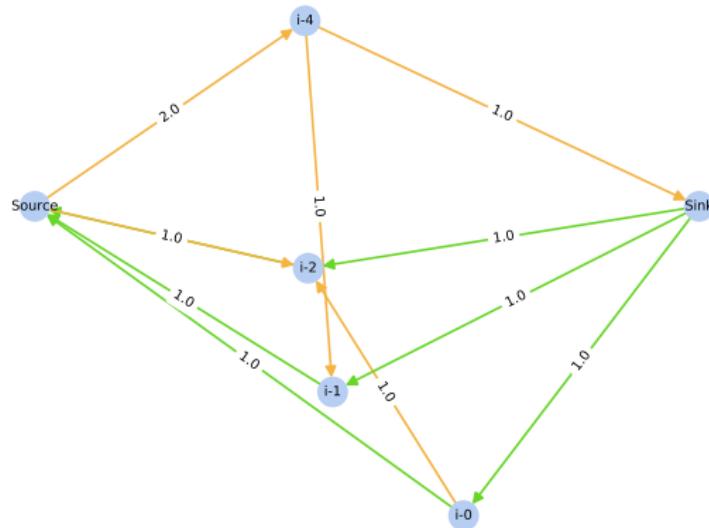
residual graph step 3



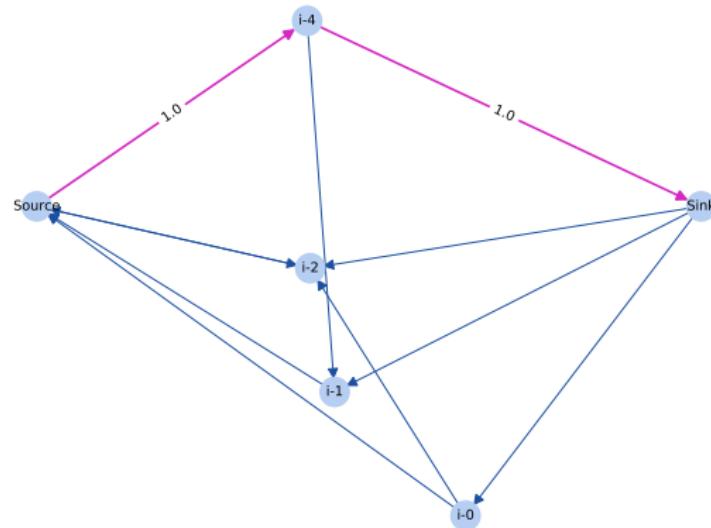
augmenting path step 3



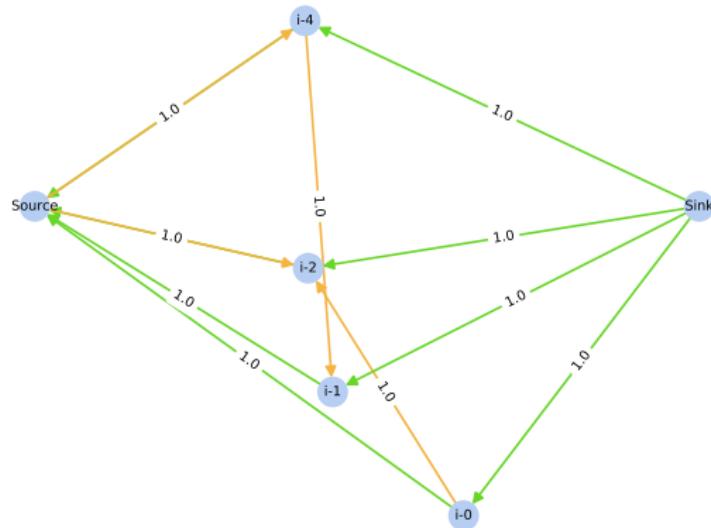
residual graph step 4



