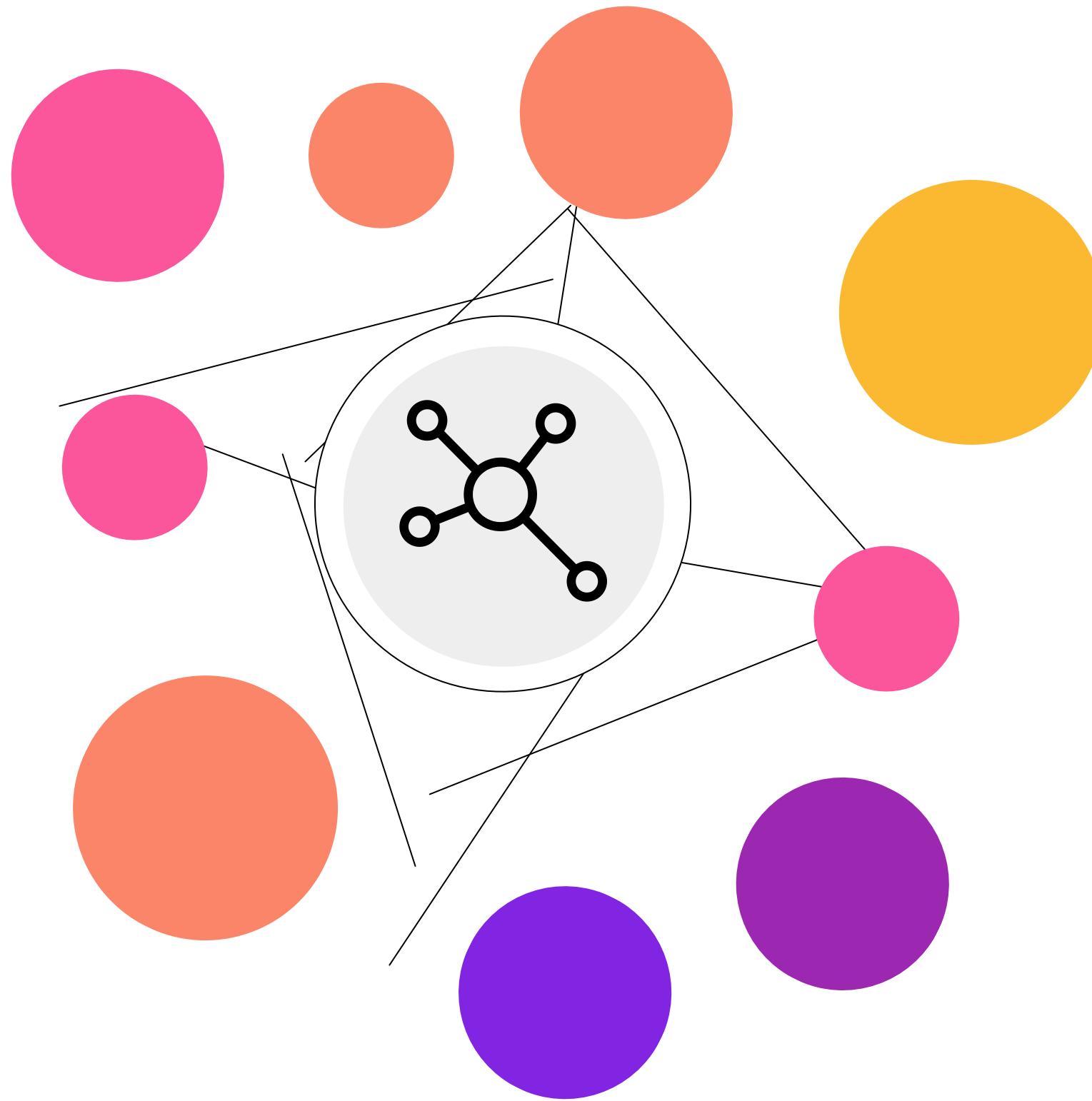


CS328



# Sparsifying Graphs While Preserving Communities

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# Context and Problem Statement



Data



Communities



Relevance



Complexity

Modelling of large data as graphs and networks is a common technique. Doing so is beneficial to capture the nature of connections between entities.

Among multiple regimes of graph analysis algorithms, community structure detection are much sought after. They extract the close relationships of social, biological and physical networks.

These algorithms are used for targeted advertising, identifying influential nodes, protein-protein interactions, brain connectivity networks and recommender systems.

However, as data size increases, the time taken to run community detection algorithms blows up. Not to mention, the storage costs also increases significantly.

Broad Problem Statement:

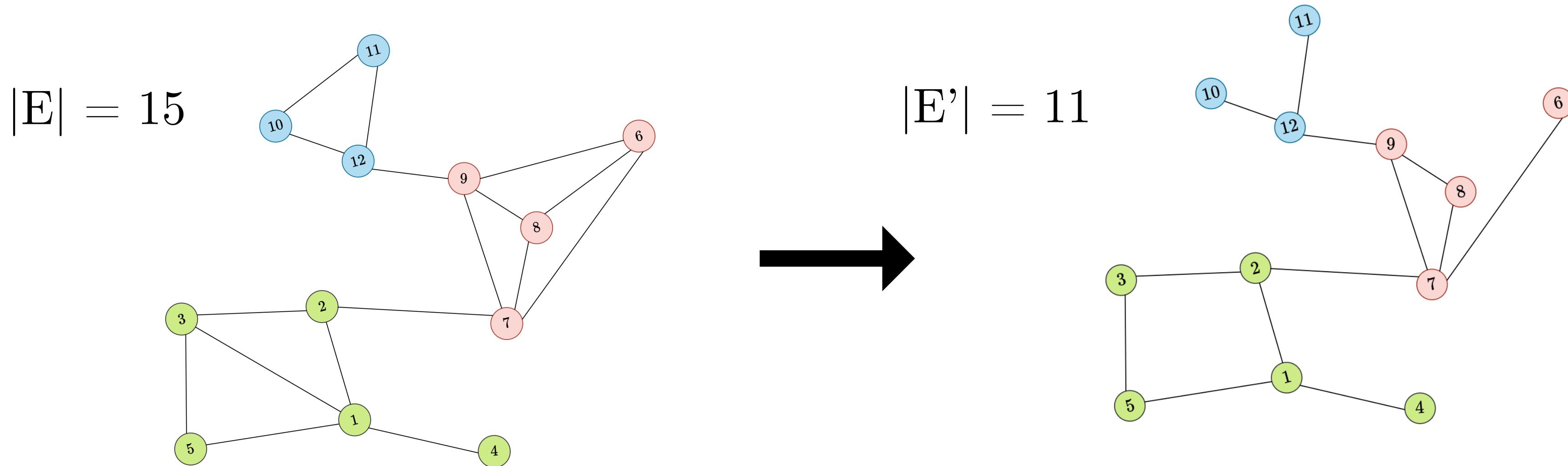
Given a graph  $G(V,E)$ , where  $V$  is the vertex set and  $E$  is the edge set, we wish to “sparsify” the graph in a “meaningful” manner and obtain a graph  $G'(V,E')$ , where  $V$  is the vertex set similar to original graph  $G$  and  $E' \subset E$  is the edge set of sparsified graph  $G'$ .

# Context and Problem Statement

## Broad Problem Statement:

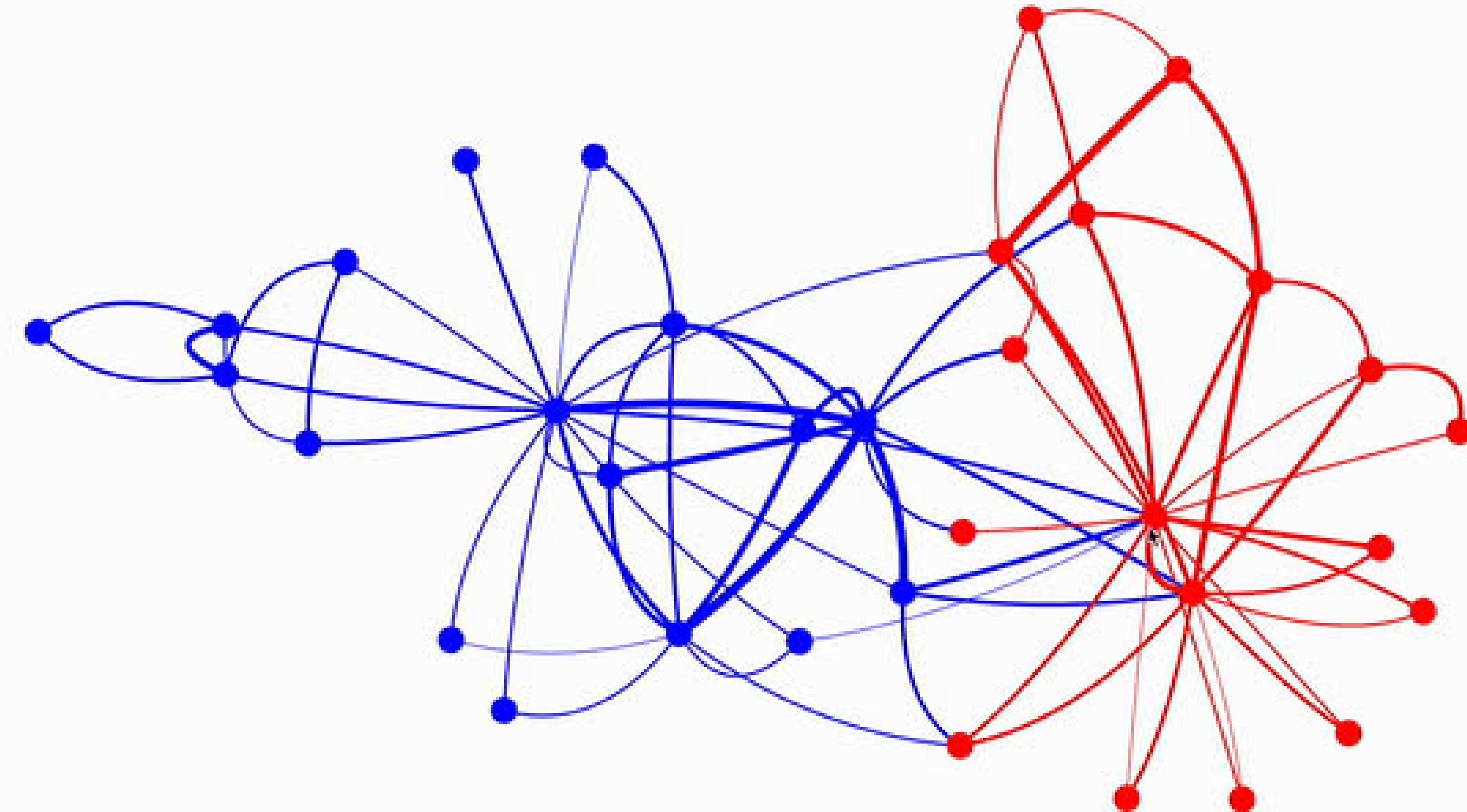
Given a graph  $G(V,E)$ , where  $V$  is the vertex set and  $E$  is the edge set, we wish to “sparsify” the graph in a “meaningful” manner and obtain a graph  $G'(V,E')$ , where  $V$  is the vertex set similar to original graph  $G$  and  $E' \subset E$  is the edge set of sparsified graph  $G'$ .

By “sparsifying” a graph in a “meaningful manner”, we intend to preserve the community structure of the original graph  $G$  by sampling a subset of edges from  $G$  so that community detection algorithms can be implemented on the “sparsified” graph  $G'$  with minimum loss of generality and accuracy.



# Graphs

Zachary's Karate Club Network



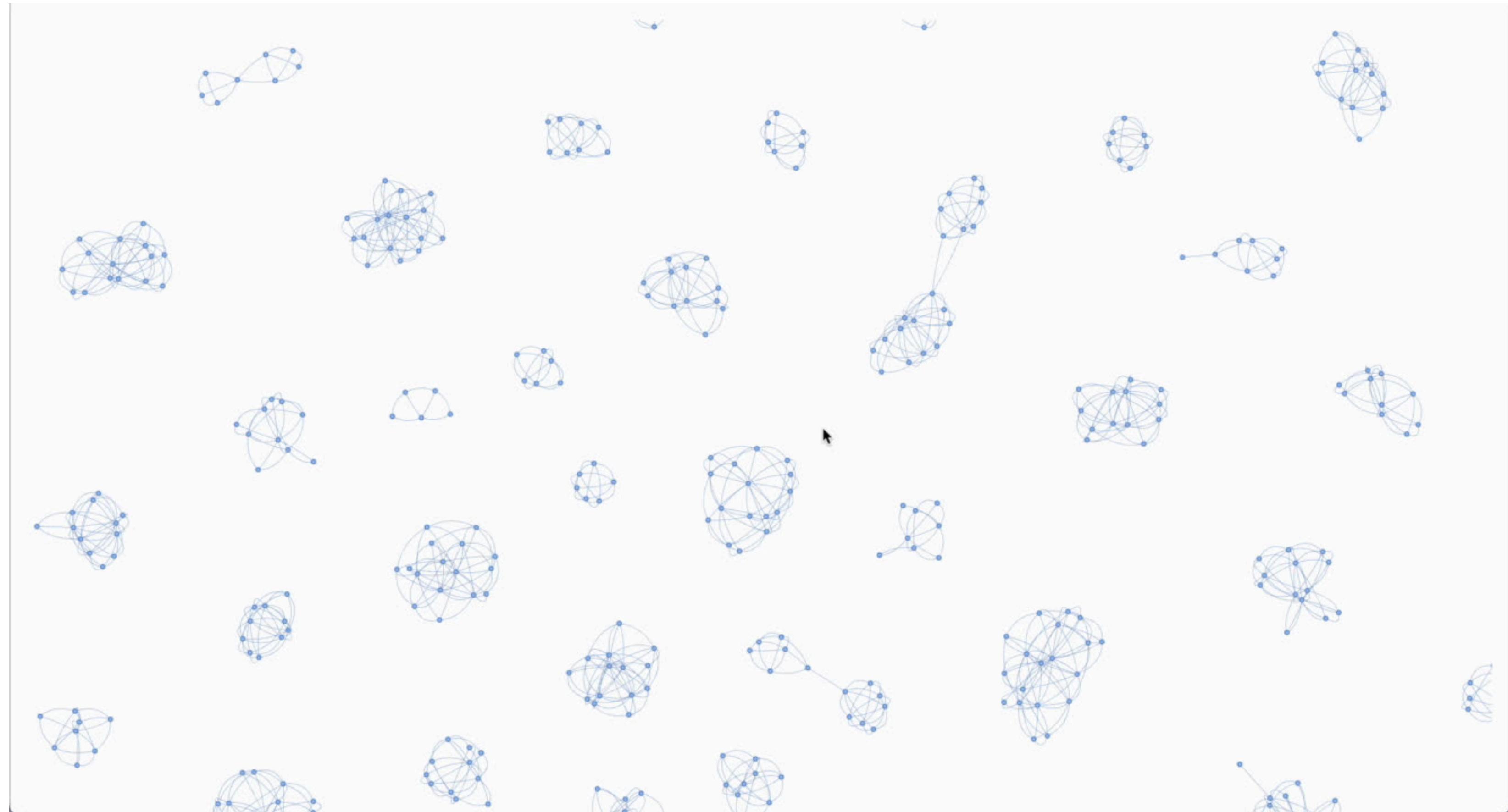
# Communities in Networks

DBLP Network



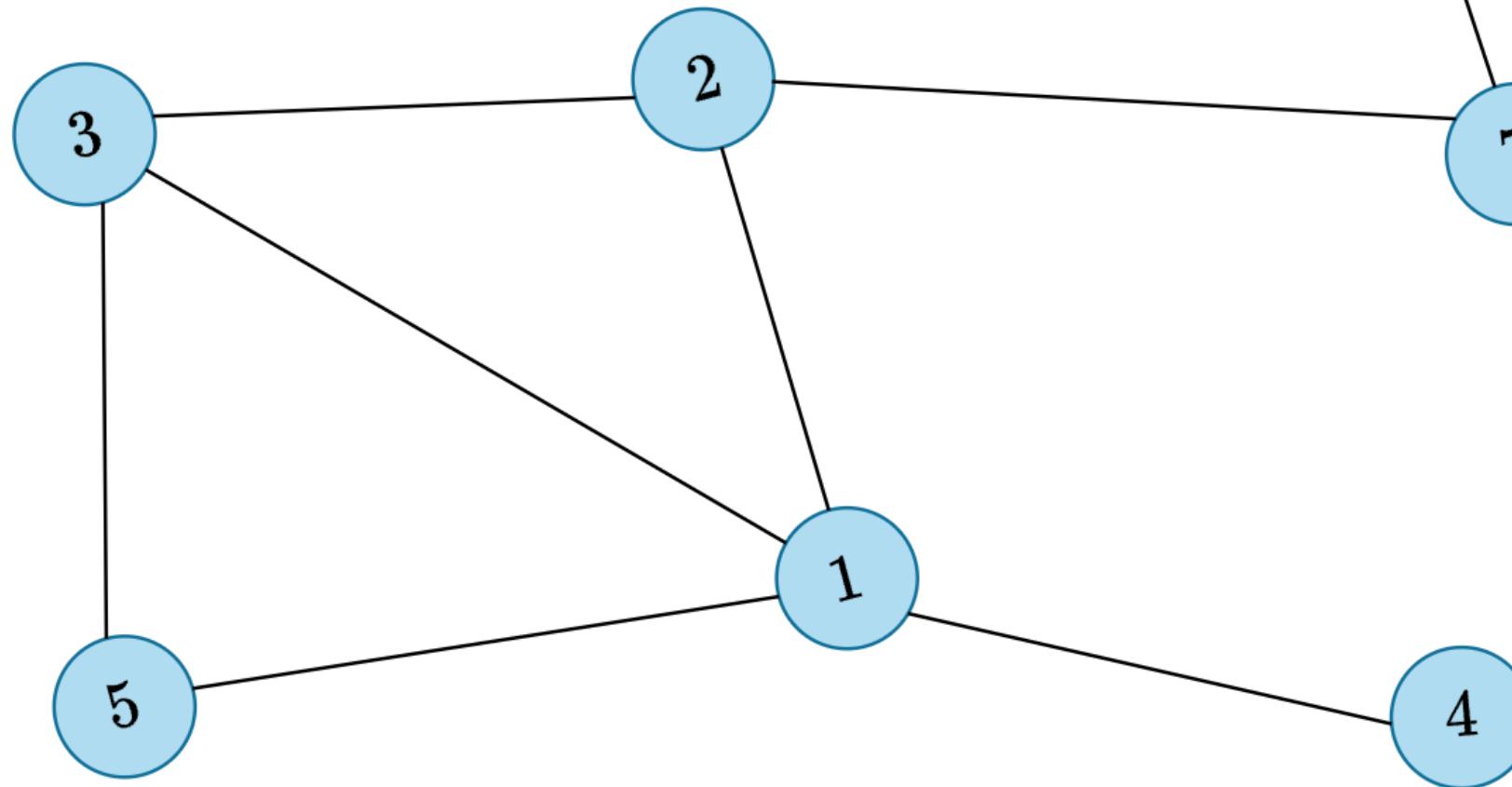
# Communities in Networks

Amazon Co-Purchase



$$|V| = 12$$

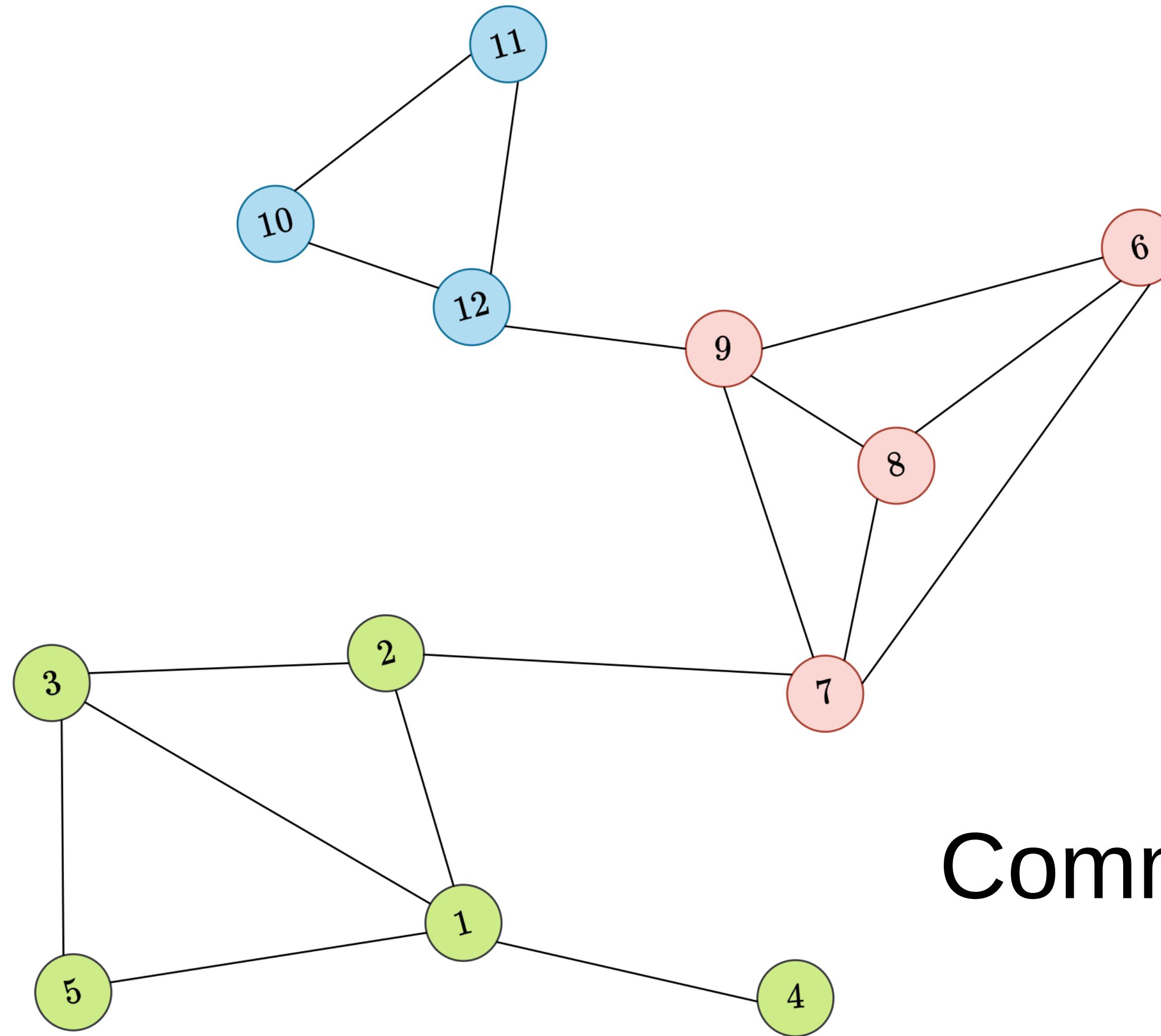
$$|E| = 15$$



Communities

$$|V| = 12$$

$$|E| = 15$$



Communities

# Salient Community Structure Properties

The number of shortest paths between pairs of nodes in a graph that pass through a particular edge. It quantifies the importance of an edge in connecting different parts of the network.