augmenting path step 4



residual graph step 5



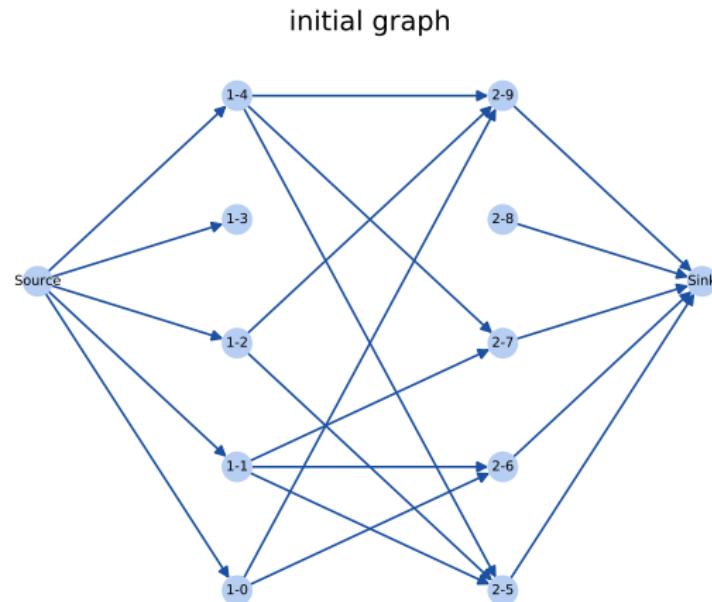
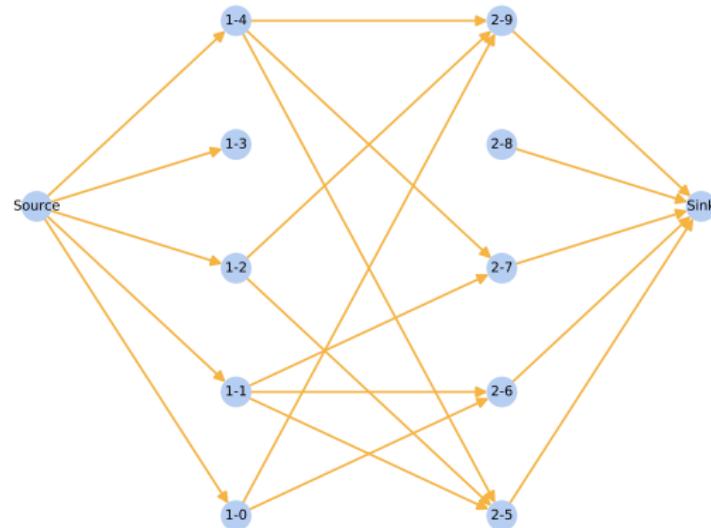
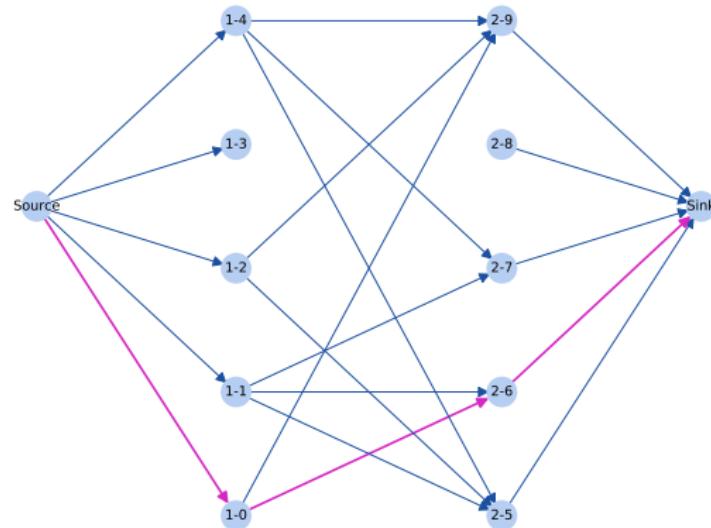


Figure: simple/initial

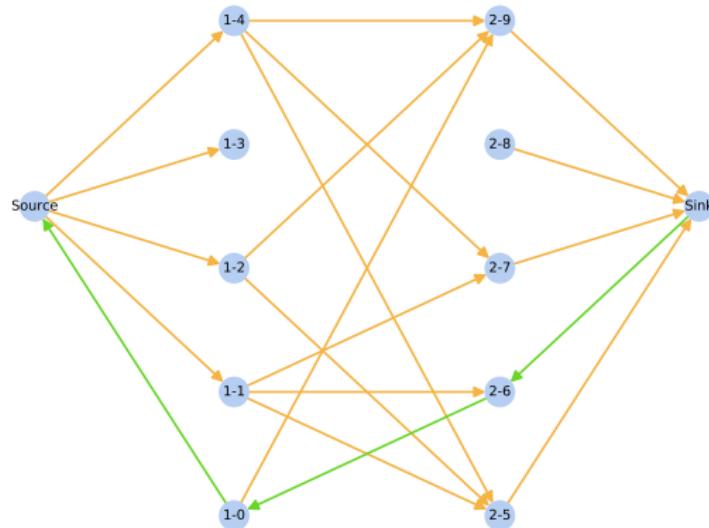
residual graph step 1



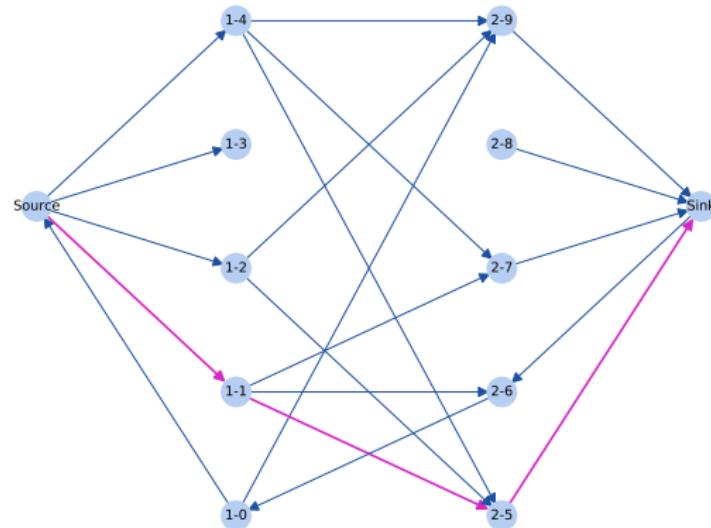
augmenting path step 1



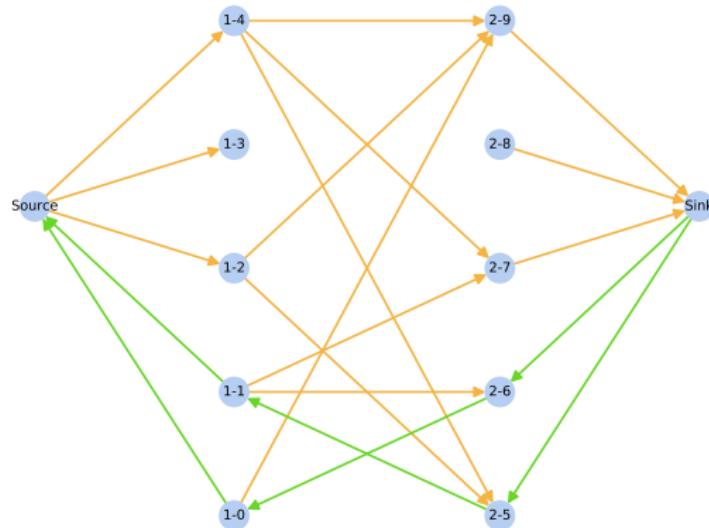
residual graph step 2



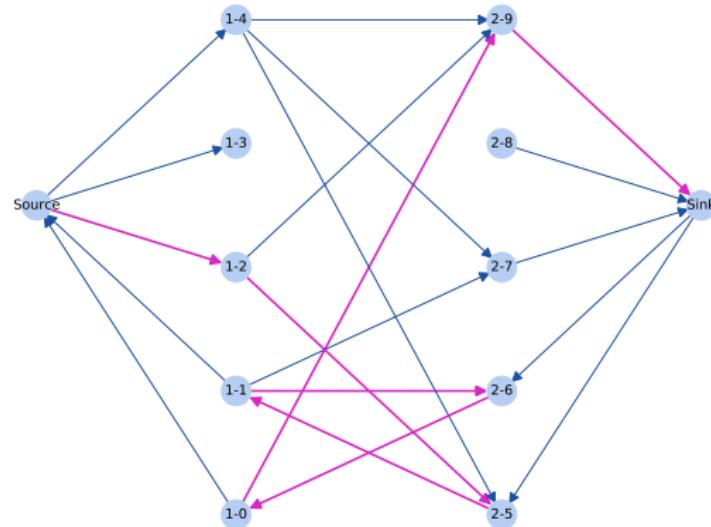
augmenting path step 2



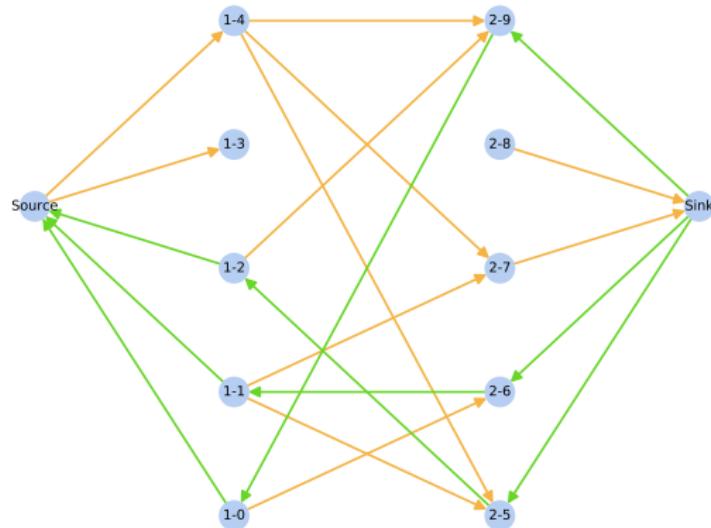
residual graph step 3



augmenting path step 3

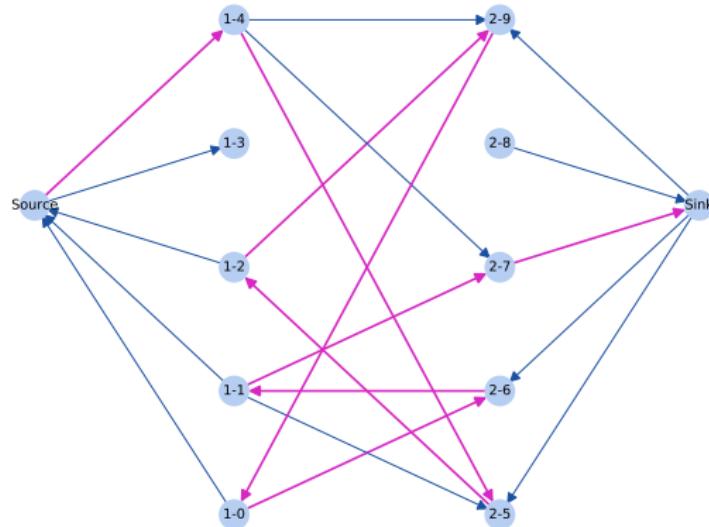


residual graph step 4

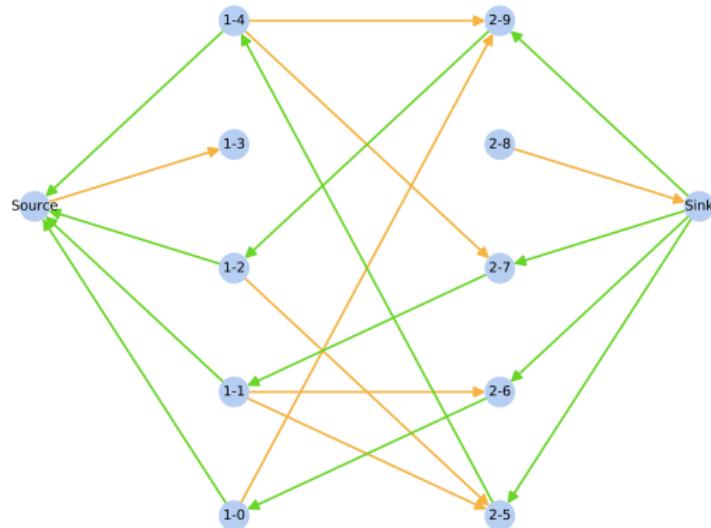


- ...
└ The Maximum flow problem
└ Solution with the Ford-Fulkerson algorithm

augmenting path step 4



residual graph step 5



...

└ The Maximum flow problem

 └ Solution with the Ford-Fulkerson algorithm

Ford Fulkerson algorithm

- ▶ We will implement the Ford Fulkerson algorithm (1956) on a general graph.

...

└ The Maximum flow problem

 └ Solution with the Ford-Fulkerson algorithm

Ford Fulkerson algorithm

Exercice 10: We will implement the Ford Fulkerson algorithm (1956)

- ▶ **cd ford_fulkerson/** and edit **generate_flow_network.py** to generate a flow network.

...

└ The Maximum flow problem

└ Solution with the Ford-Fulkerson algorithm

Algorithm

- ▶ We will now use the functions contained in **ford_functions.py** and call them from **apply_ford_fulkerson.py**

Algorithm

Exercice 11 : step 1

- ▶ Modify **find_augmenting_paths()** in order to find the augmenting paths.