## Edge Betweenness

Quantifies the degree to which a network is partitioned into communities or modules. Compares the number of edges within communities to the number of edges expected in a random network with the same degree distribution, indicating the presence of densely connected communities.

## Jaccard Similarity

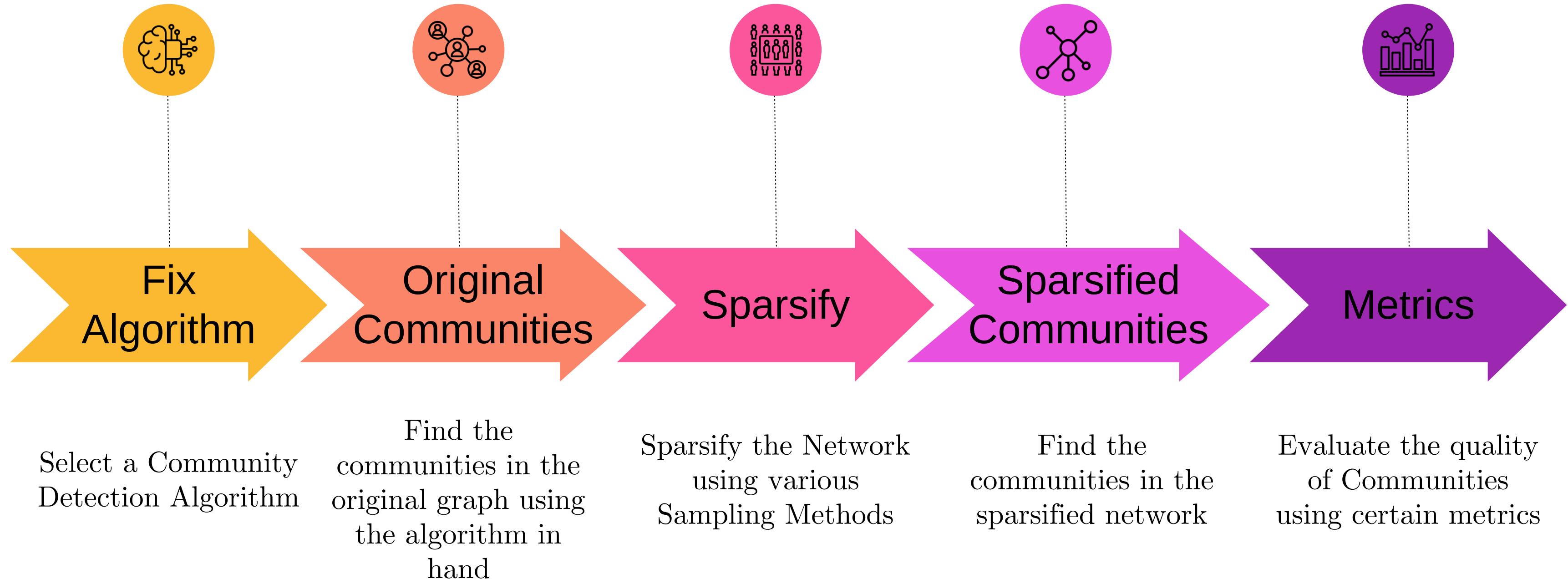
Measures similarity between two sets by comparing their intersection to their union. It is often used to measure the similarity between the sets of neighbors of two nodes.

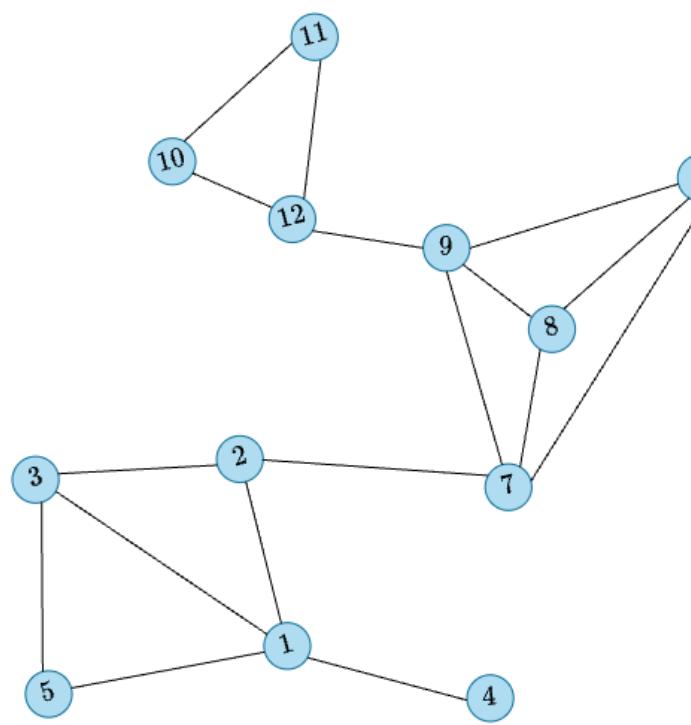
## Modularity

## Clustering Coefficients

Measures the degree to which nodes in a graph tend to cluster together. It quantifies the likelihood that two neighbors of a node are connected, providing insights into the local clustering structure of the network.