Algorithm

Exercice 11 : step 2

- ▶ now edit **augment_flow()**

...

└ The Maximum flow problem

 └ Solution with the Ford-Fulkerson algorithm

Algorithm

Exercice 11 : step 3

- ▶ finally, edit the computation of the value of the flow

...

└ The Maximum flow problem

└ Solution with the Ford-Fulkerson algorithm

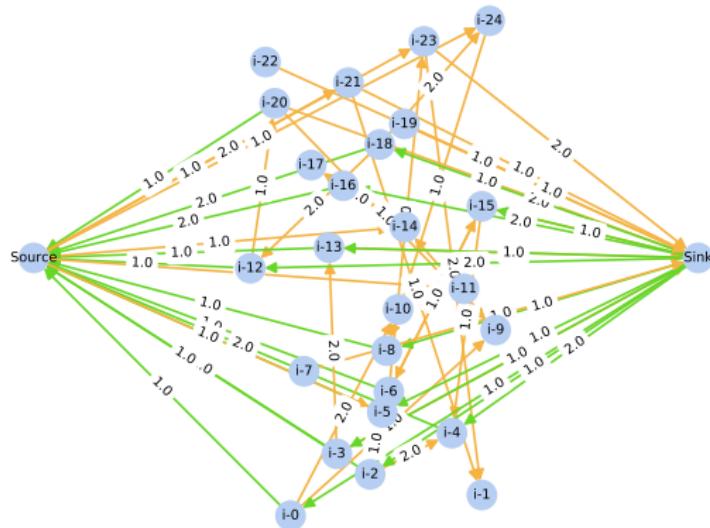
- ▶ Now the algorithm should be able to run

...

- The Maximum flow problem

- Solution with the Ford-Fulkerson algorithm

residual graph step 15



- ...
└ The Maximum flow problem
 └ Solution with the Ford-Fulkerson algorithm

Complexity

What is the complexity of Ford Fulkerson ?

...

└ The Maximum flow problem

 └ Solution with the Ford-Fulkerson algorithm

Complexity

What is the complexity of Ford Fulkerson ?

$$\mathcal{O}(|f^*| \times |E|) \tag{8}$$

...

└ The Maximum flow problem

 └ Solution with the Ford-Fulkerson algorithm

Modification of Ford Fulkerson

What would we an intuitive and potentially faster modification of the algorithm ?

...

└ The Maximum flow problem

 └ Solution with the Ford-Fulkerson algorithm

Modification of the algorithm

What would we an intuitive and potentially faster modification of the algorithm ?

Use the shortest augmenting path with positive capacity.

...

└ The Maximum flow problem

 └ Solution with the Ford-Fulkerson algorithm

Termination

- ▶ When the capacities are **integer numbers** or **rational numbers** Ford Fulkerson terminates.

...

└ The Maximum flow problem

 └ Solution with the Ford-Fulkerson algorithm

Termination

- ▶ When the capacities are **integer numbers** or **rational numbers** Ford Fulkerson terminates.
- ▶ However, when the capacities are general **real numbers**, the algorithm might not terminate.

...

└ The Maximum flow problem

└ Connection with the matching problem

Link with the matching problem

- ▶ We now go back to the matching problem, in the case of a **bipartite graph** ("problme d'affectation")
- ▶ We will show that in that case, we can connect the two problems.

...

- └ The Maximum flow problem

- └ Connection with the matching problem

Bipartite graph

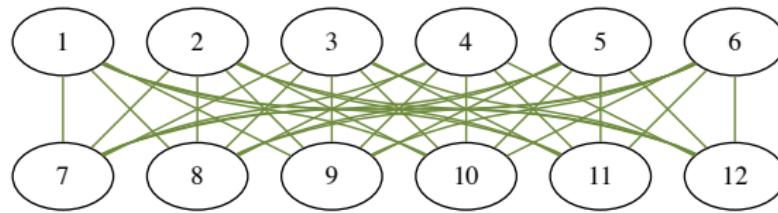


Figure: Complete bipartite graph (not all bipartite graphs are complete)

Matching problem

We now go back to the matching problem, in the case of a **bipartite graph**.