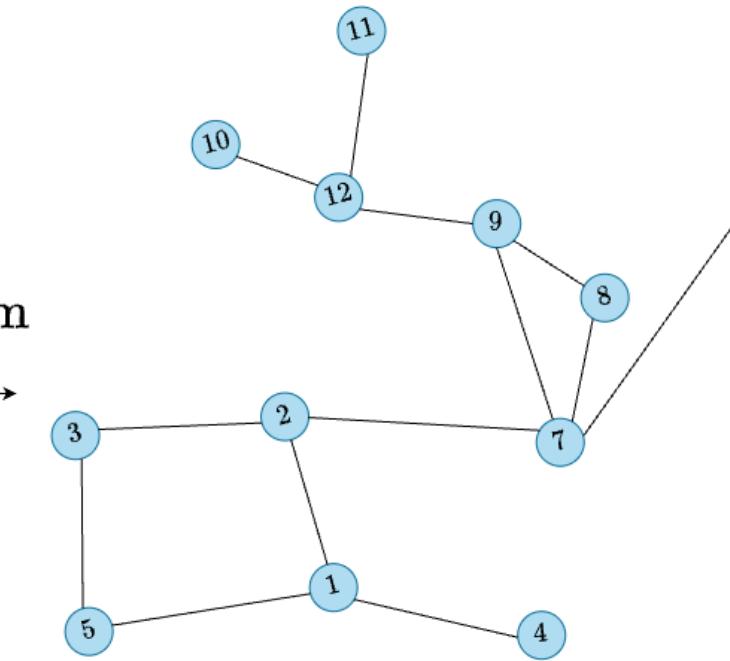
# Evaluation Pipeline





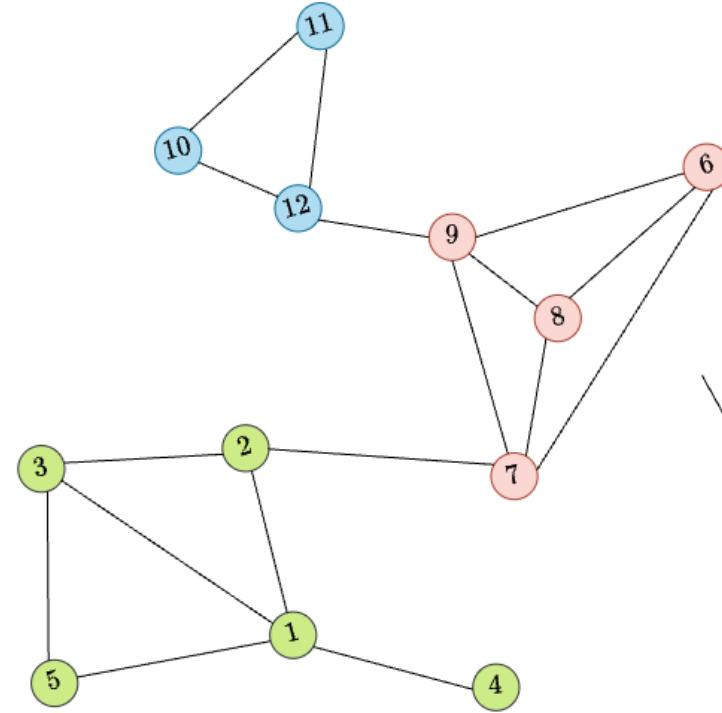
Original Graph

Sparsification Algorithm



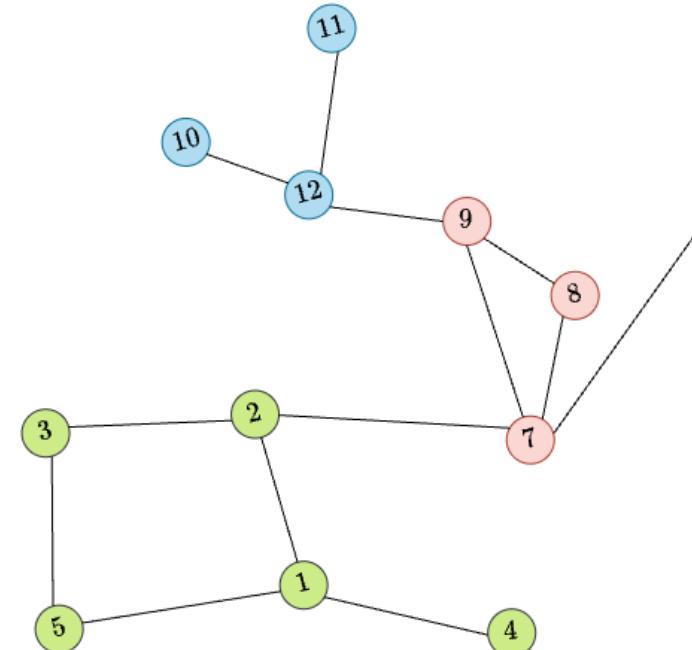
Sparsified Graph

Community Detection Algorithm

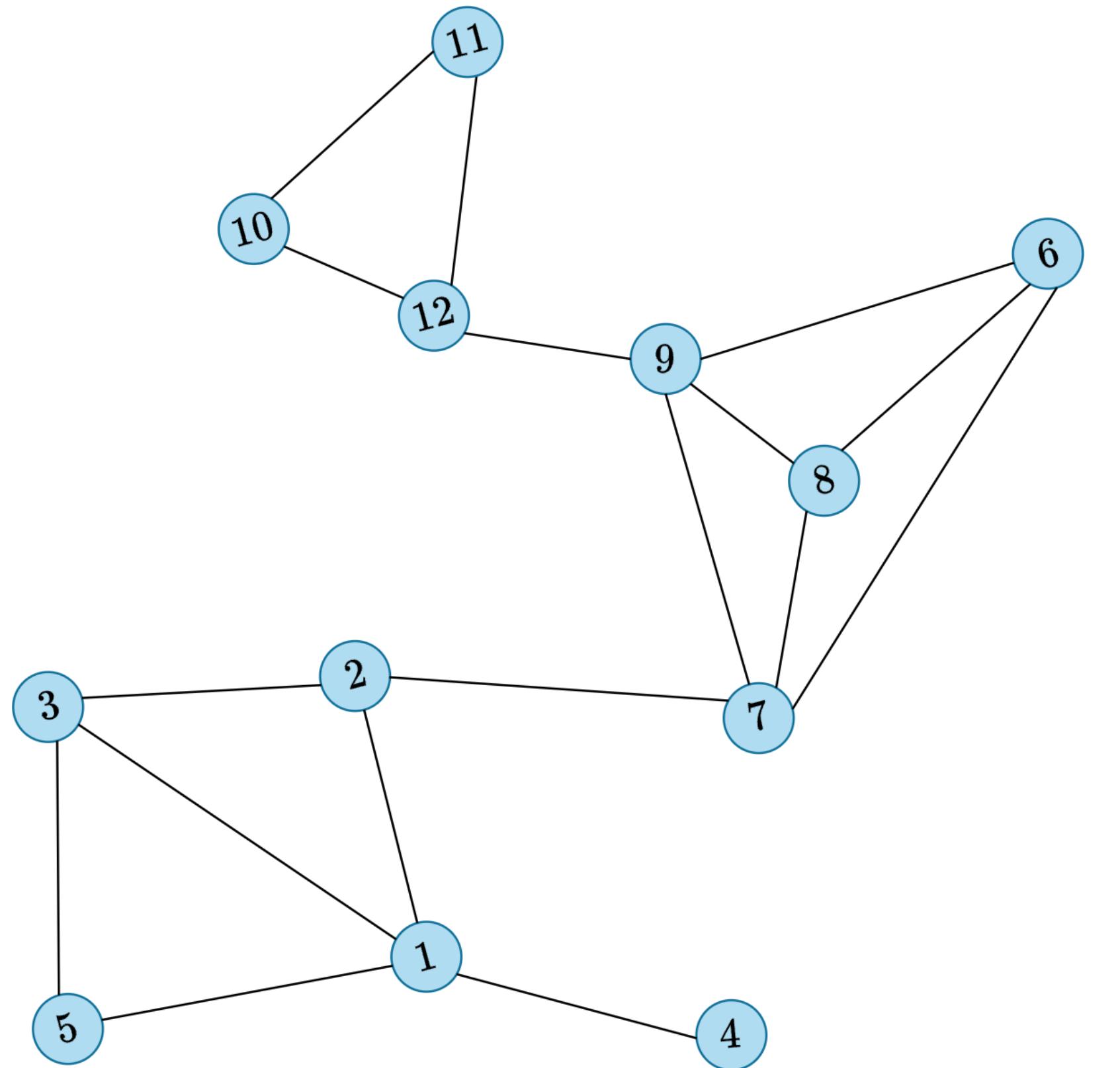


Original Graph Communities

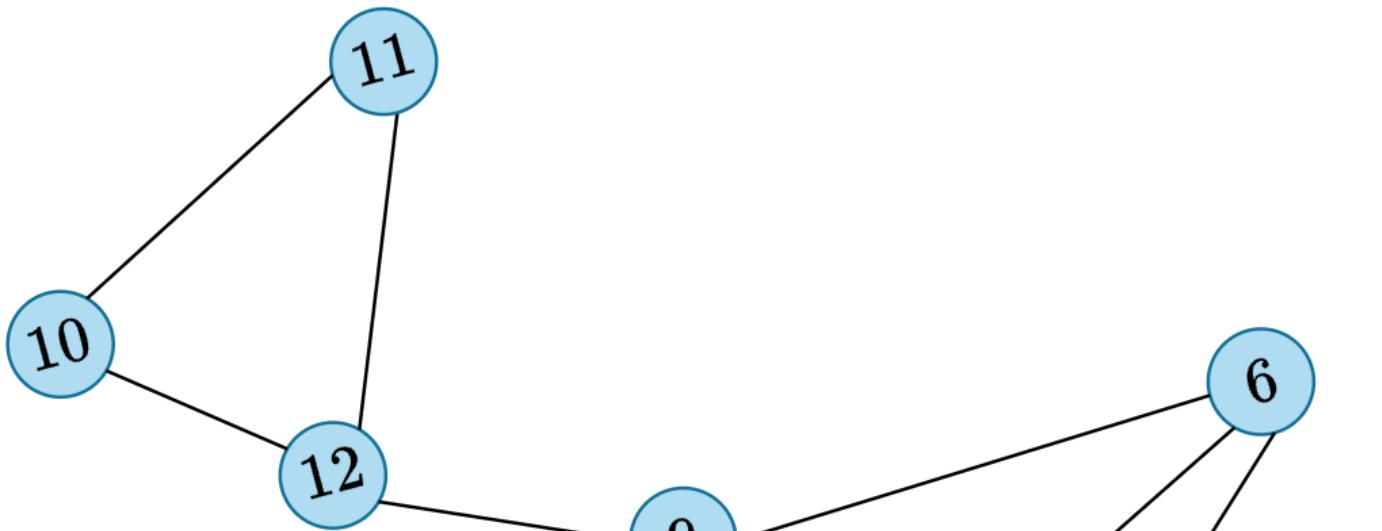
Metric



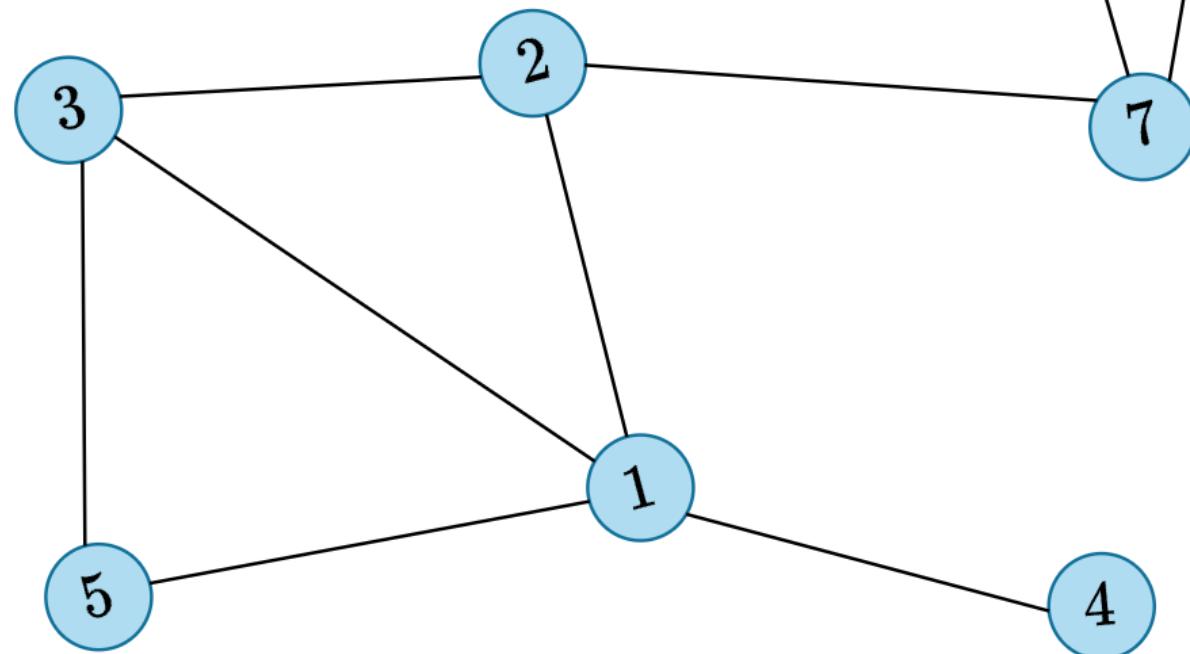
Sparsified Graph Communities



Original Graph

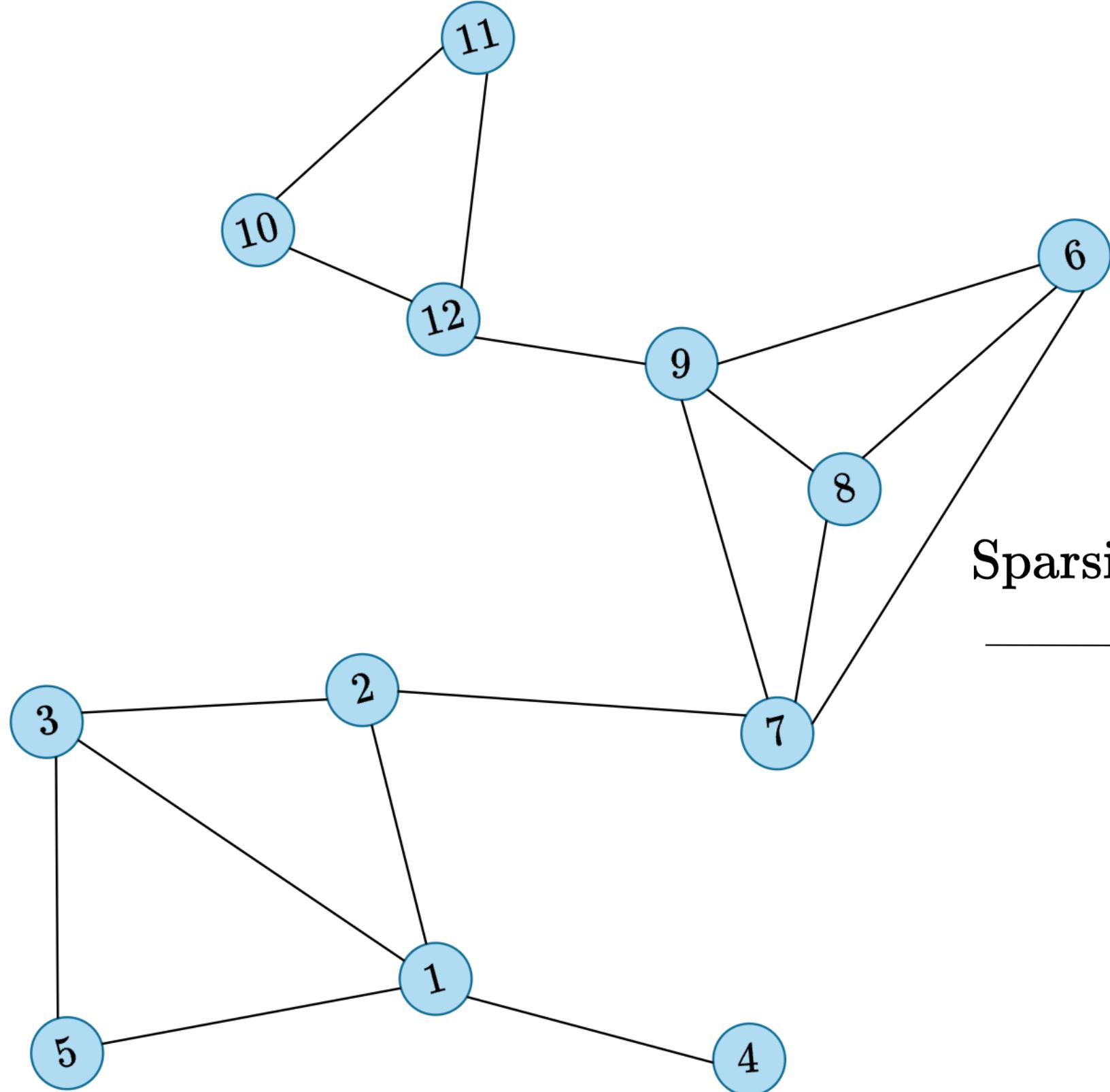


Original Graph



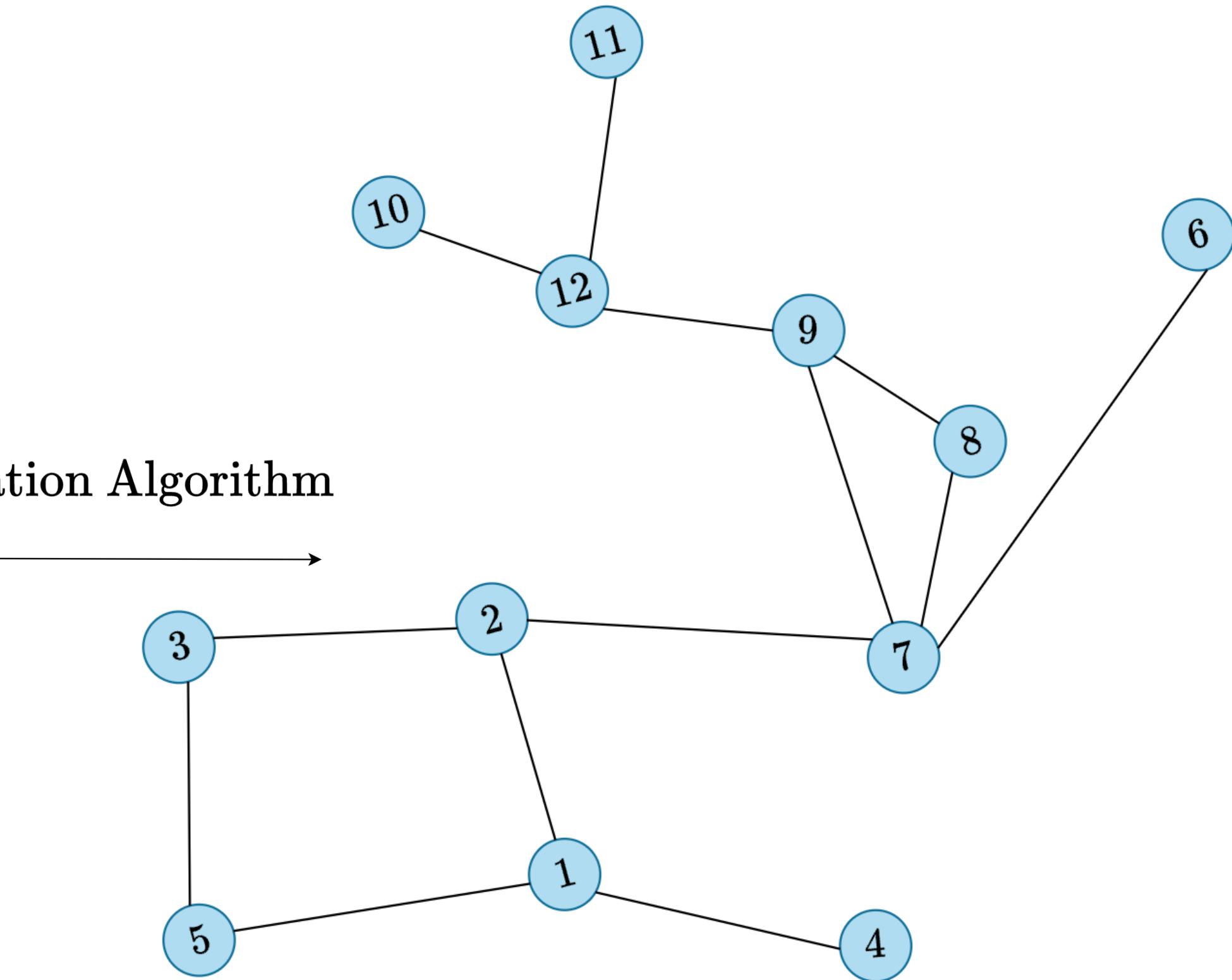
Sparsification Algorithm



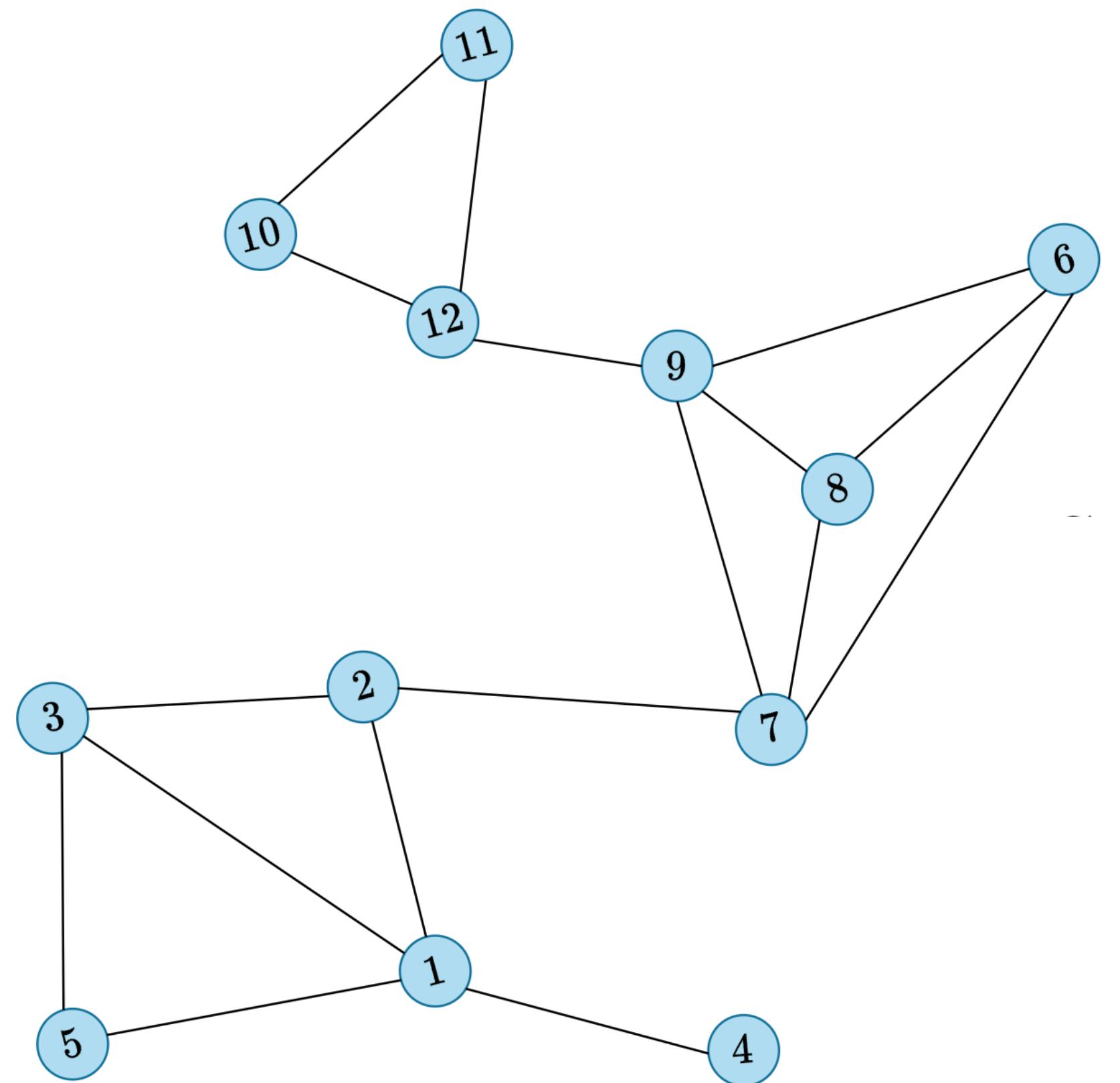


Original Graph

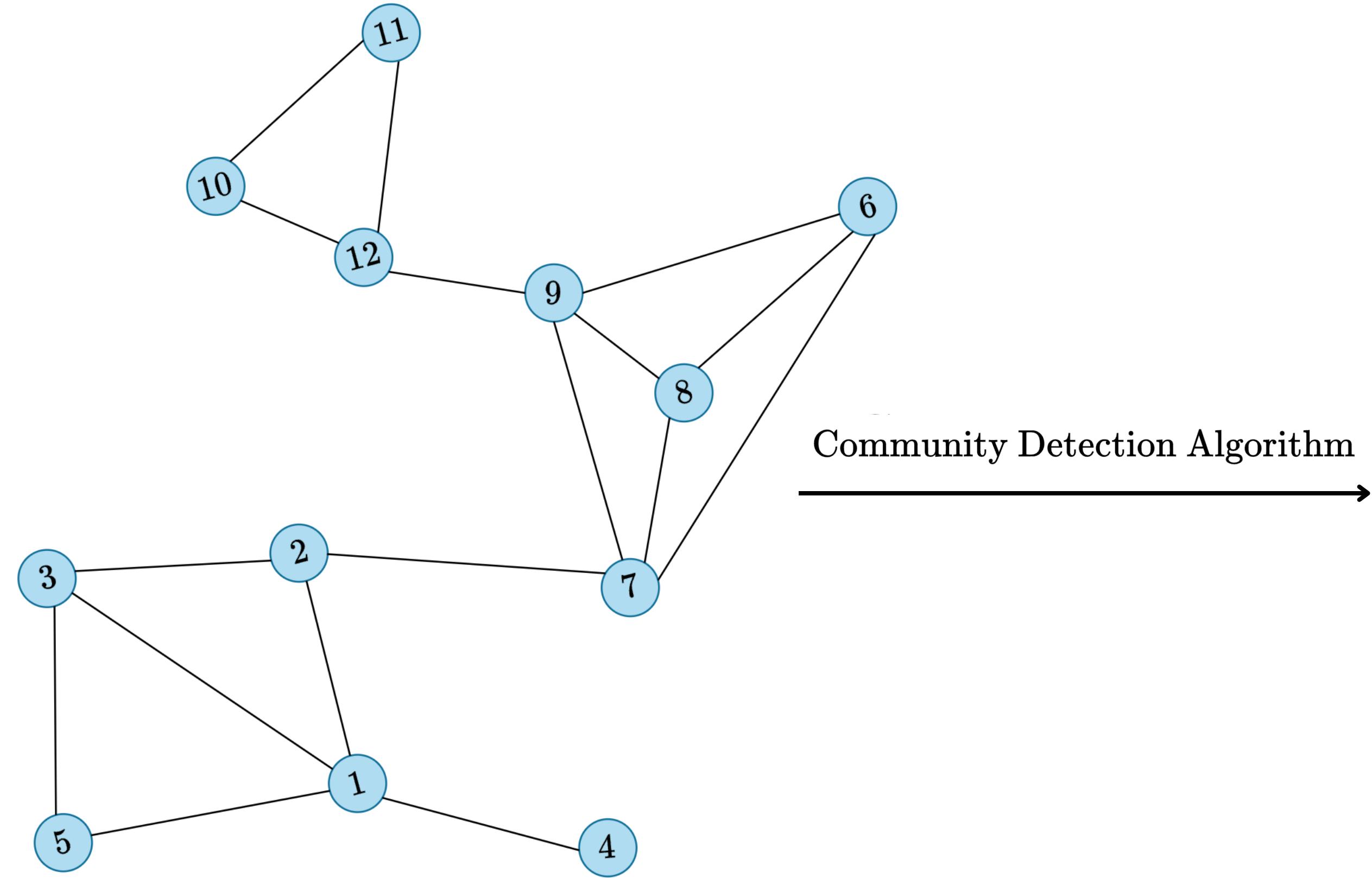
Sparsification Algorithm

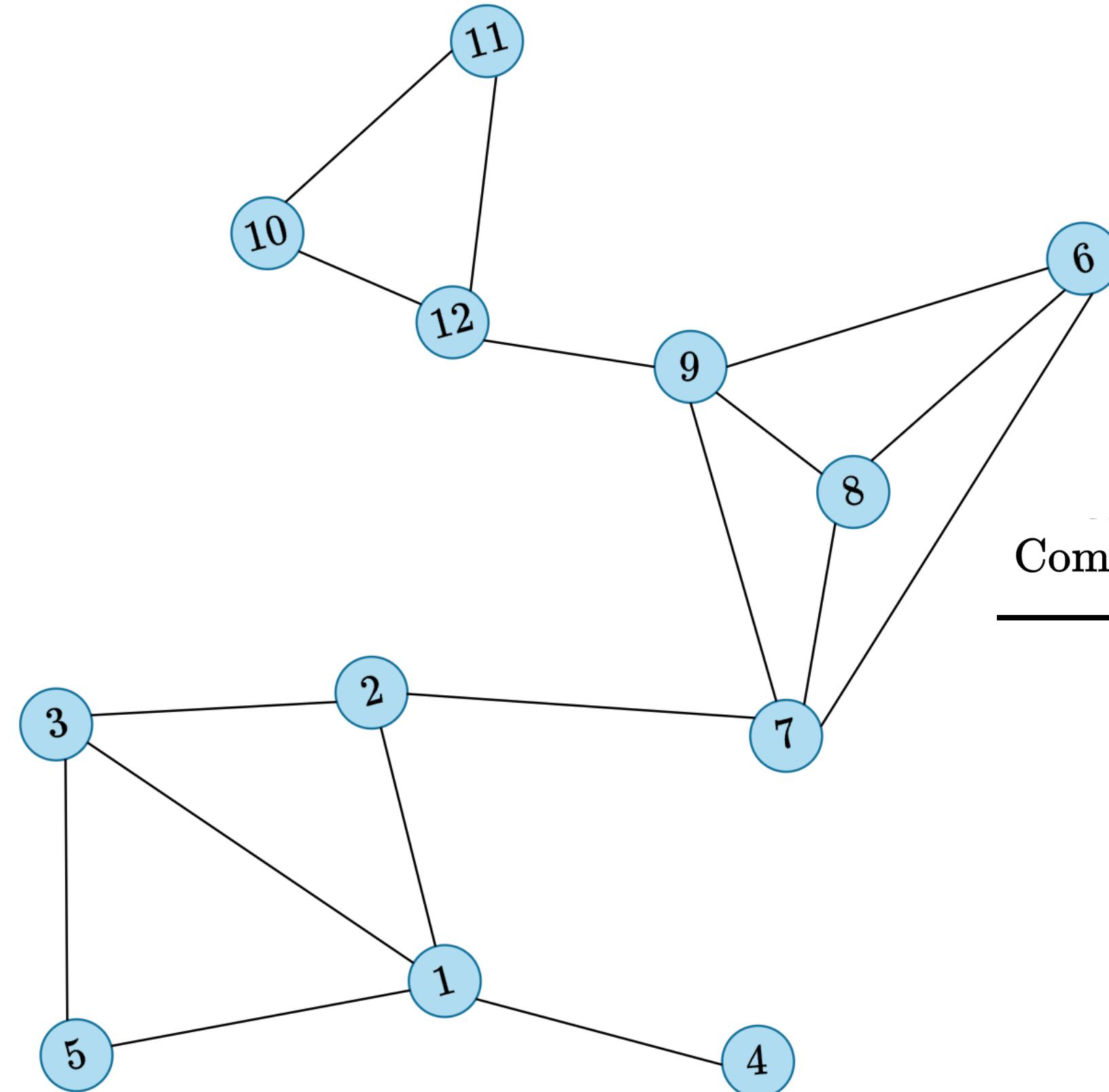


Sparsified Graph



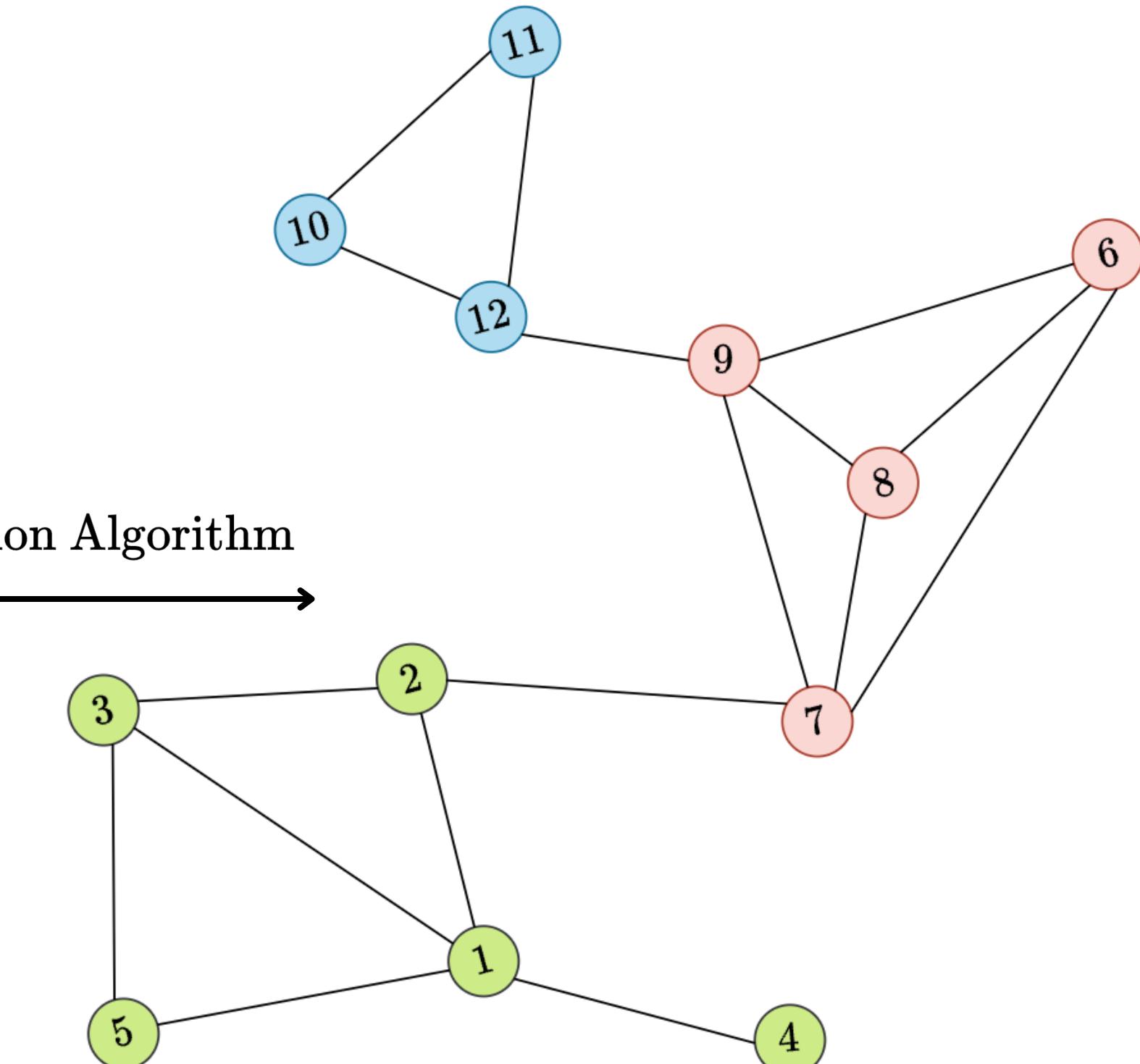
Original Graph



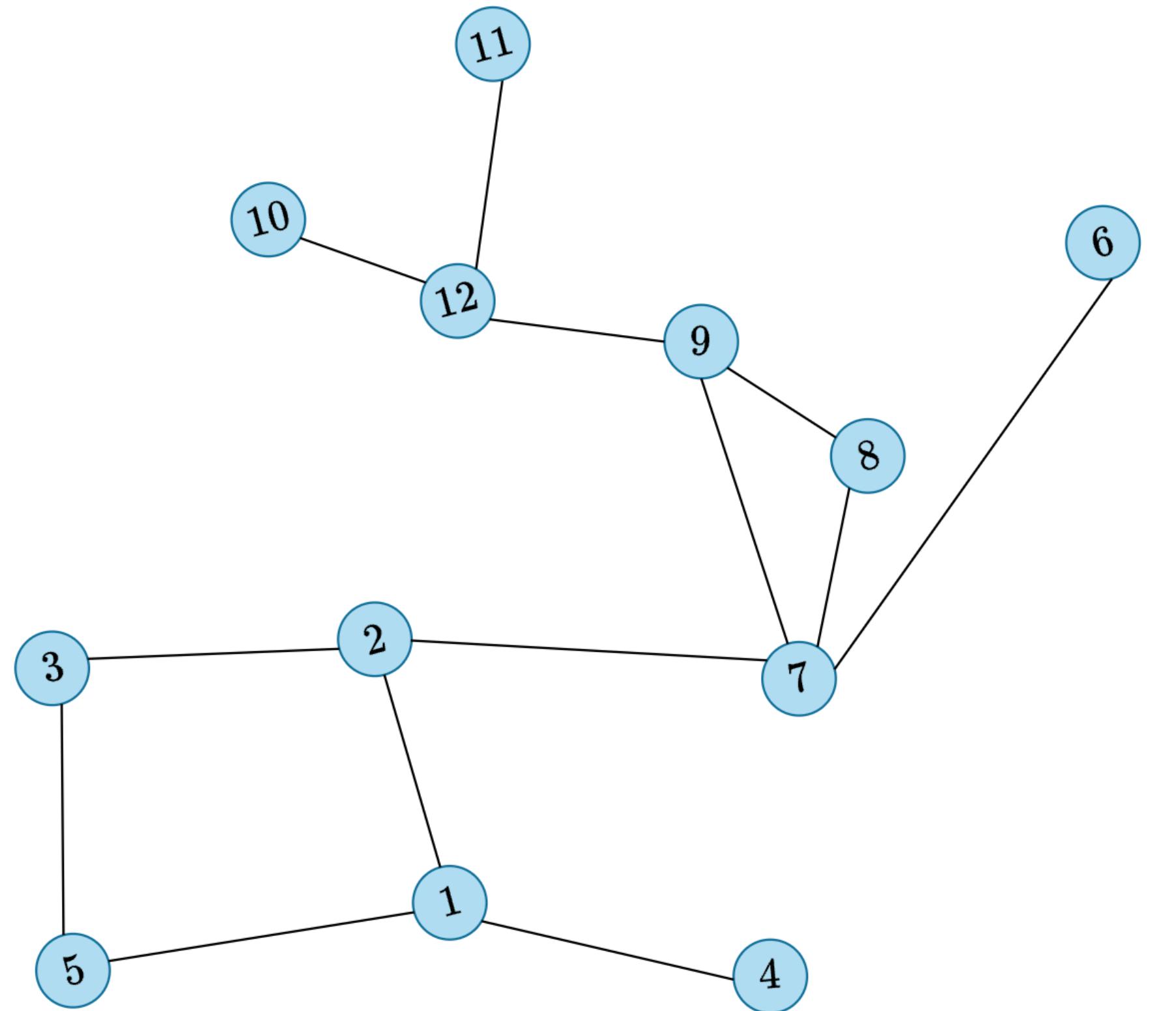


Original Graph

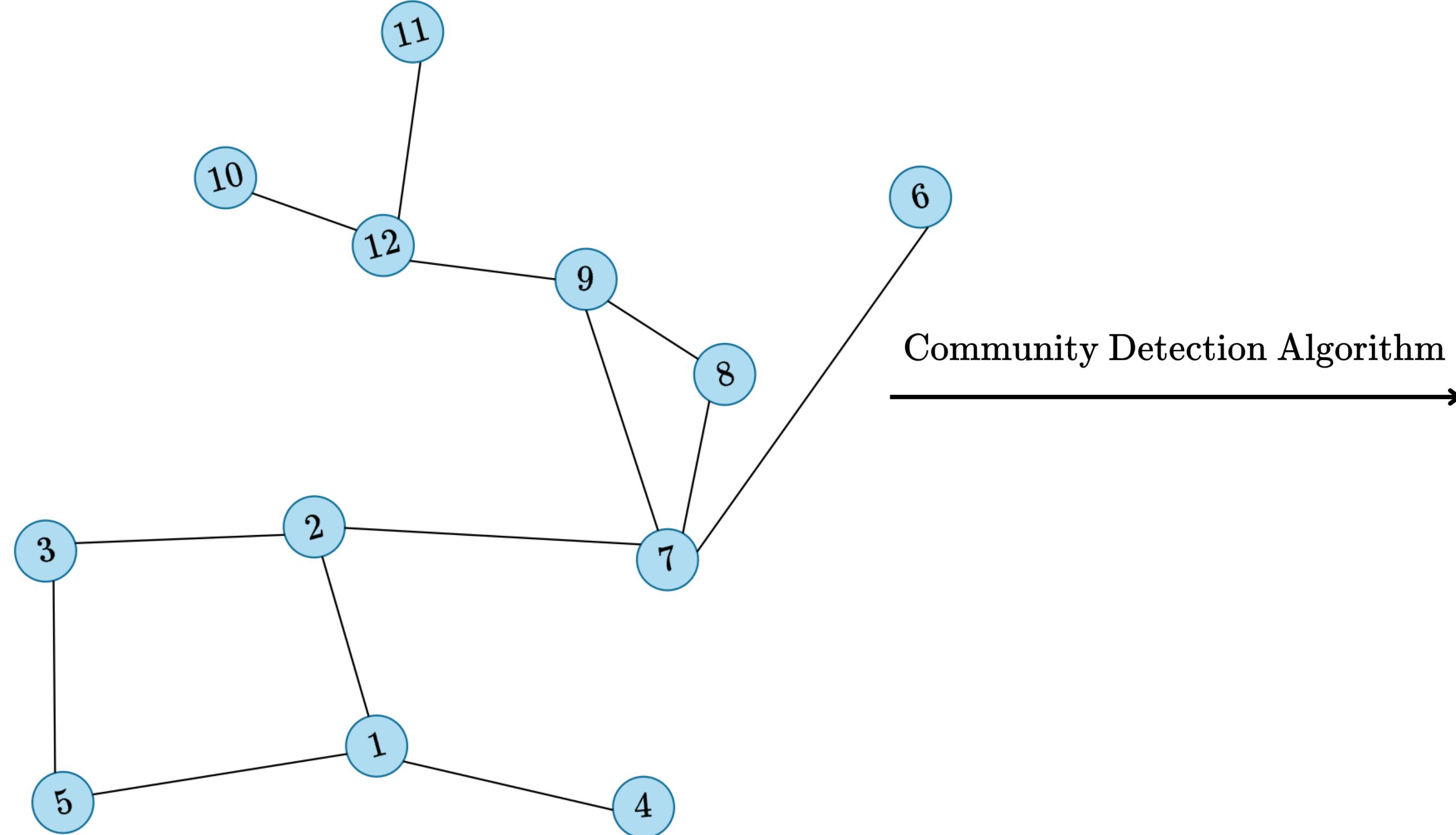
Community Detection Algorithm



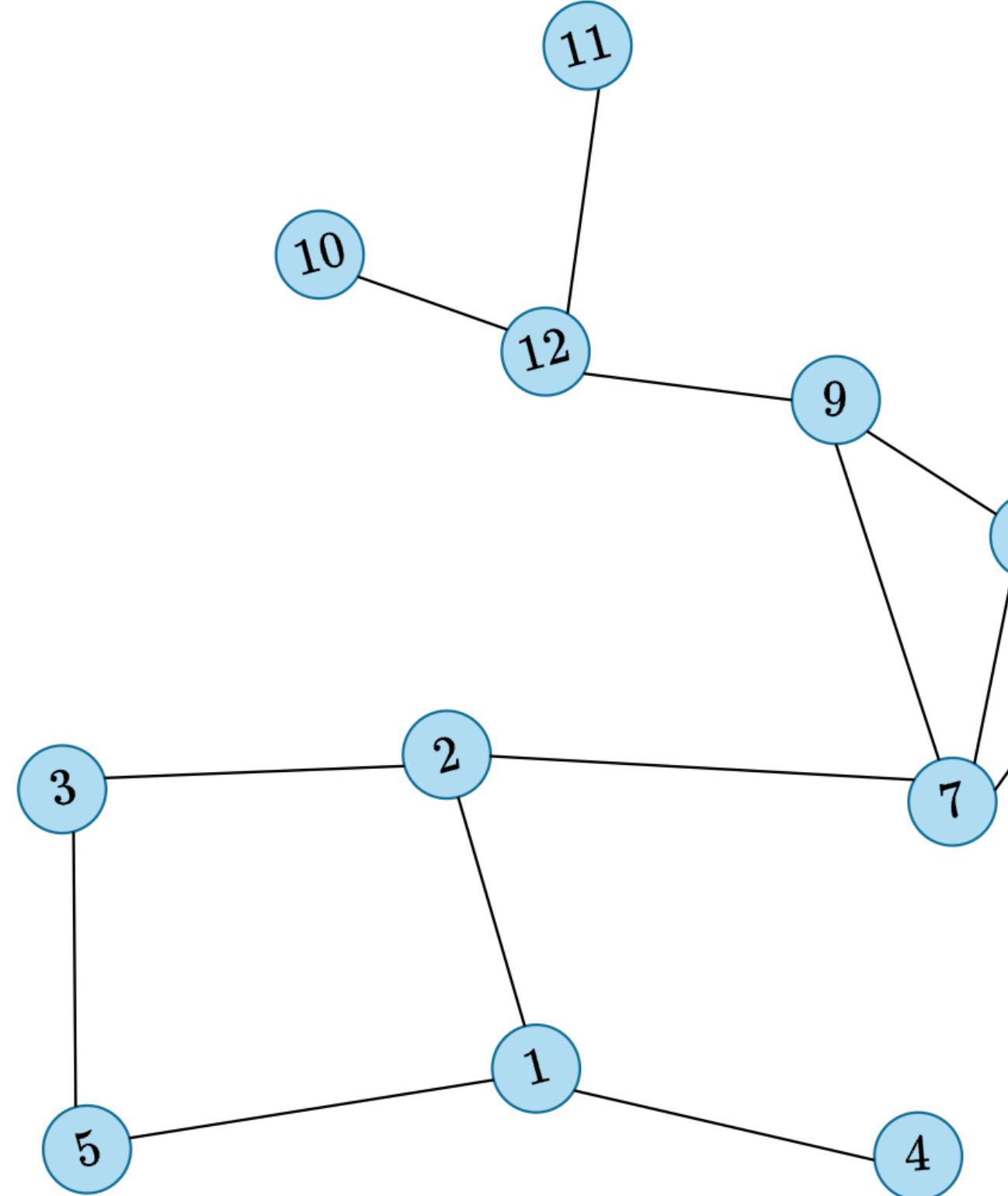
Original Graph Communities



Sparsified Graph

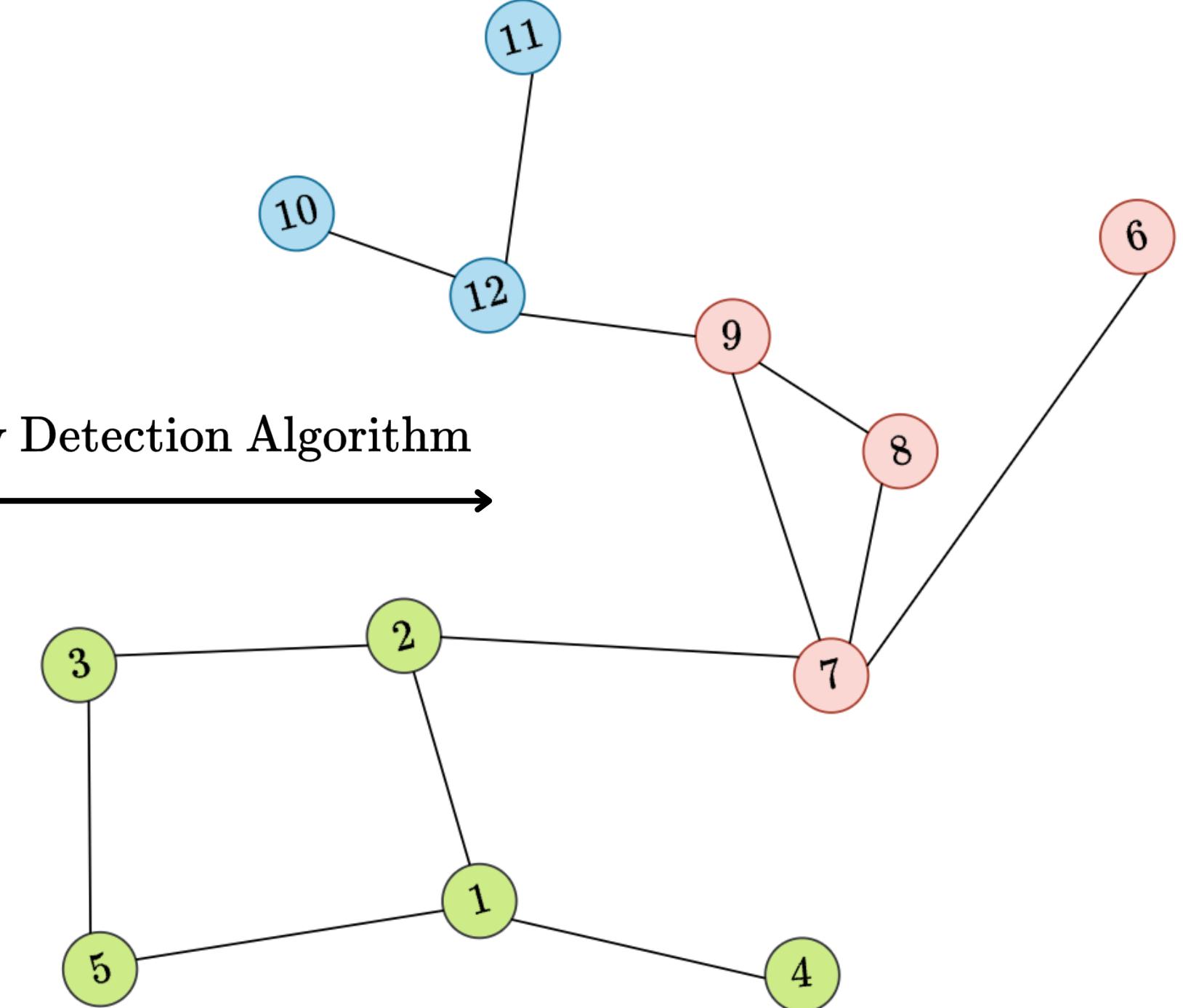


Sparsified Graph

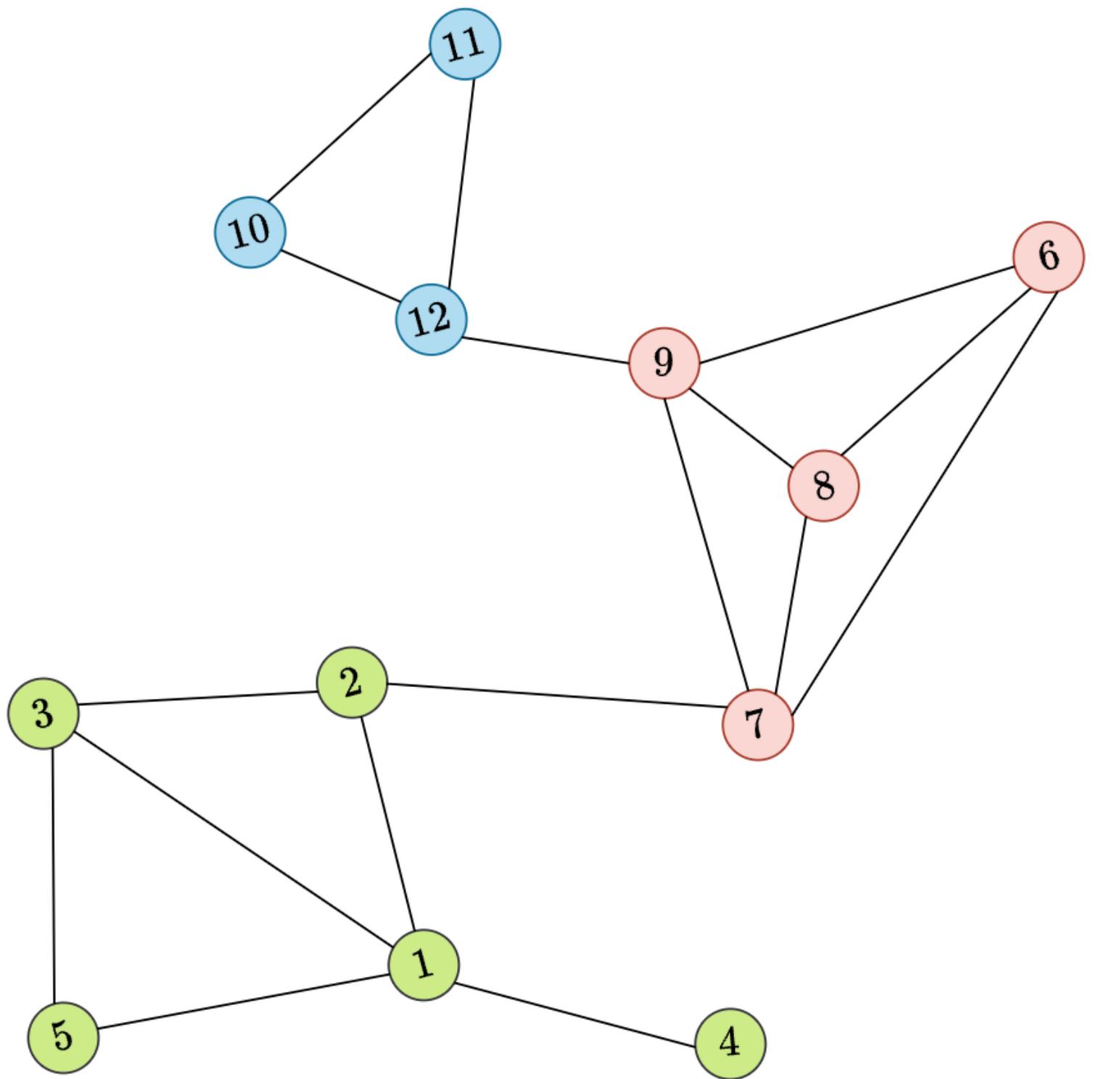


Sparsified Graph

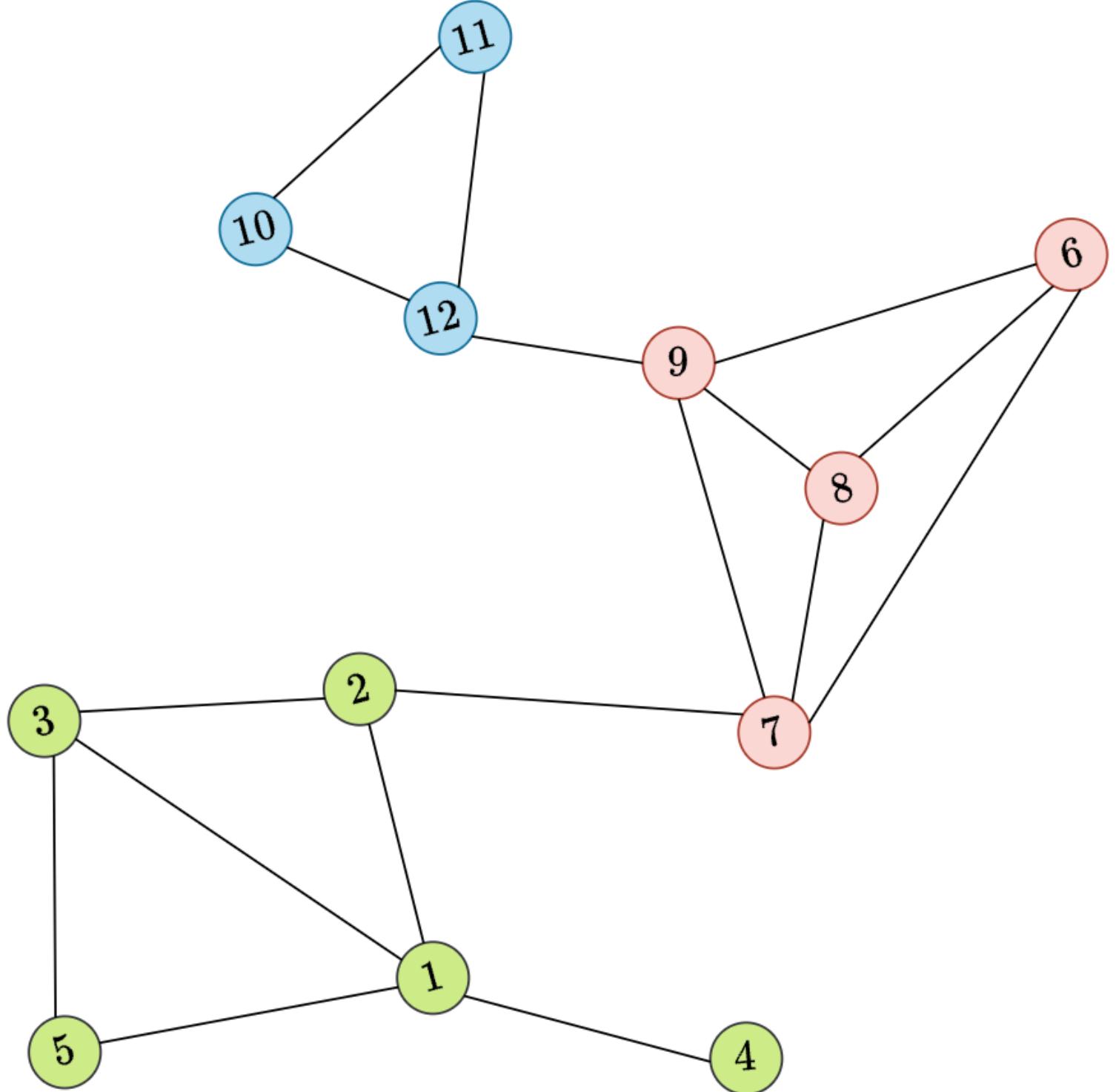
Community Detection Algorithm



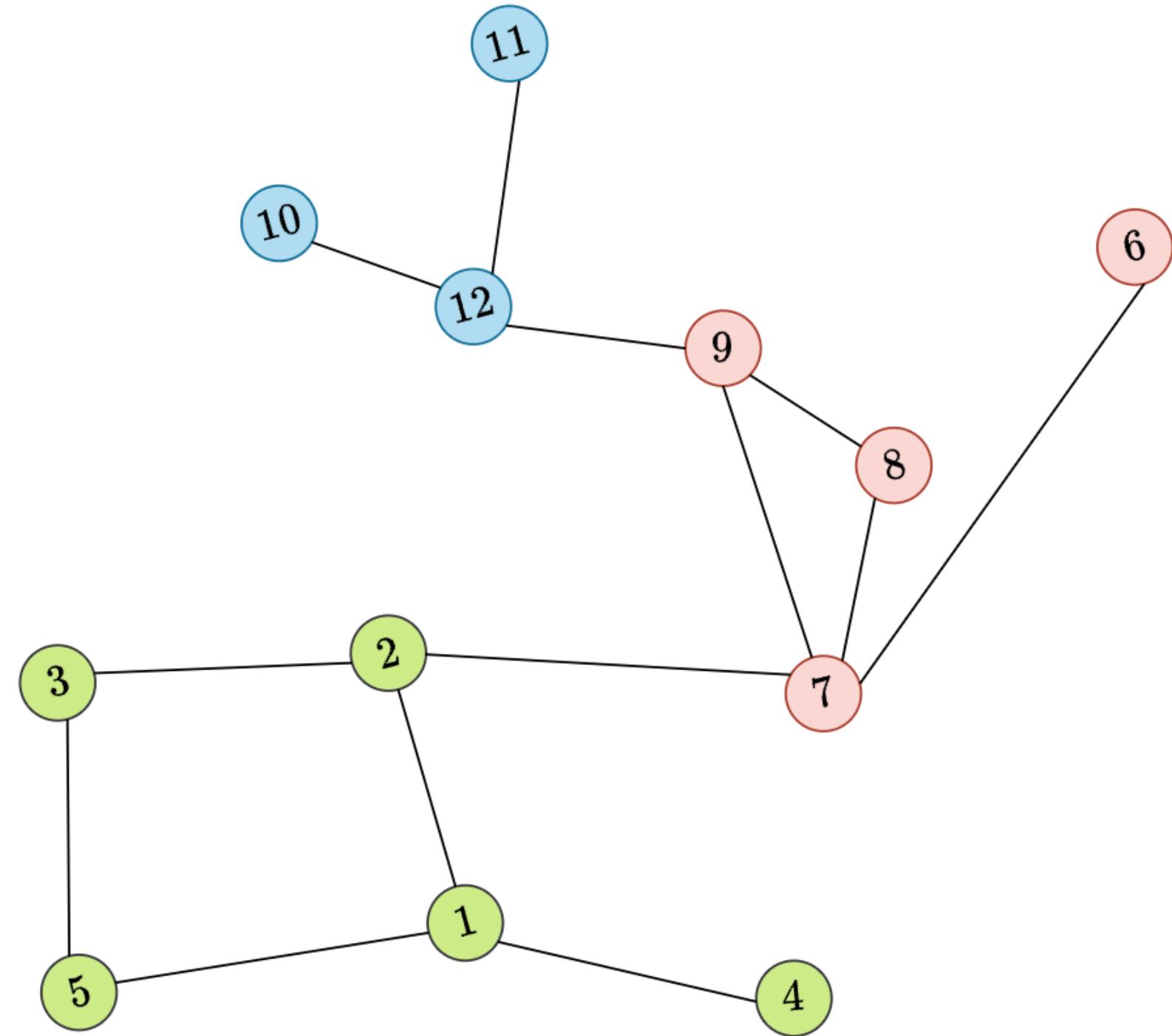
Sparsified Graph Communities



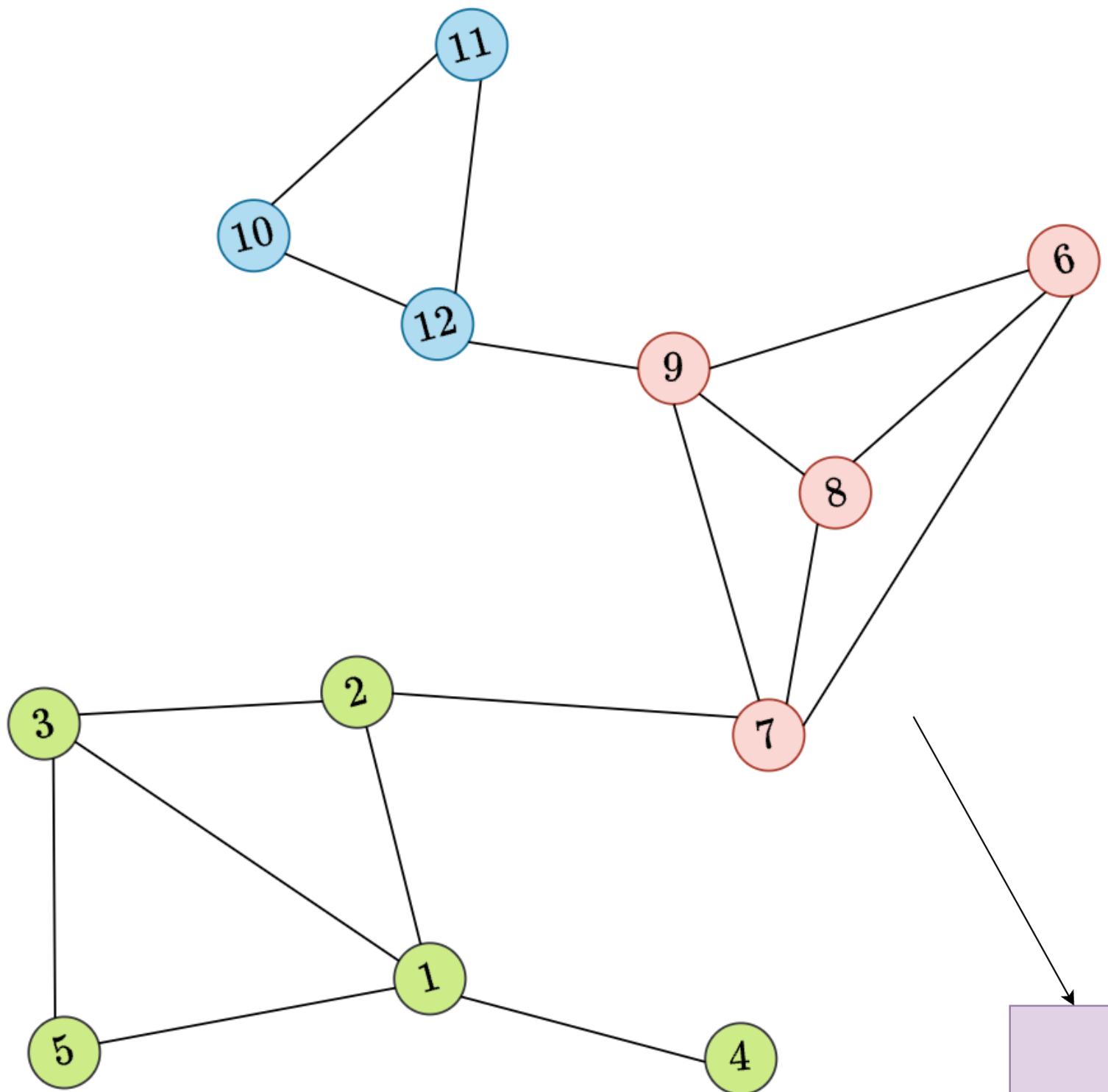
Original Graph Communities



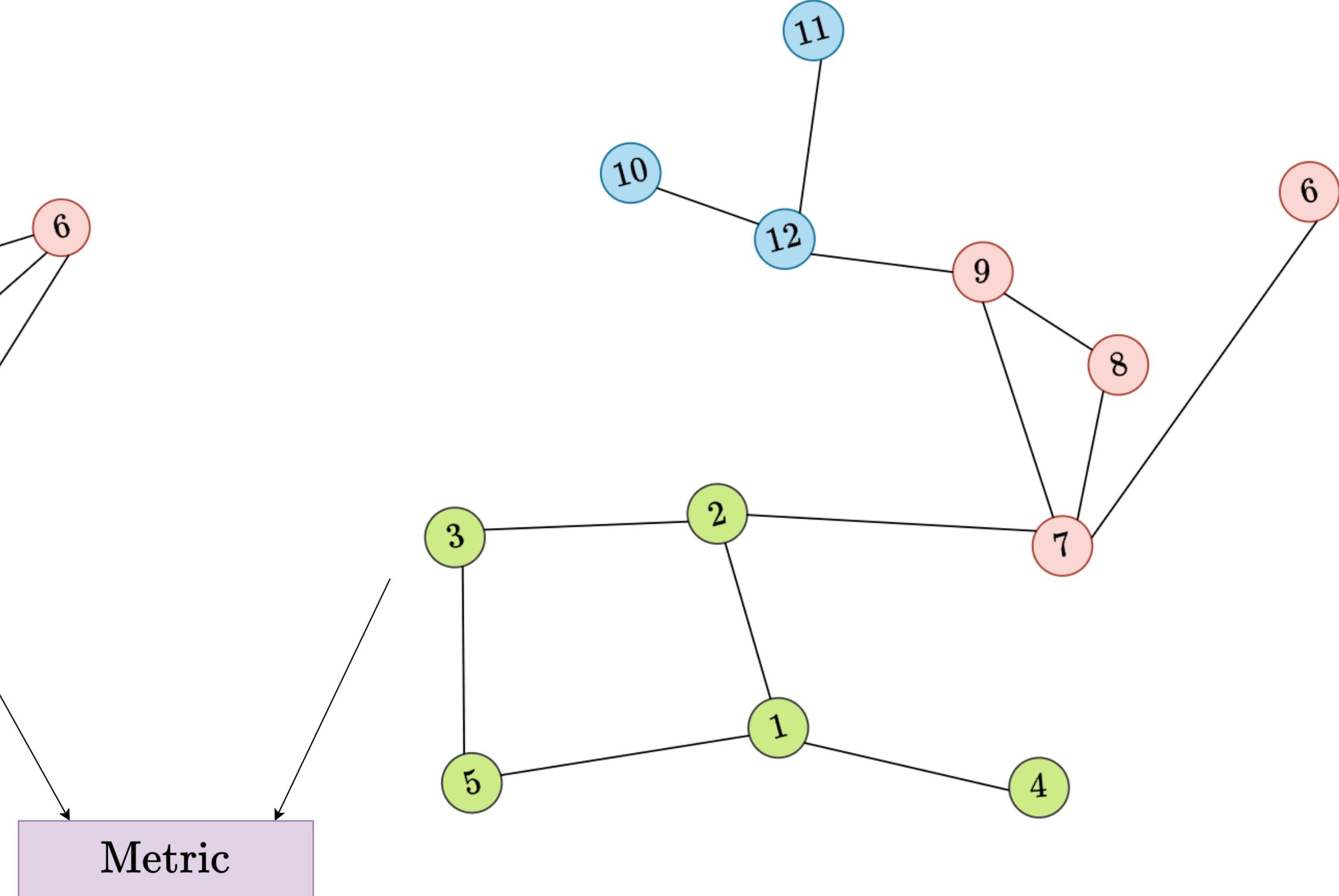
Original Graph Communities



Sparsified Graph Communities

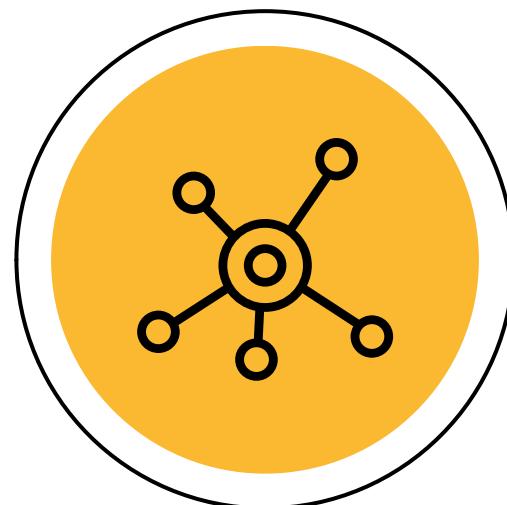