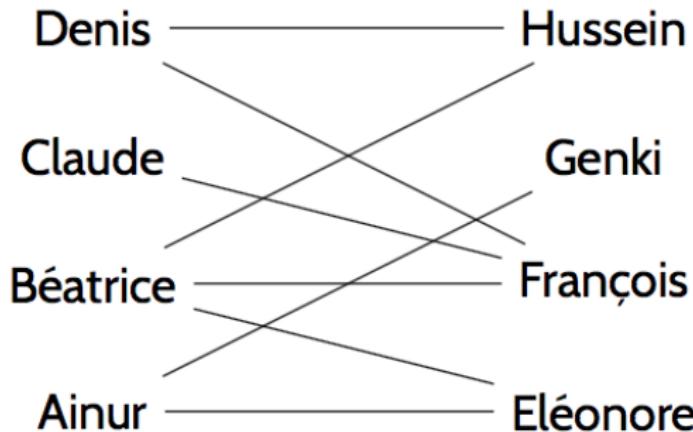


Figure: Bipartite graph

Equivalence between matching and flow

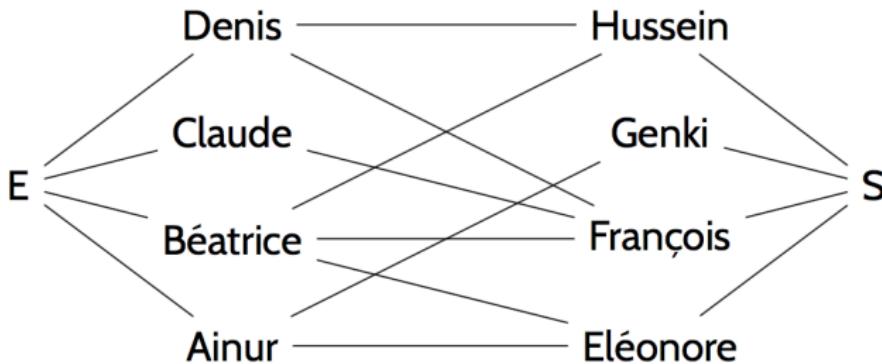


Figure: Introduce two more nodes. All edges have capacity 1. We consider **flows with integer values**