Original Graph Communities

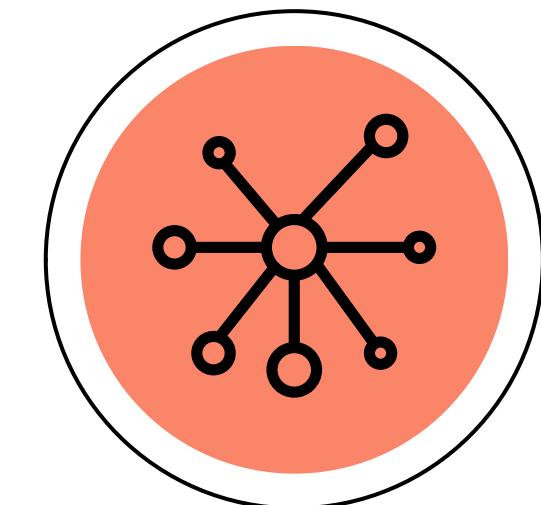


Sparsified Graph Communities

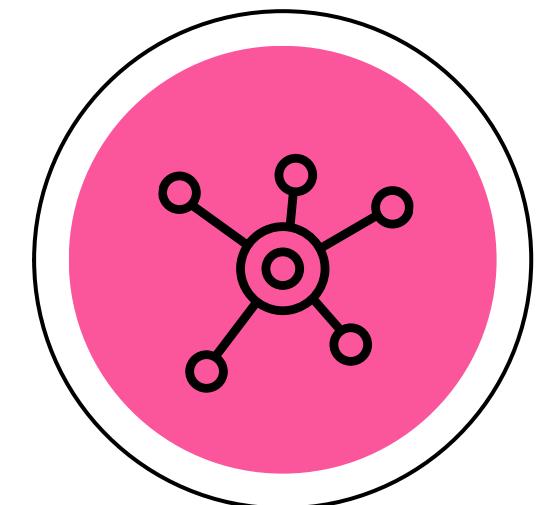
# Sparsification Methods



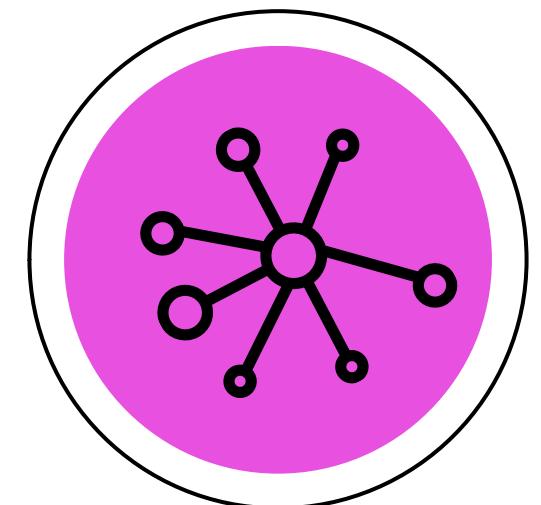
**Random  
Sampling**



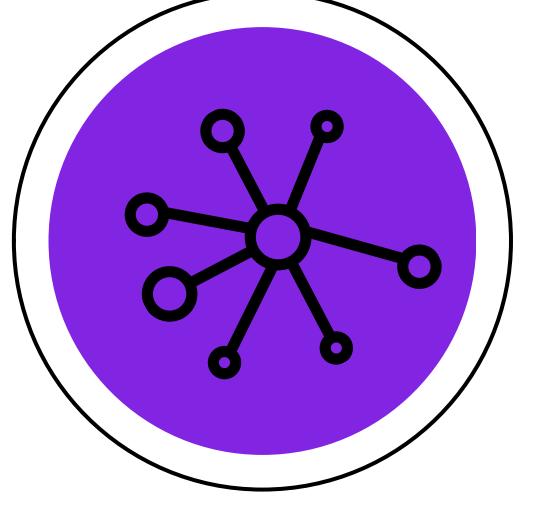
**Edge  
Betweenness  
Based**



**Global Similarity  
Based**



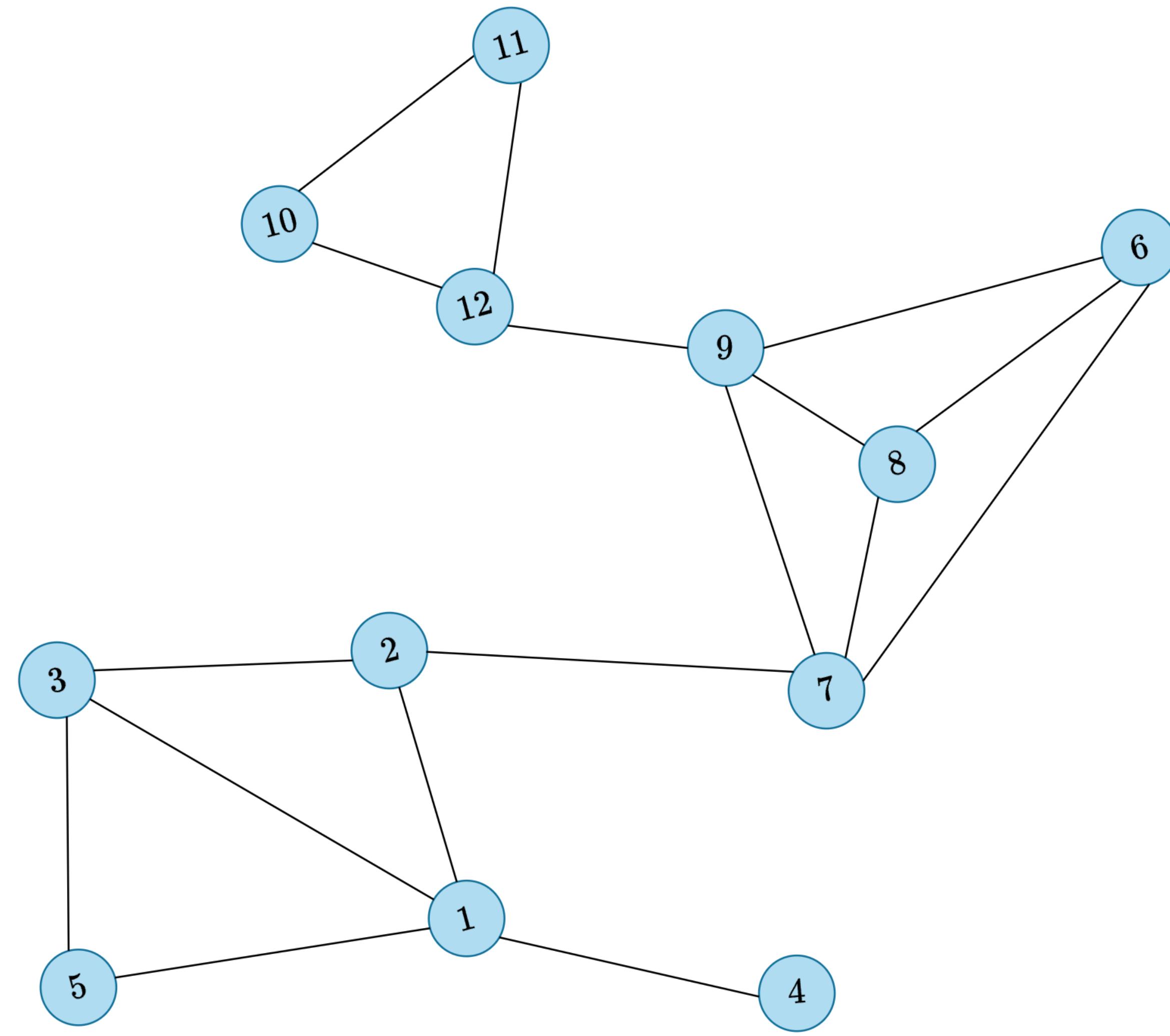
**Local Similarity  
Based**



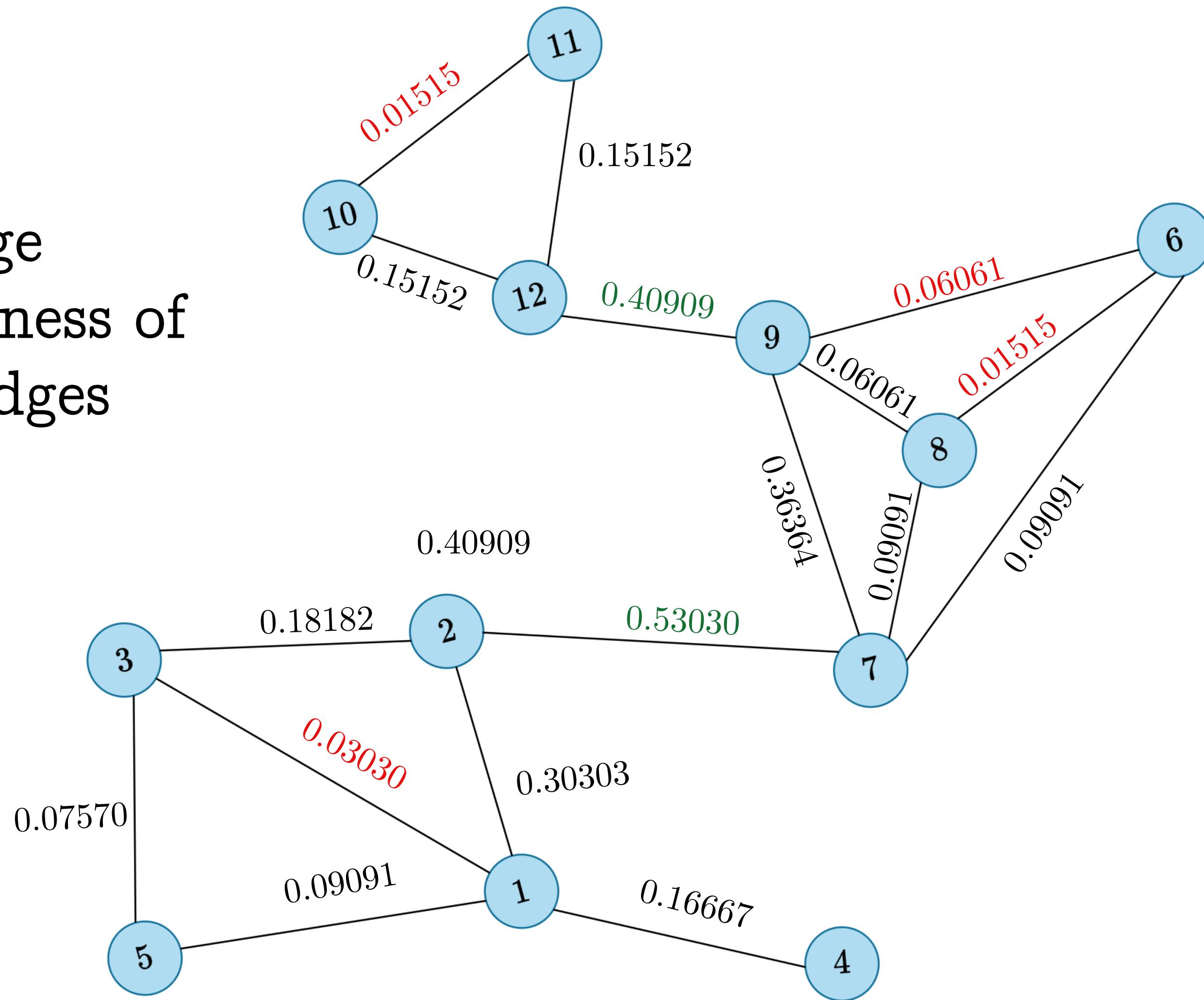
**Clustering  
Coefficient  
Based**

# Edge Betweenness

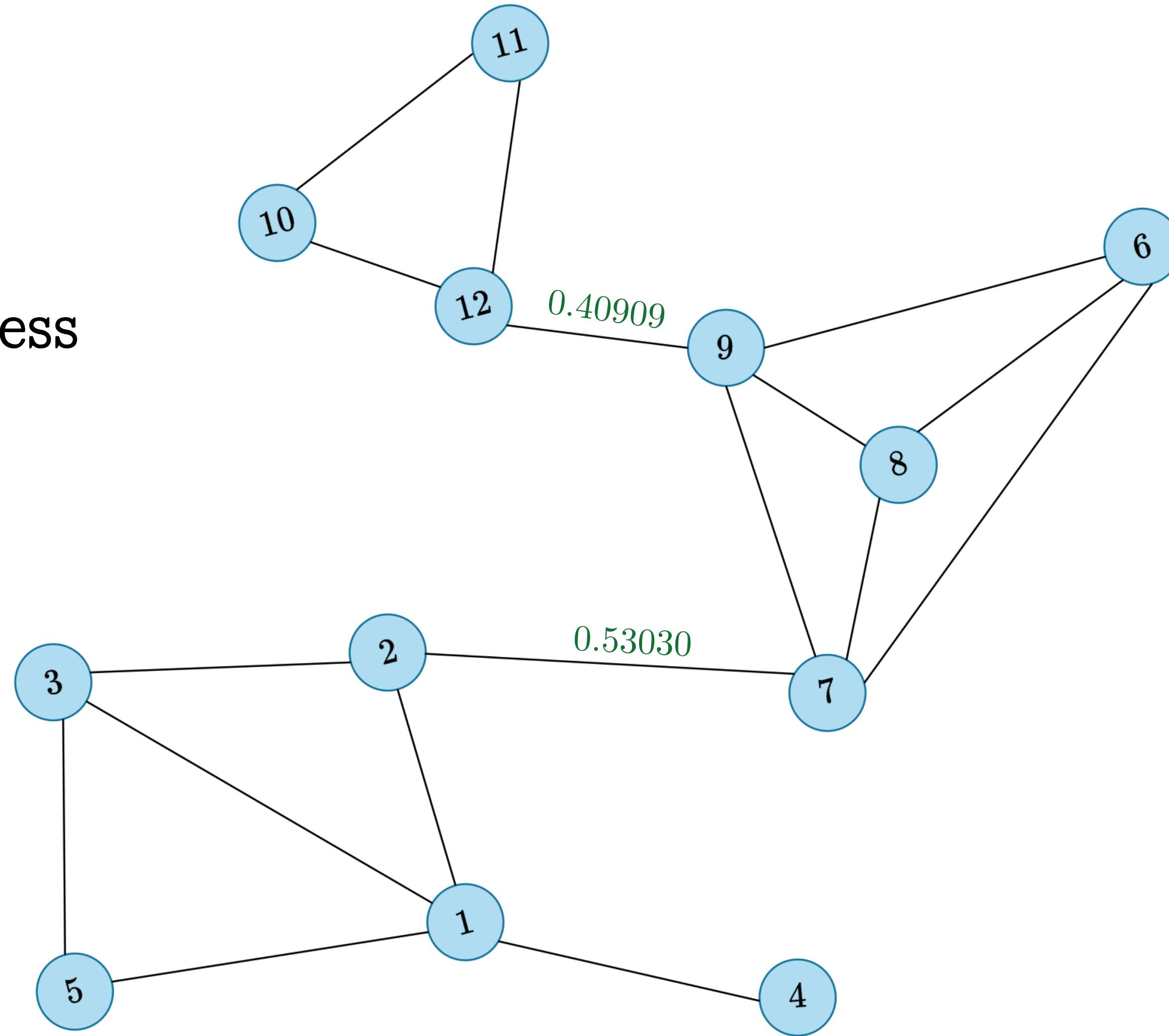
$$c_B(e) = \sum_{s,t \in V} \frac{\sigma(s, t|e)}{\sigma(s, t)} \longrightarrow \begin{array}{l} \text{No. of shortest } (s, t) \text{-paths crossing e} \\ \text{Total No. of shortest } (s, t) \text{-paths} \end{array}$$

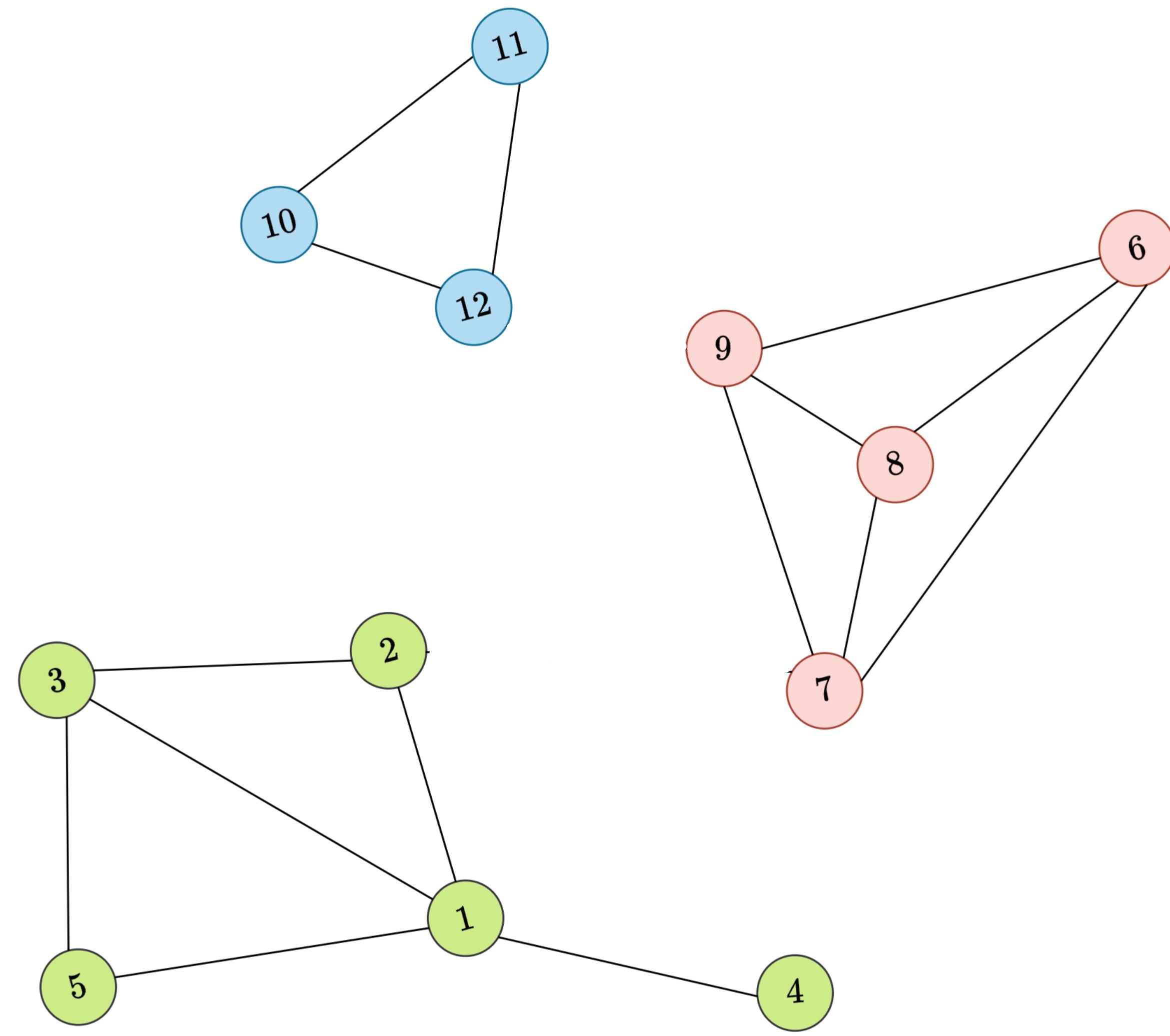


# Edge Betweenness of the Edges

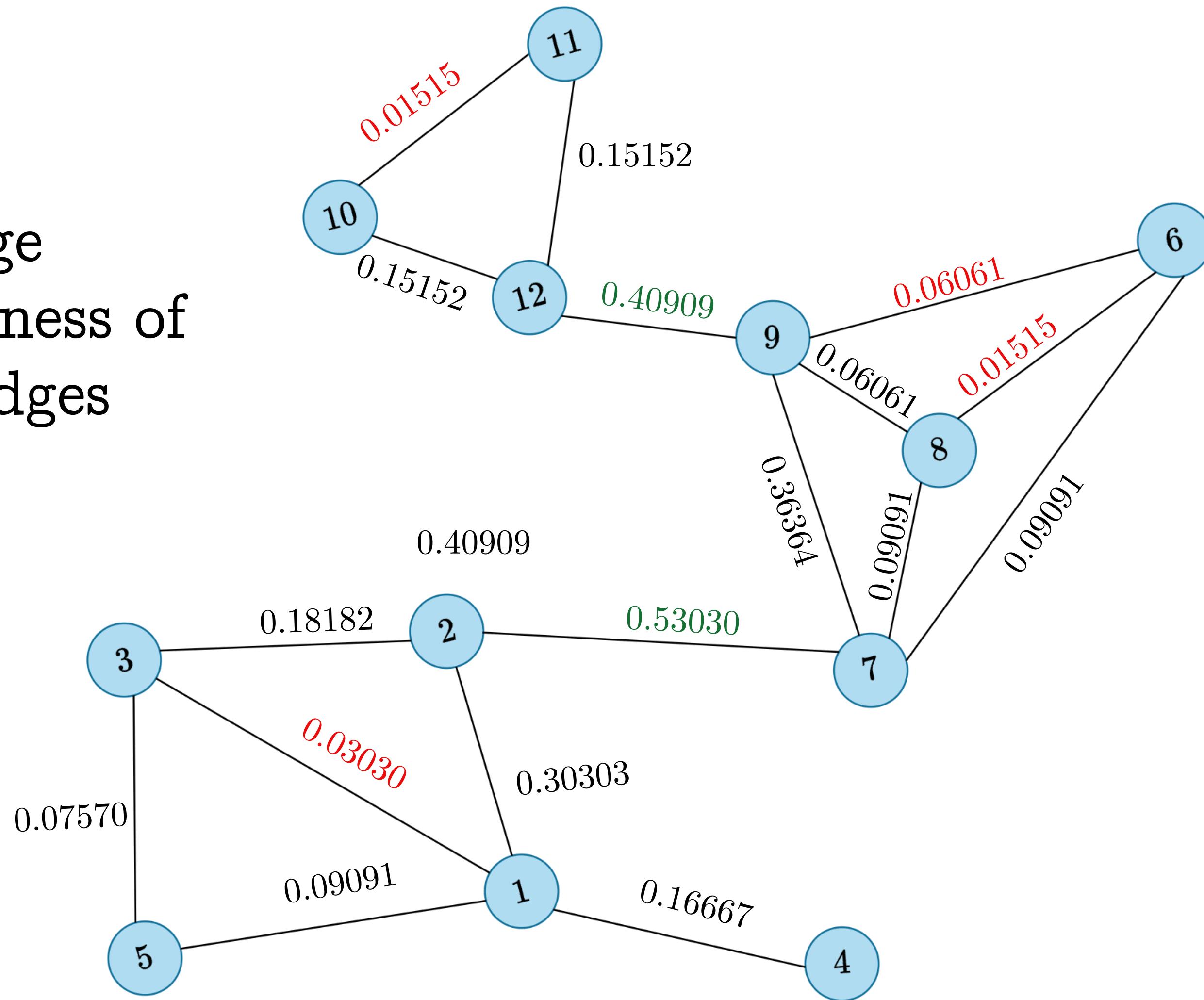


High  
Betweenness  
Edges

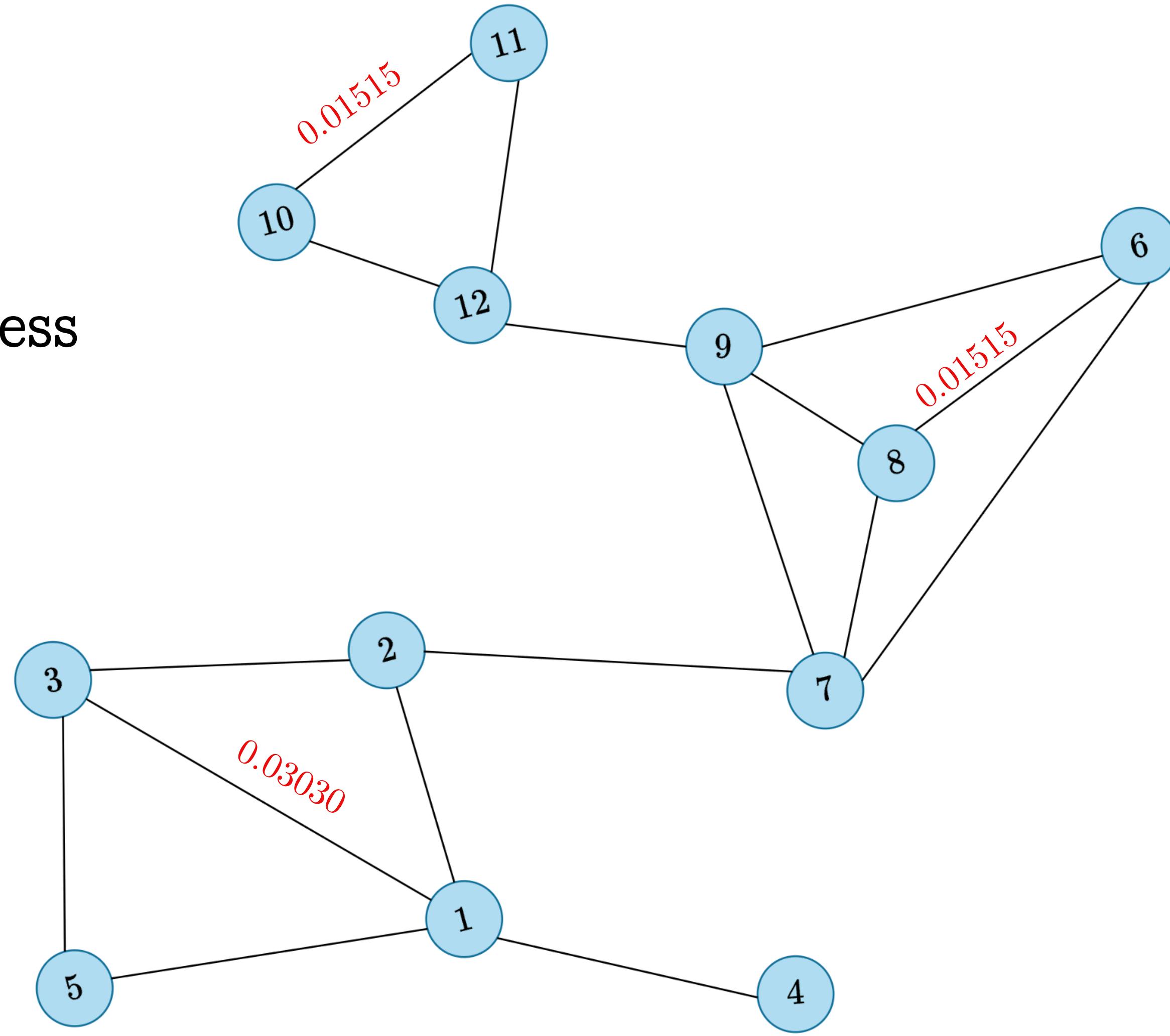




# Edge Betweenness of the Edges

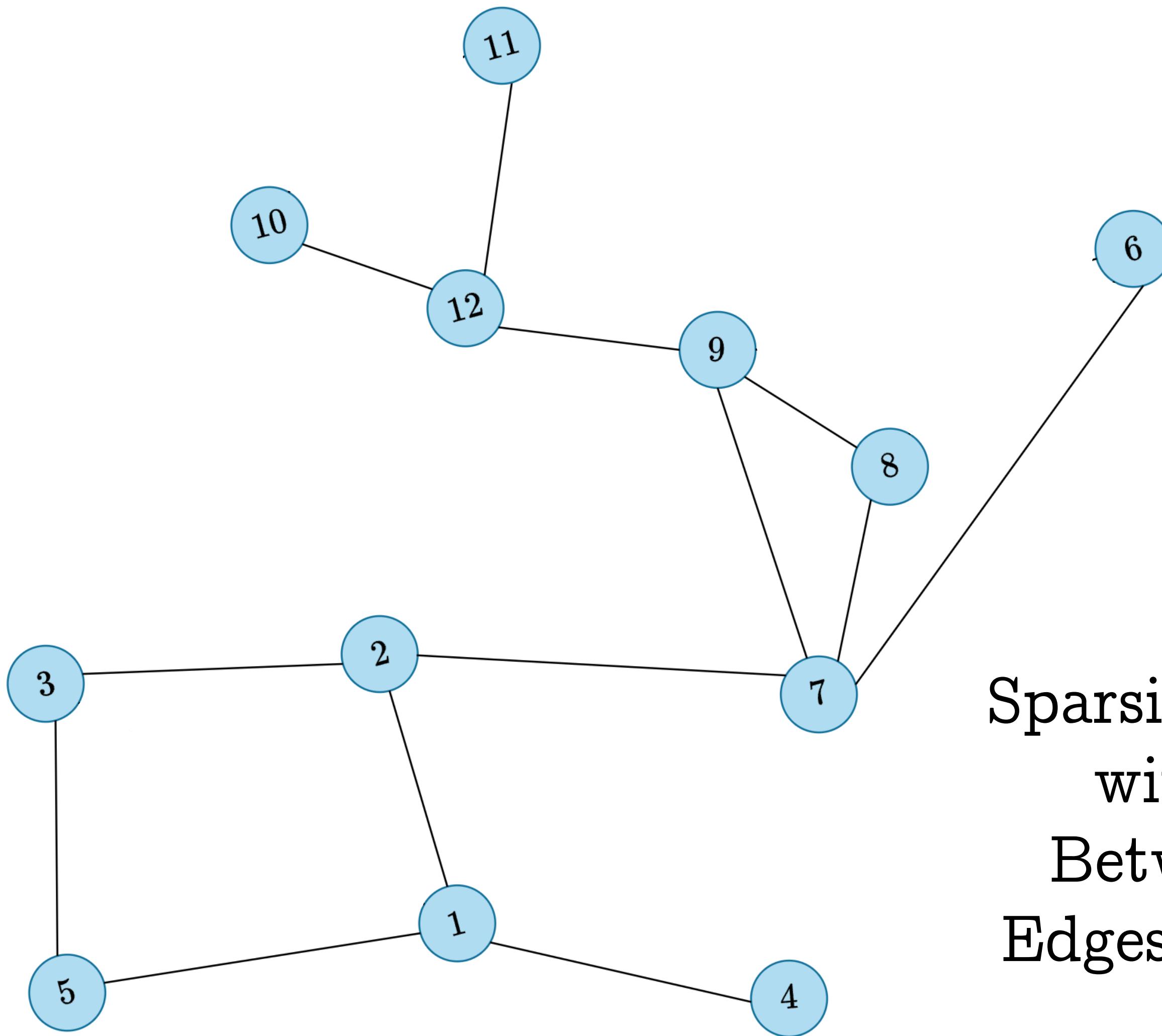


Low  
Betweenness  
Edges

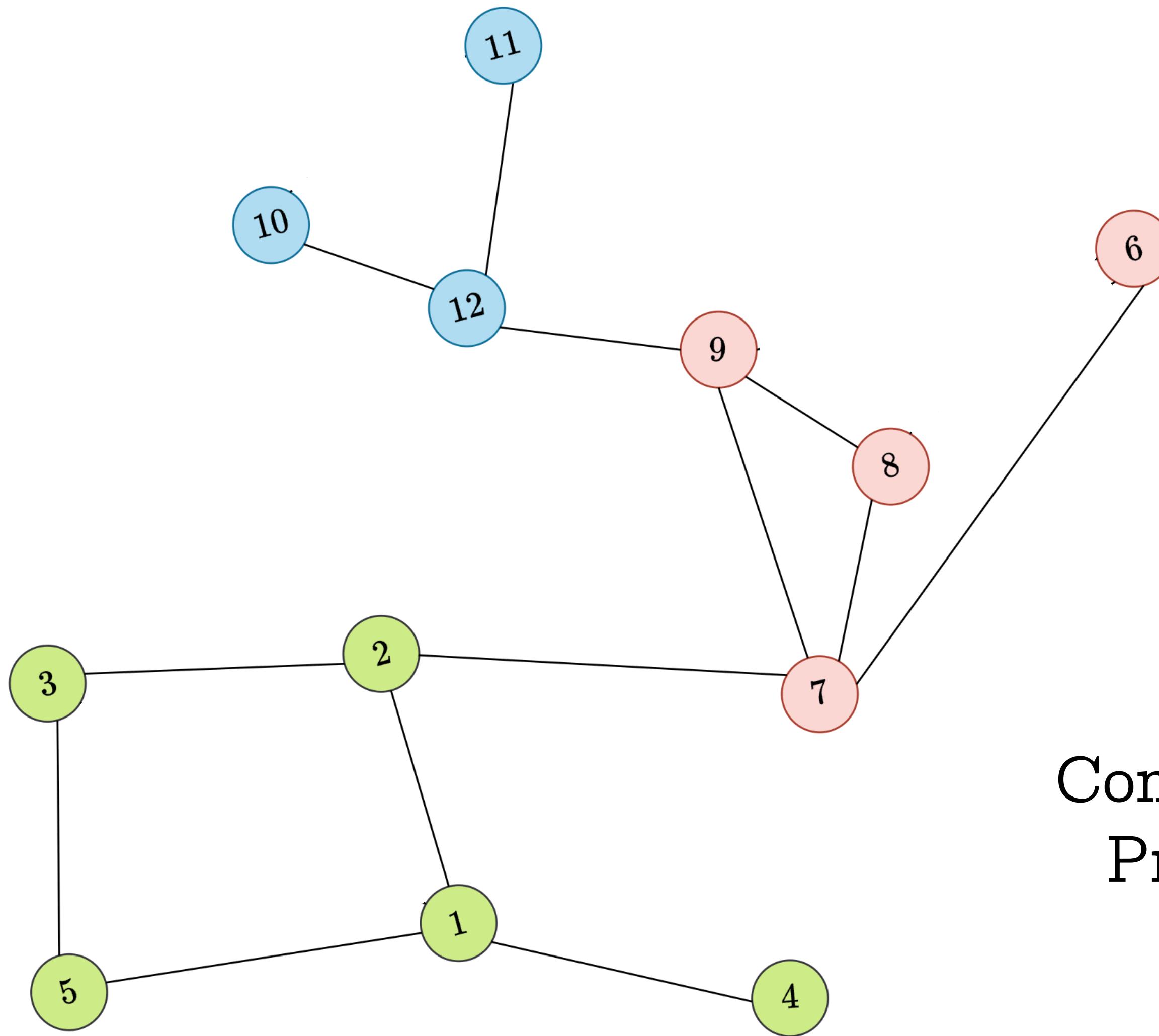


$$|V| = 12$$

$$|E| = 11$$

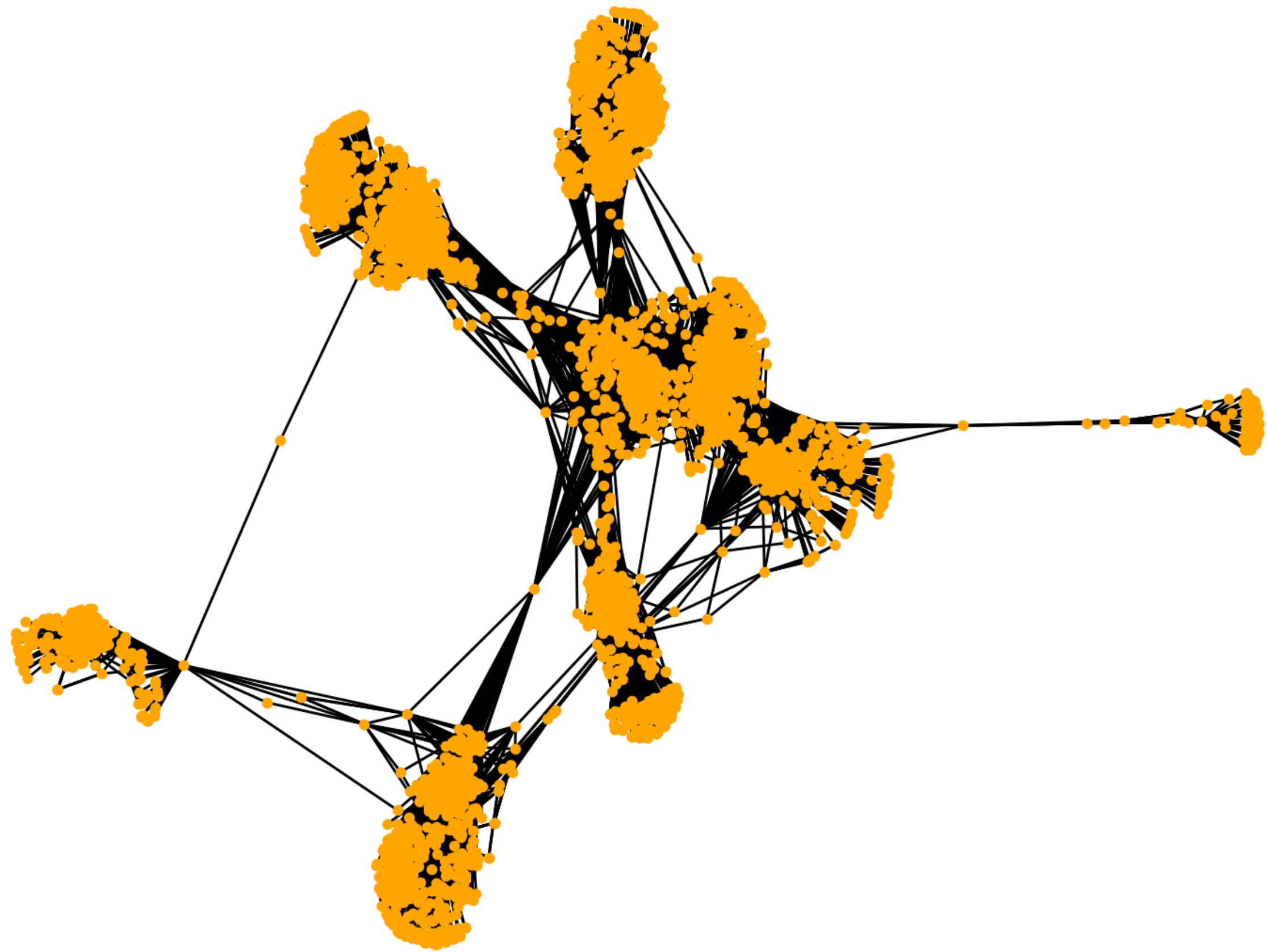


Sparsified Graph  
with Low  
Betweenness  
Edges Removed



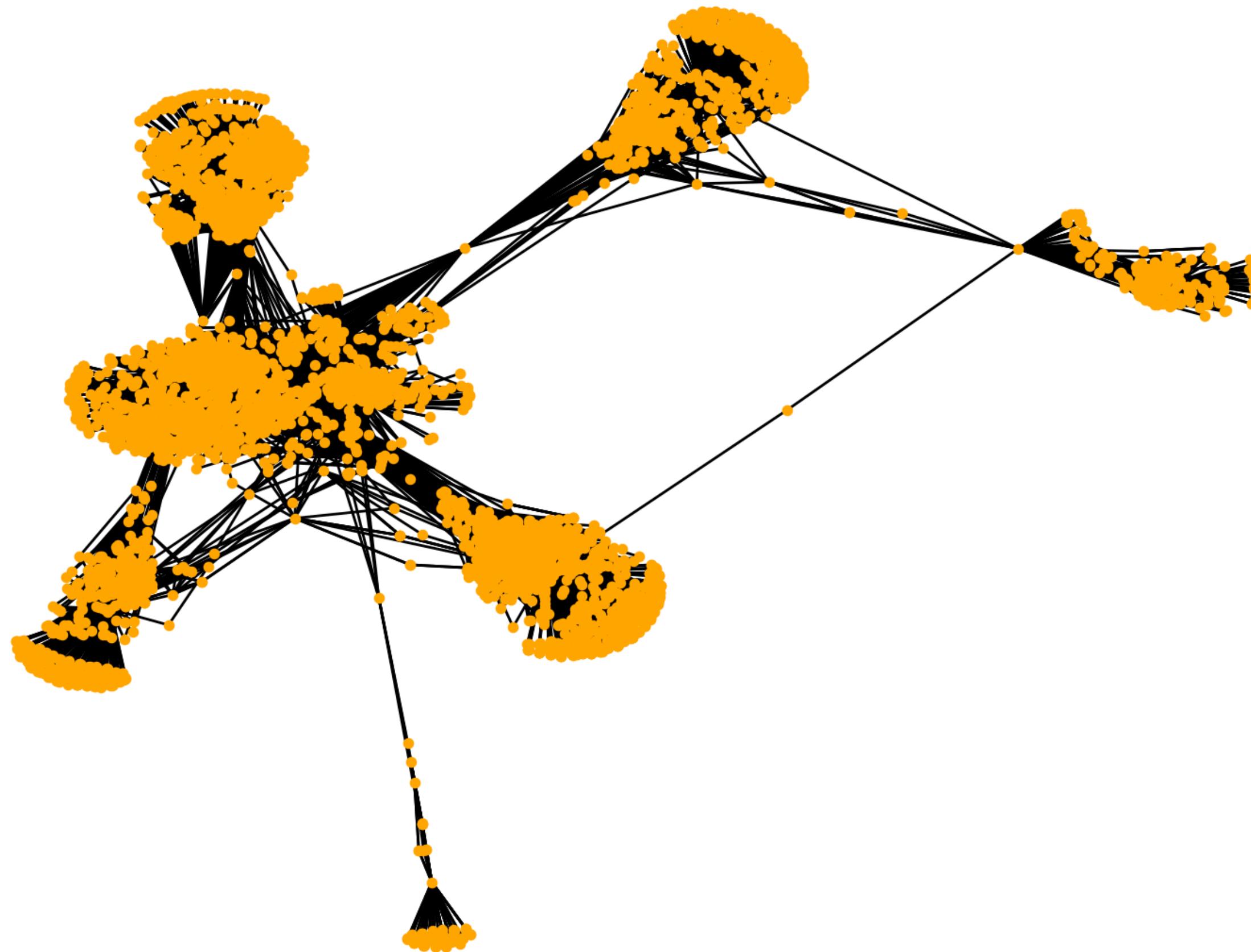
Communities  
Preserved

Graph with Top 50.0 % Highest Betweenness Edges Retained  
Number of edges: 44117



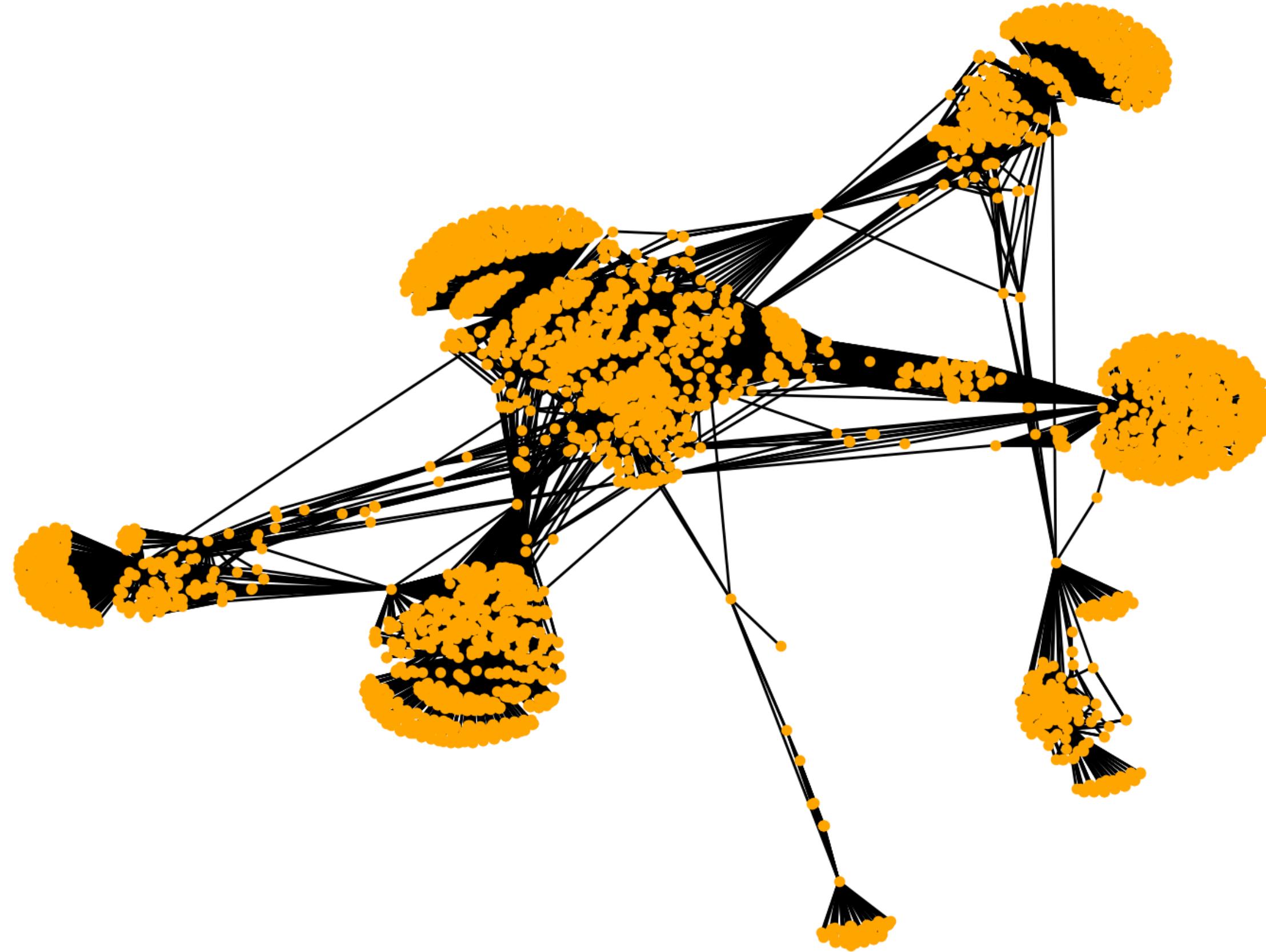
FaceBook

Graph with Top 30.0 % Highest Betweenness Edges Retained  