Ford Fulkerson for matching

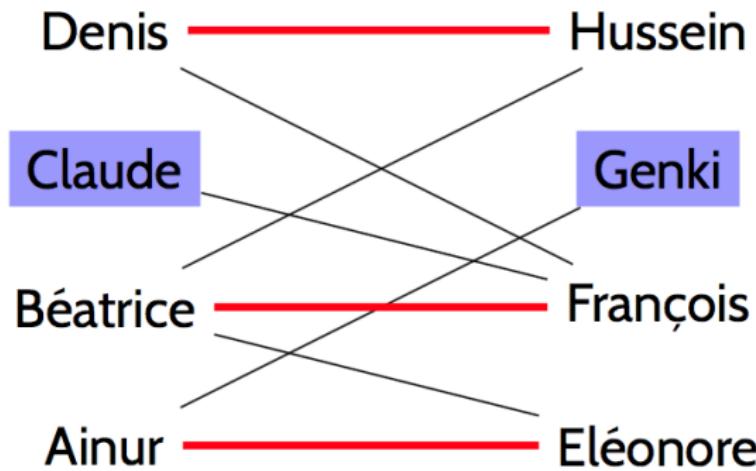


Figure: Non optimal solution

Ford Fulkerson for matching

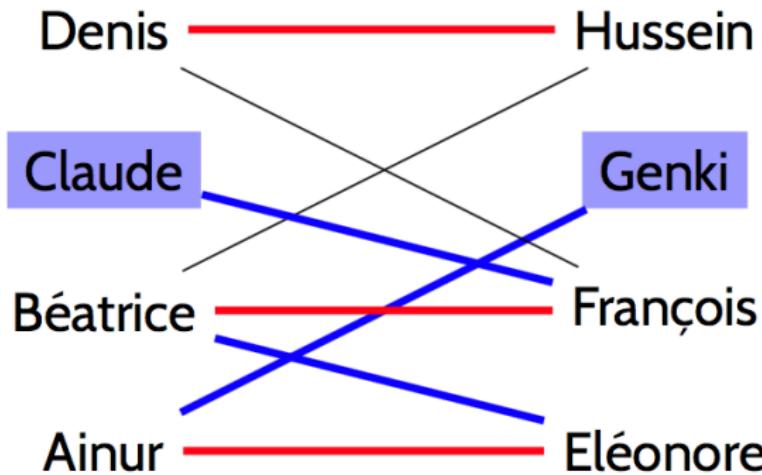


Figure: Optimal solution

Connection

Exercice 11: Find a connection between the two problems

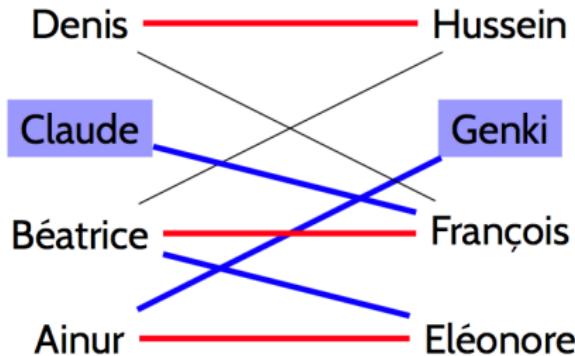


Figure: Optimal solution

Exercice 12 : Ford Fulkerson and matching

- ▶ We will transpose Ford Fulkerson to a bipartite graph in order to find an optimal matching.
- ▶ **cd ford_matching/**
- ▶ edit **generate_matching_problem.py** in order to generate an instance of the problem.

...

└ The Maximum flow problem

└ Connection with the matching problem

Exercice 12: Ford Fulkerson and matching

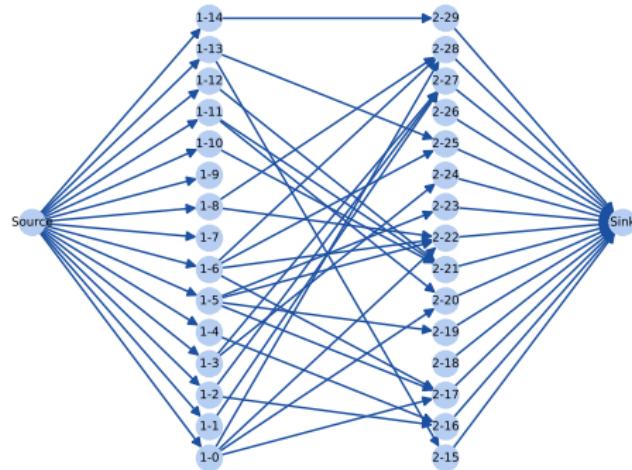
- ▶ Apply the algorithm on an example generated by the previous function.
- ▶ Apply the algorithm to as an instance of your choice.

...

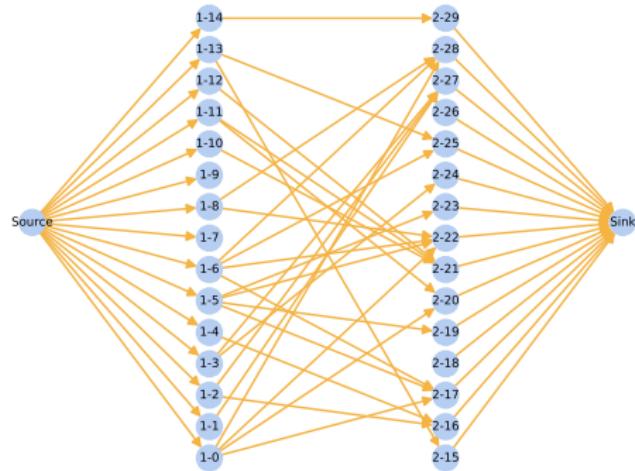
The Maximum flow problem

Connection with the matching problem

initial graph



residual graph step 1

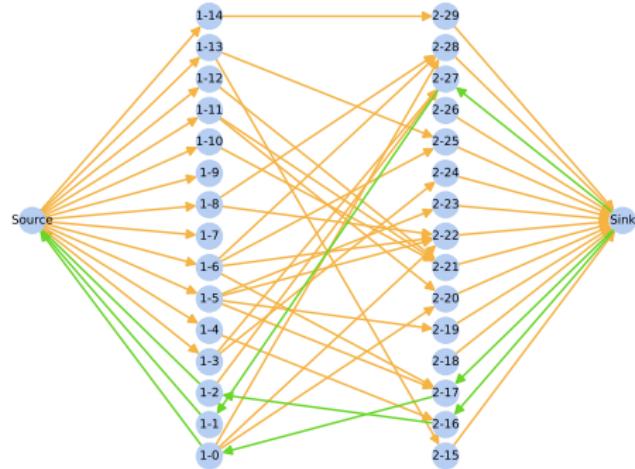


...