Number of edges: 26471



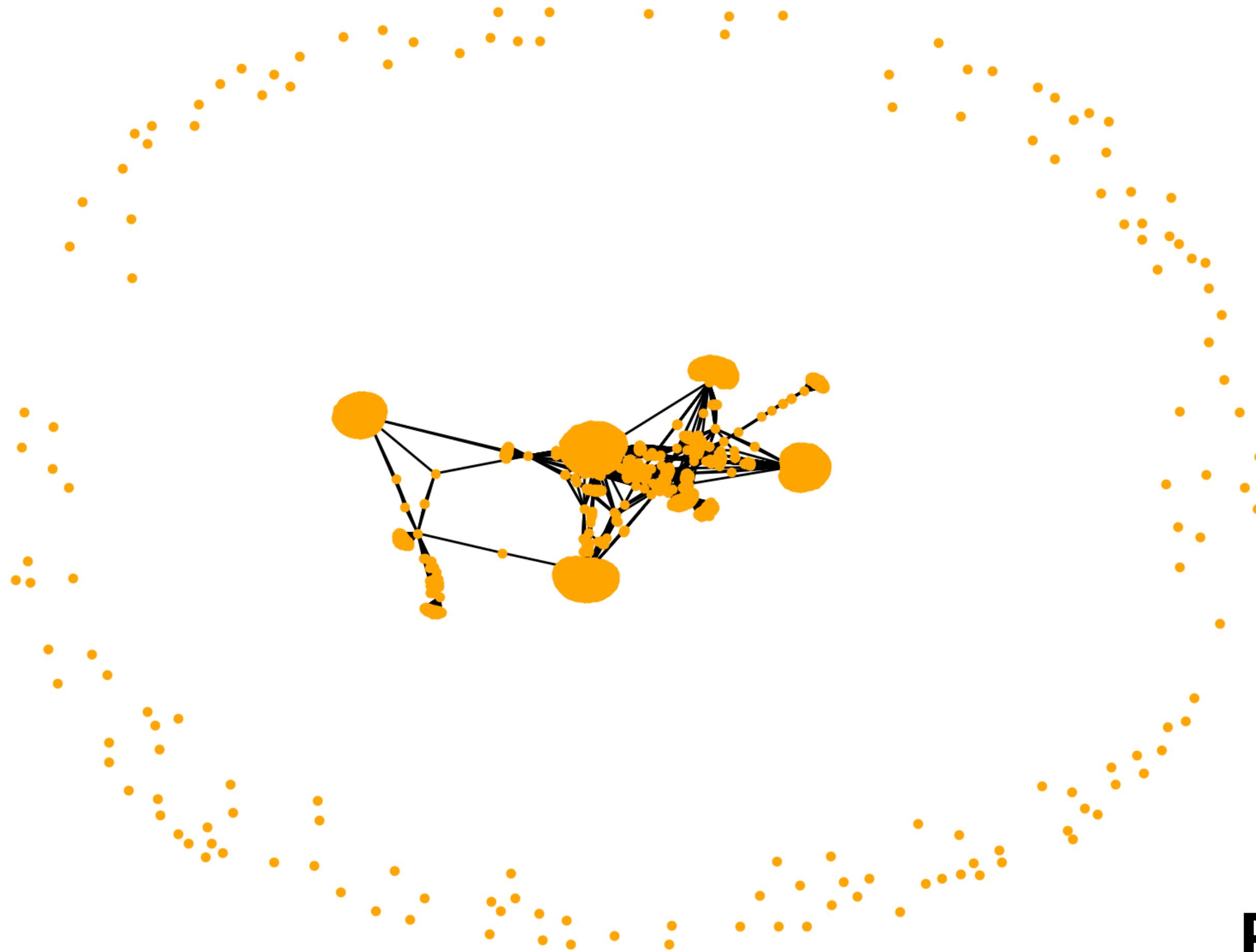
FaceBook

Graph with Top 10.0 % Highest Betweenness Edges Retained  
Number of edges: 8824



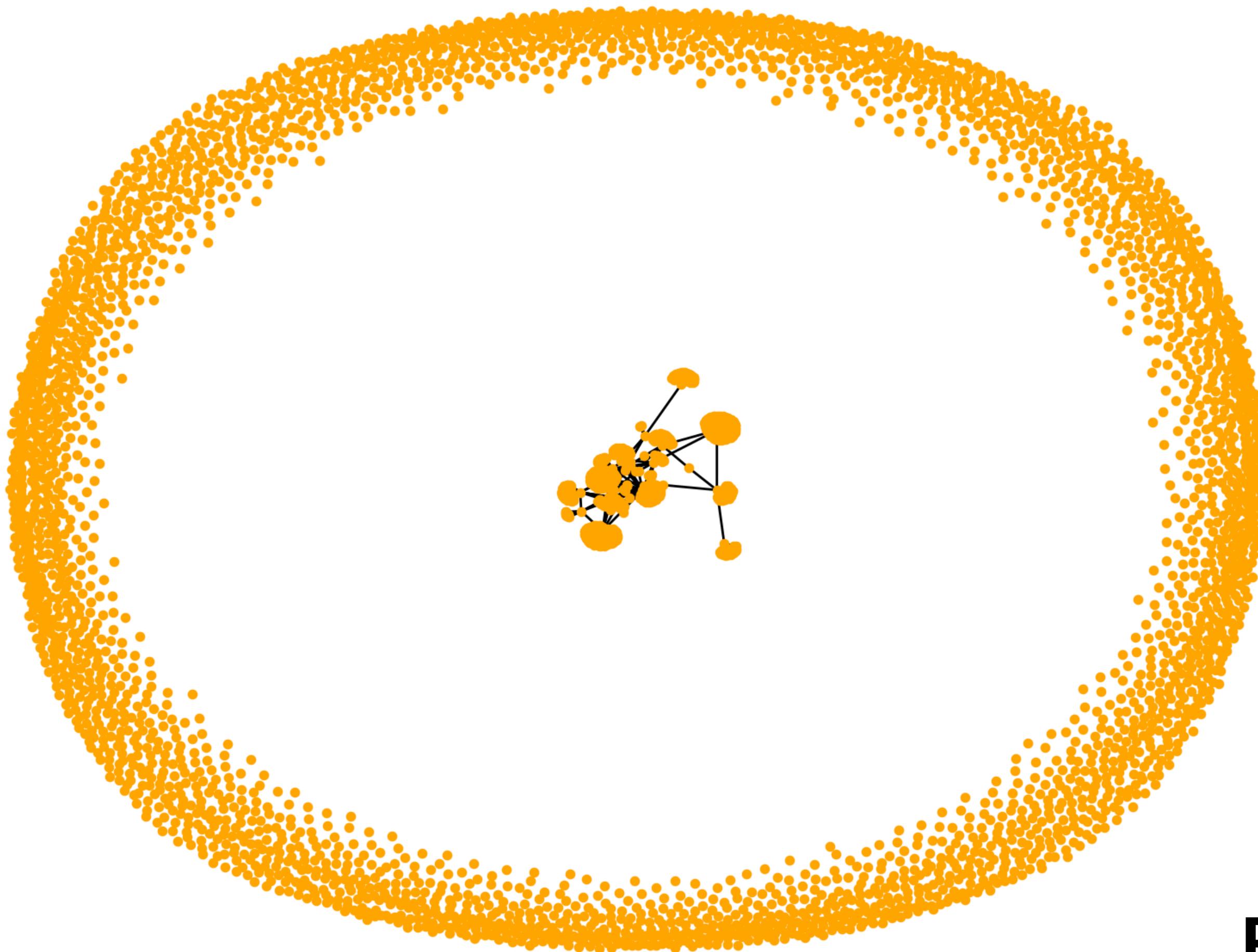
FaceBook

Graph with Top 5.0 % Highest Betweenness Edges Retained  
Number of edges: 4412



**FaceBook**

Graph with Top 1.0 % Highest Betweenness Edges Retained  
Number of edges: 883



FaceBook

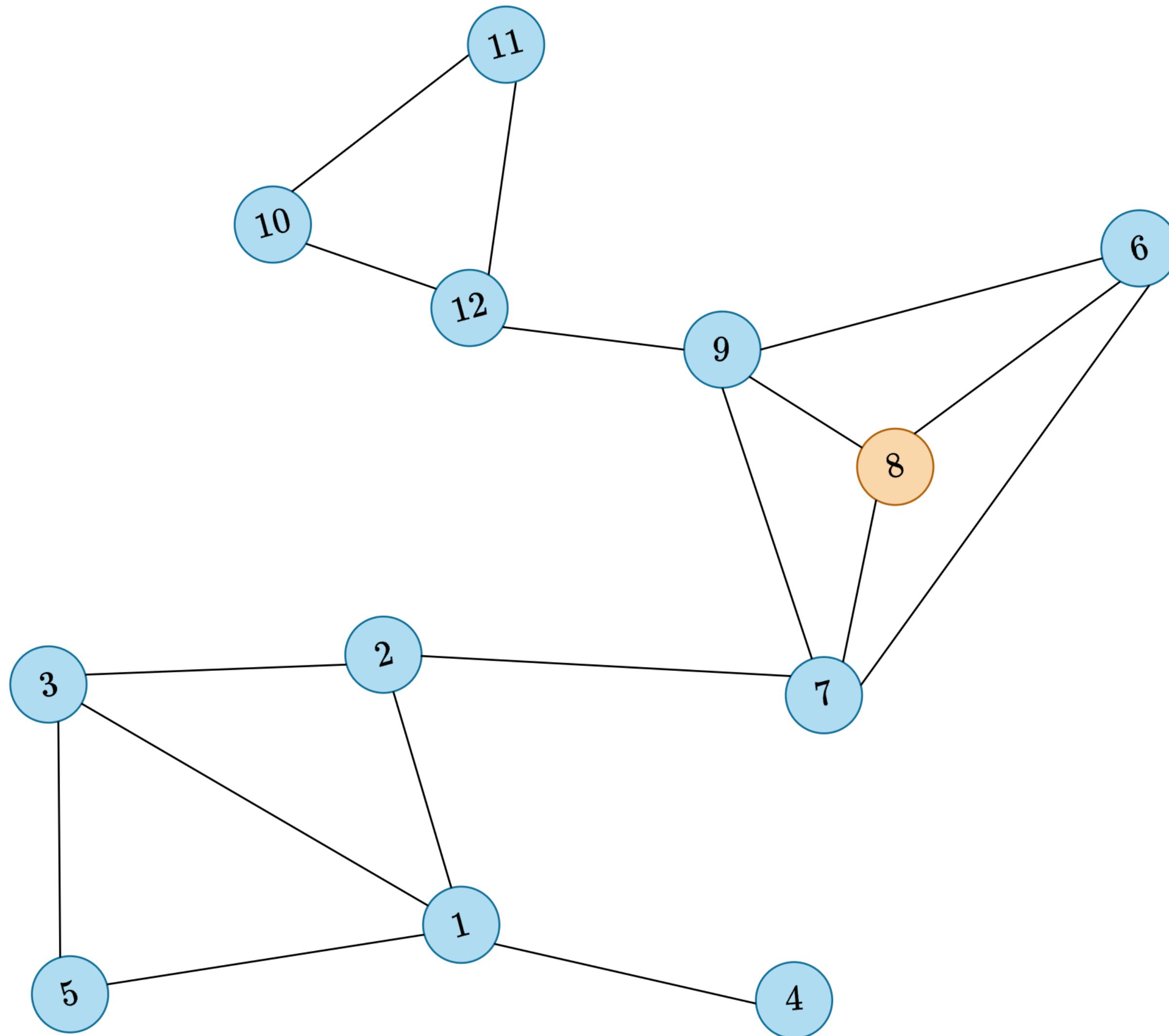
# Jaccard Similarity

An edge  $(i, j)$  is *likely* to lie within a cluster if the vertices  $i$  and  $j$  have adjacency lists with *high overlap*.

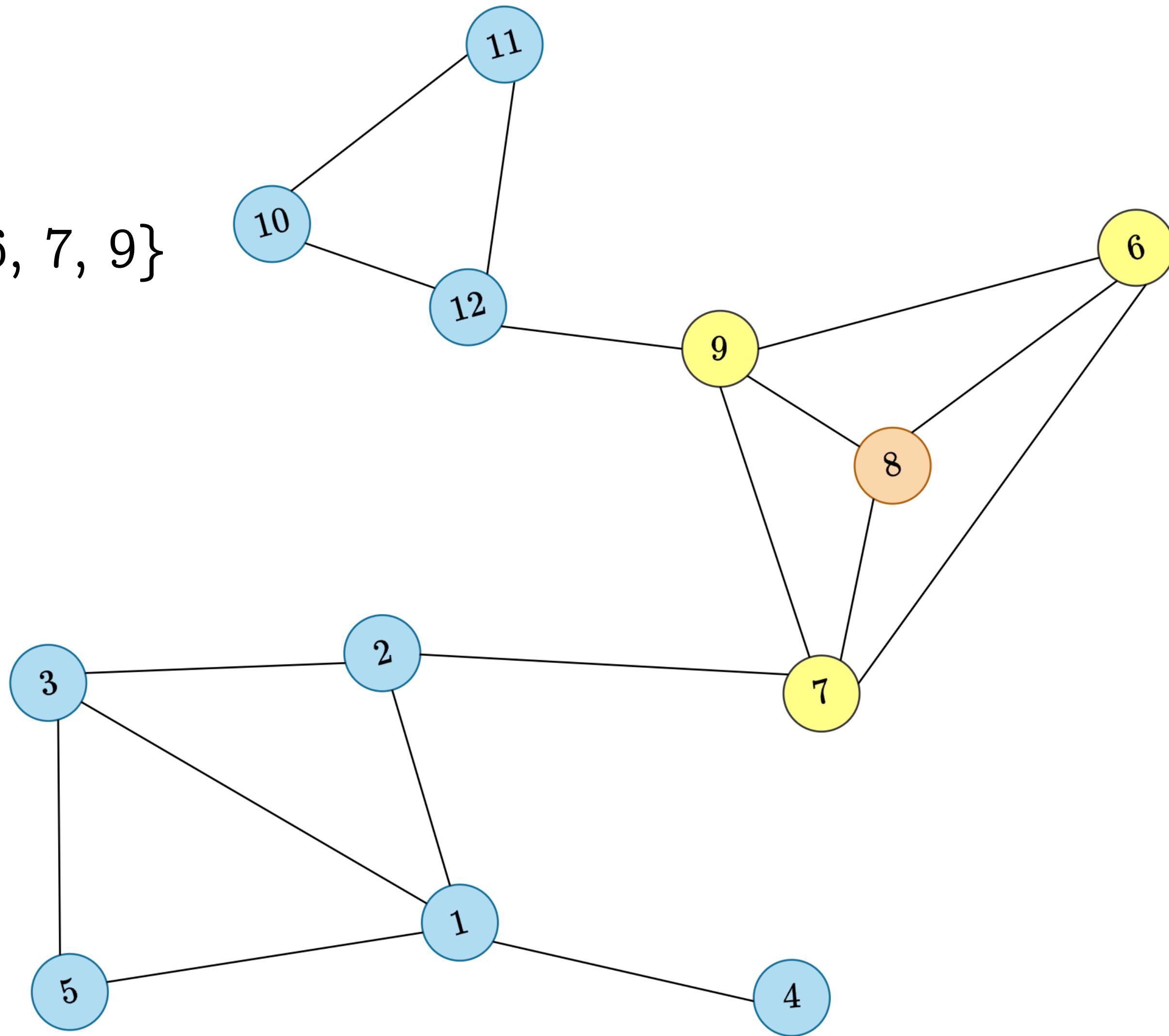
$$Sim(i, j) = \frac{|Adj(i) \cap Adj(j)|}{|Adj(i) \cup Adj(j)|}$$