- The Maximum flow problem

- Connection with the matching problem

residual graph step 4

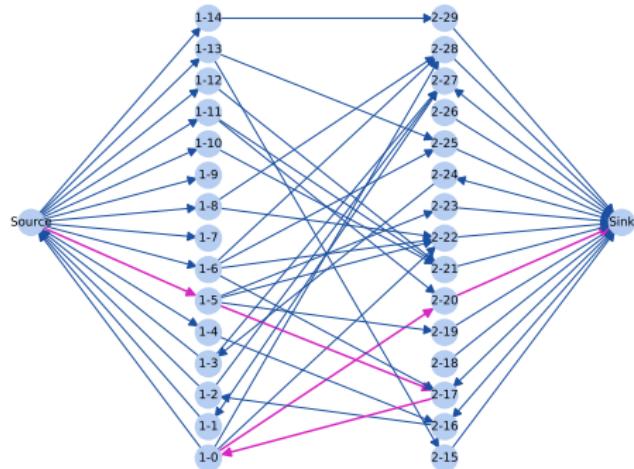


...

- The Maximum flow problem

- Connection with the matching problem

augmenting path step 5

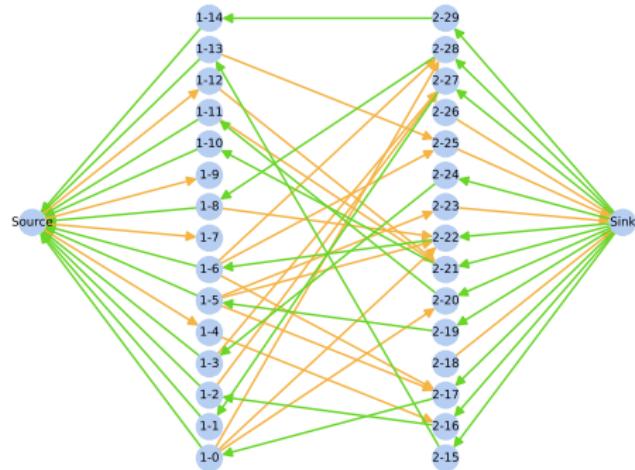


...

The Maximum flow problem

Connection with the matching problem

residual graph step 12



Famous theorem

The maximum flow theorem is equivalent to another famous problem, the **minimum cut** theorem.

Perfect matching

In the case of a bipartite graph, what is the best matching possible ?

Perfect matching

In the case of a bipartite graph, what is the best matching possible ?

A matching where **all nodes are allocated**. It is called a **perfect** matching.

We must have that the two parts of the graph are of same cardinality in order to have a perfect matching.

Hall's marriage theorem

This theorem gives a condition that is necessary and sufficient for the existence of a perfect matching in a bipartite graph : the "marriage condition".

If $G = (U, V, E)$ is bipartite, the condition means that :

$$\forall X \subset U, |N_G(X)| \geq |X| \tag{9}$$

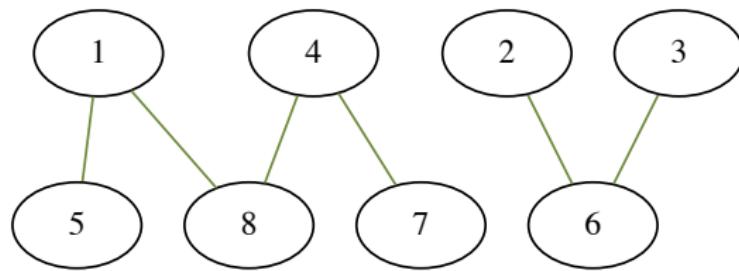
where $N_G(X)$ is the set of neighbors of X in G .

Hall's theorem

Exercice 13: Application of the theorem. Can you think of a graph that does not abide by the marriage condition and thus has **no perfect matching** ?

Illustration of Hall's theorem

Exercice 13 : Application of the theorem



Case of a non bipartite graph

In the case of a **non-bipartite**, we can not use the Ford-Fulkerson algorithm.

Other methods exist such as the **Blossom algorithm**.
(Edmonds-Karp)

Conclusion

Ford Fulkerson and its variants (Edmonds-Karp) are polynomial.
As a result they can run on datasets that are way bigger than
exhaustive search algorithms.

- ...
└ The Maximum flow problem
└ More results on the two problems

See you tomorrow