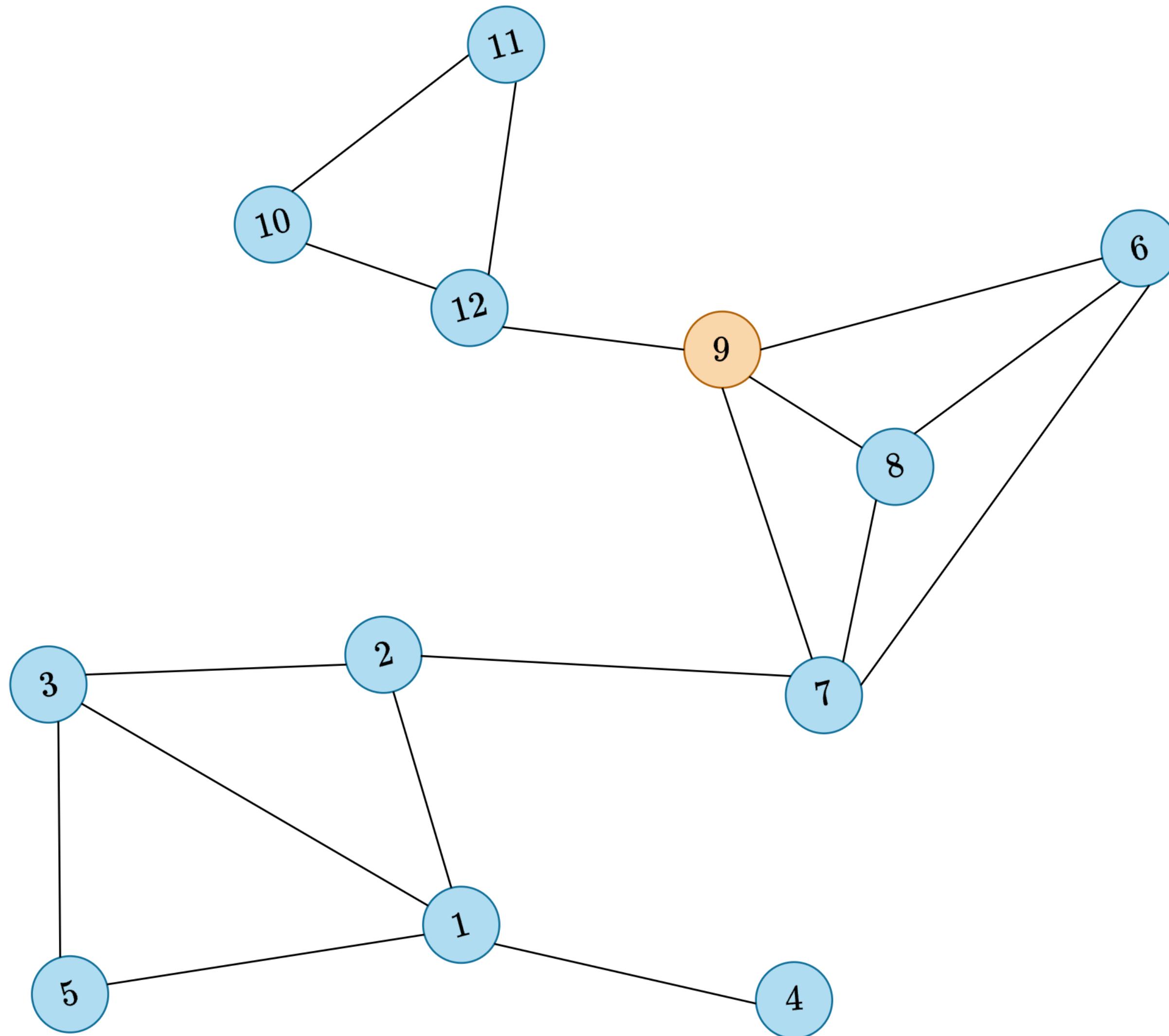


Adjacency List of Node i

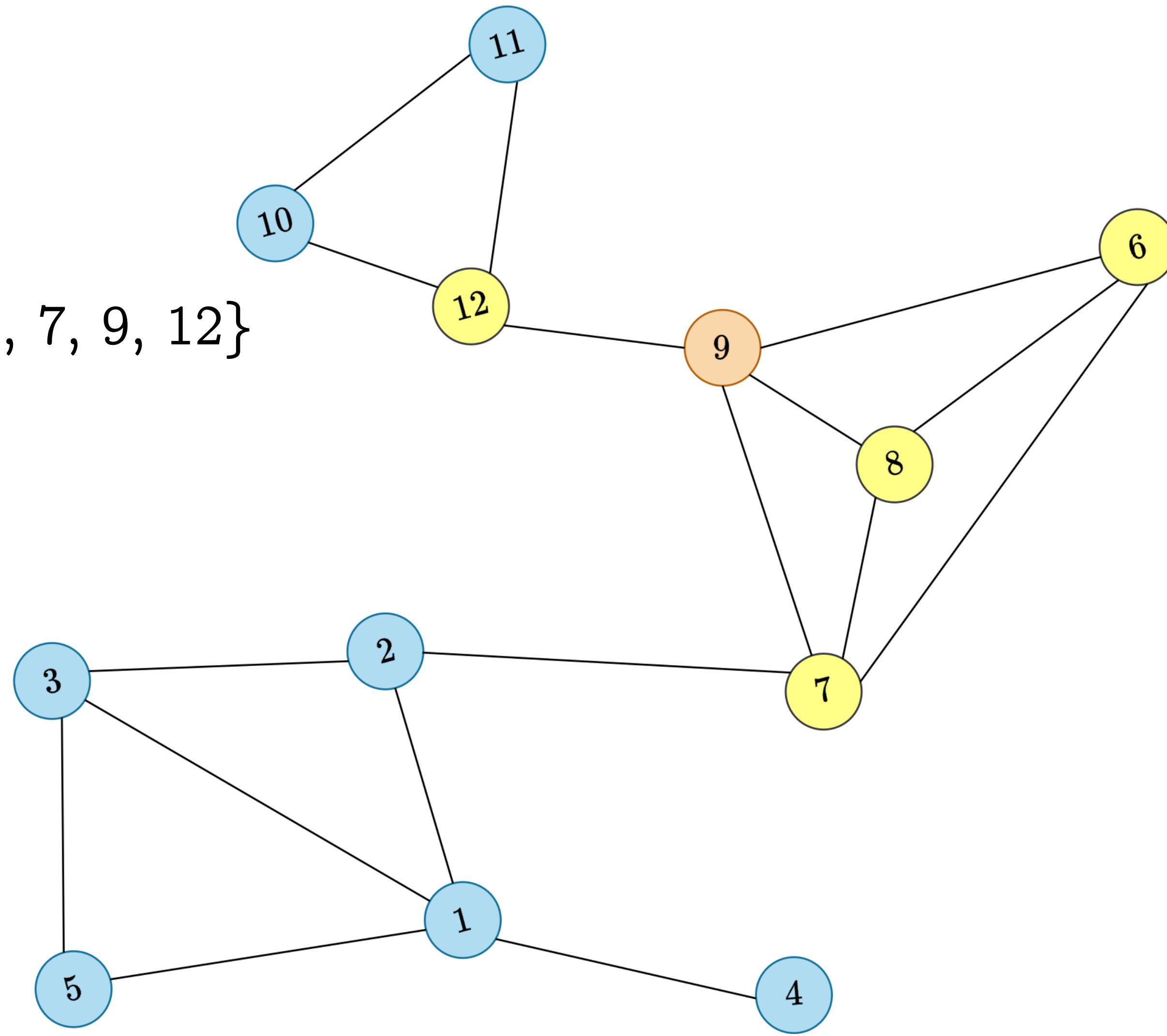


$$\text{Adj}(8) = \{6, 7, 9\}$$





$$\text{Adj}(9) = \{6, 7, 9, 12\}$$



$$\text{Adj}(8) = \{6, 7, 9\}$$

$$\text{Adj}(9) = \{6, 7, 9, 12\}$$

$$\text{Adj}(8) = \{6, 7, 9\}$$

$$\text{Adj}(9) = \{6, 7, 9, 12\}$$

$$\text{Sim}(8, 9) = \frac{|\{6, 7, 9\} \cap \{6, 7, 9, 12\}|}{|\{6, 7, 9\} \cup \{6, 7, 9, 12\}|}$$

$$\text{Adj}(8) = \{6, 7, 9\}$$

$$\text{Adj}(9) = \{6, 7, 9, 12\}$$

$$\text{Sim}(8, 9) = \frac{3}{4}$$

---

**Algorithm 1** Global Sparsification Algorithm

---

**Input:** Graph  $G = (V, E)$ , Sparsification ratio  $s$

$G_{sparse} \leftarrow \emptyset$

**for** each edge  $e=(i,j)$  in  $E$  **do**

$e.sim = Sim(i, j)$  according to Eqn 1

**end for**

Sort all edges in  $E$  by  $e.sim$

Add the top  $s\%$  edges to  $G_{sparse}$

**return**  $G_{sparse}$

---

---

## Algorithm 2 Local Sparsification Algorithm

---

**Input:** Graph  $G = (V, E)$ , Local Sparsification exponent  $e$

**Output:** Sparsified graph  $G_{sparse}$

$G_{sparse} \leftarrow \emptyset$

**for** each node  $i$  in  $V$  **do**

    Let  $d_i$  be the degree of  $i$

    Let  $E_i$  be the set of edges incident to  $i$

**for** each edge  $e=(i,j)$  in  $E_i$  **do**

$e.sim = Sim(i, j)$  according to Eqn. 1

**end for**

    Sort all edges in  $E_i$  by  $e.sim$

    Add top  $d_i^e$  edges to  $G_{sparse}$

**end for**

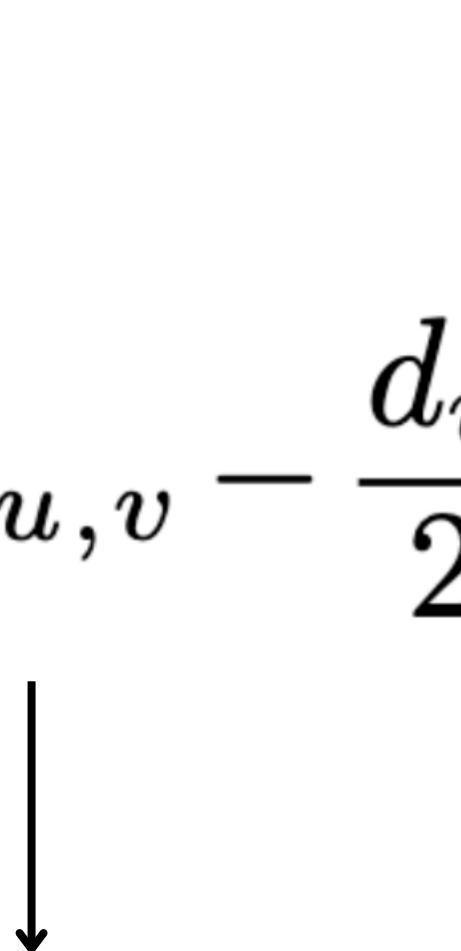
**return**  $G_{sparse}$

---

# Modularity

$$Q(\mathcal{C}) = \frac{1}{2m} \sum_{C \in \mathcal{C}} \sum_{u \in C, v \in C} \left( A_{u,v} - \frac{d_u d_v}{2m} \right)$$

# Expected Edges b/w u, v



# Edges b/w u, v

# Clustering Coefficients

# Networks Used

1.

Amazon Co-Purchase

2.

DBLP

3.

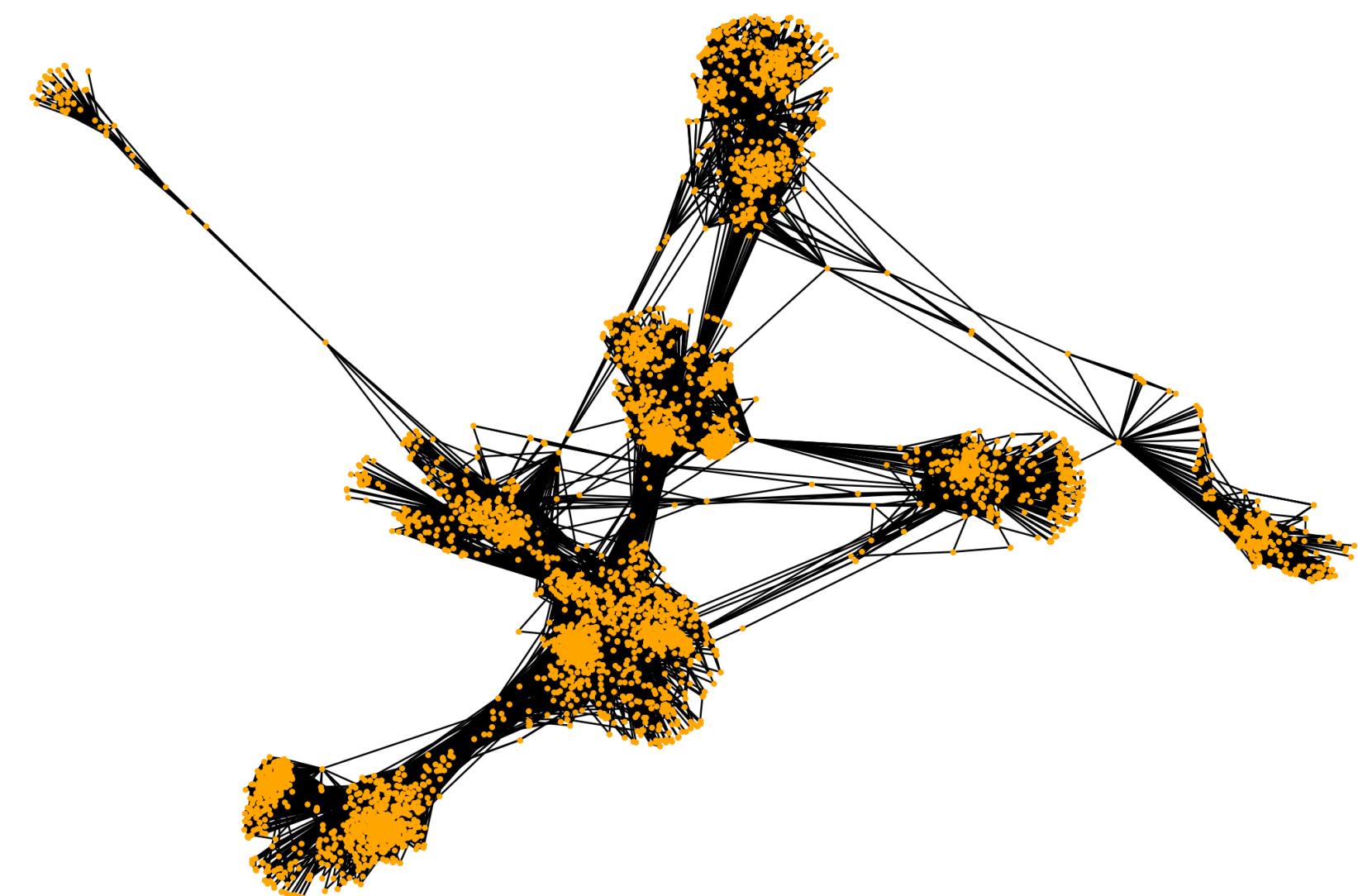
Facebook Social

4.

YouTube Social

5.

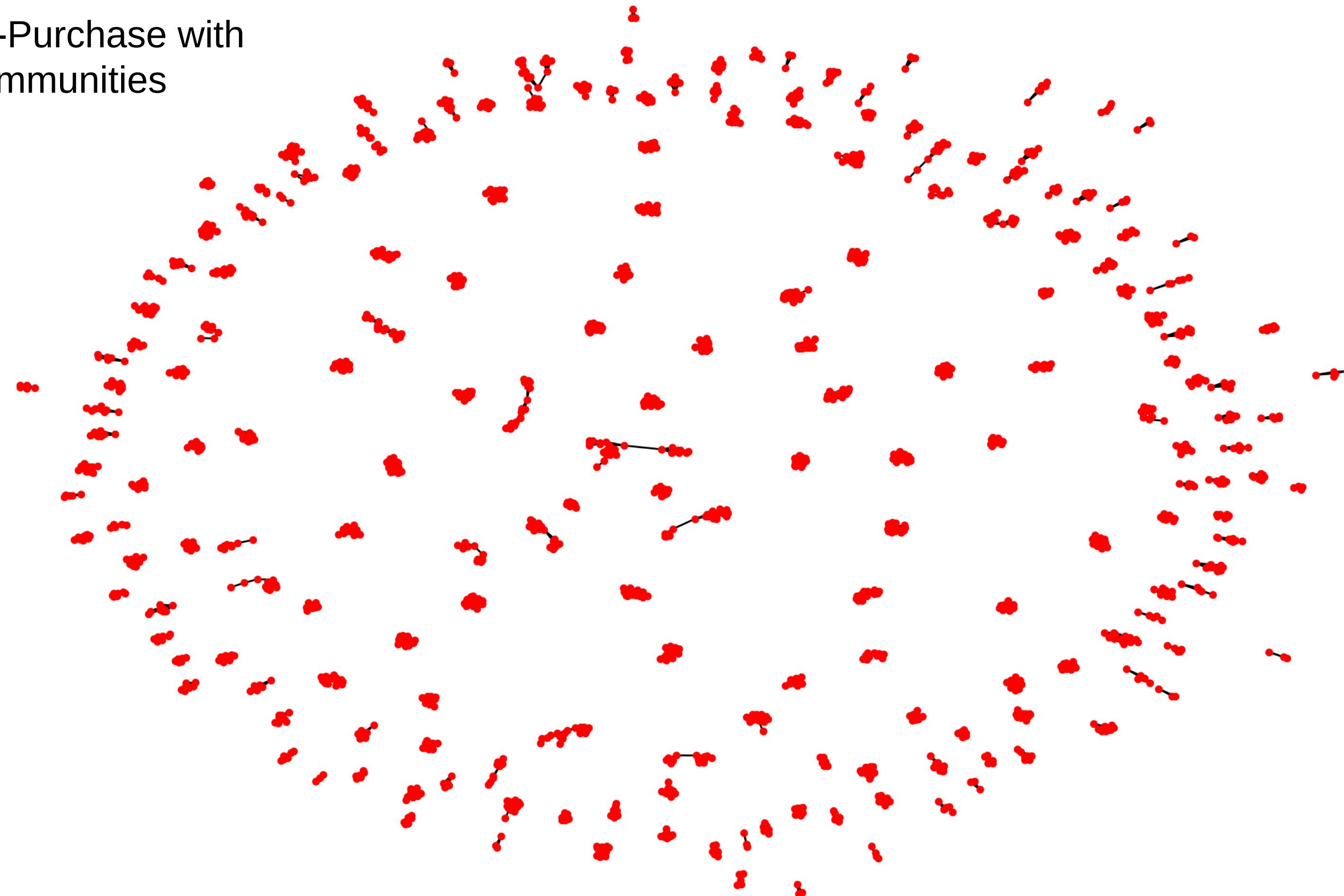
Email EU Core



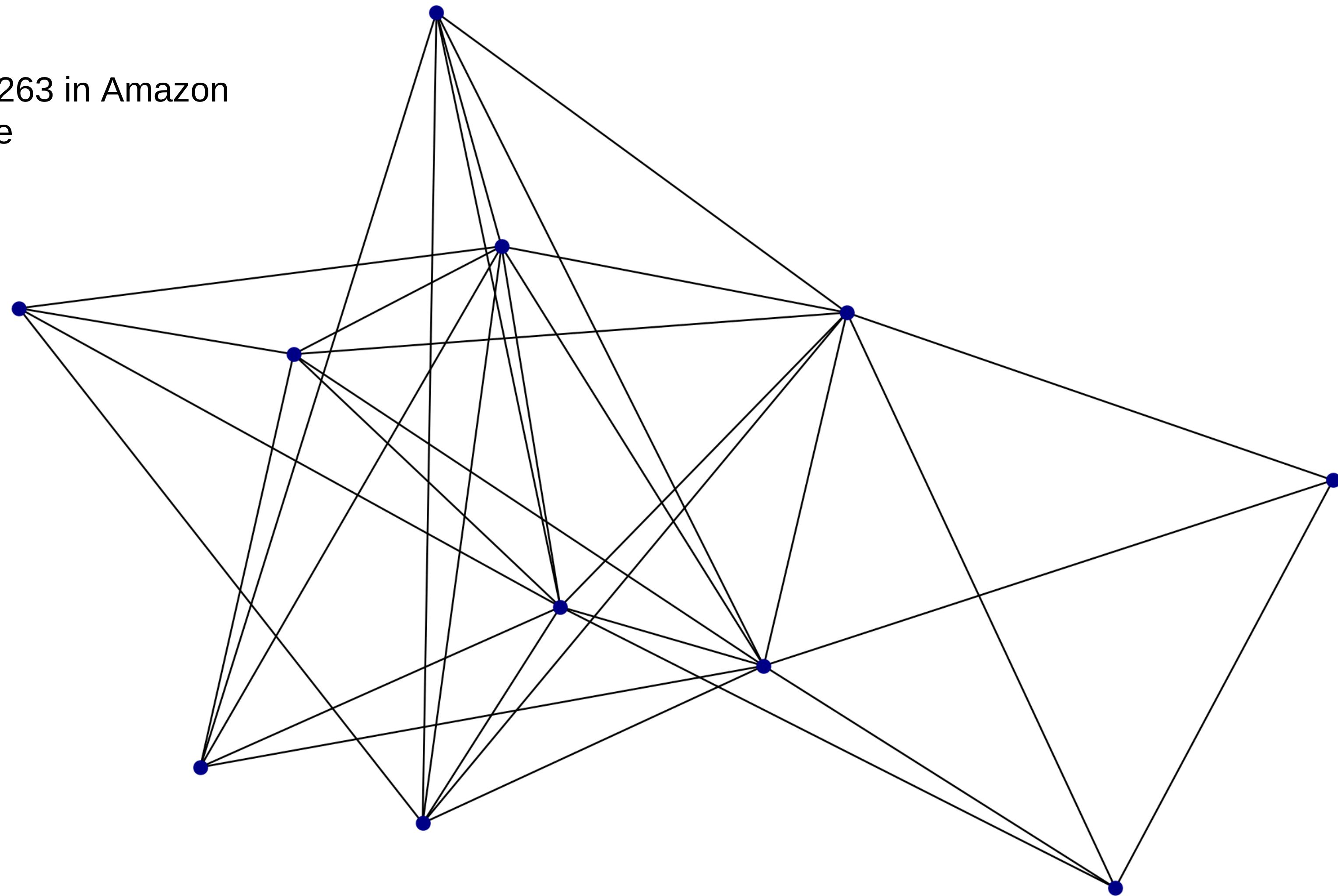
FaceBook Network

<b>Network</b>	<b> V </b>	<b> E </b>	<b> C </b>	<b> V <sub>ind</sub></b>	<b> E <sub>ind</sub></b>
DBLP	317080	1049866	150	1420	4609
Amazon	334863	925872	300	2008	5960
YouTube	1134890	2987624	100	4890	20787
EU	1005	16064	42	1005	16064
Facebook	4039	88234	NA	4039	88234

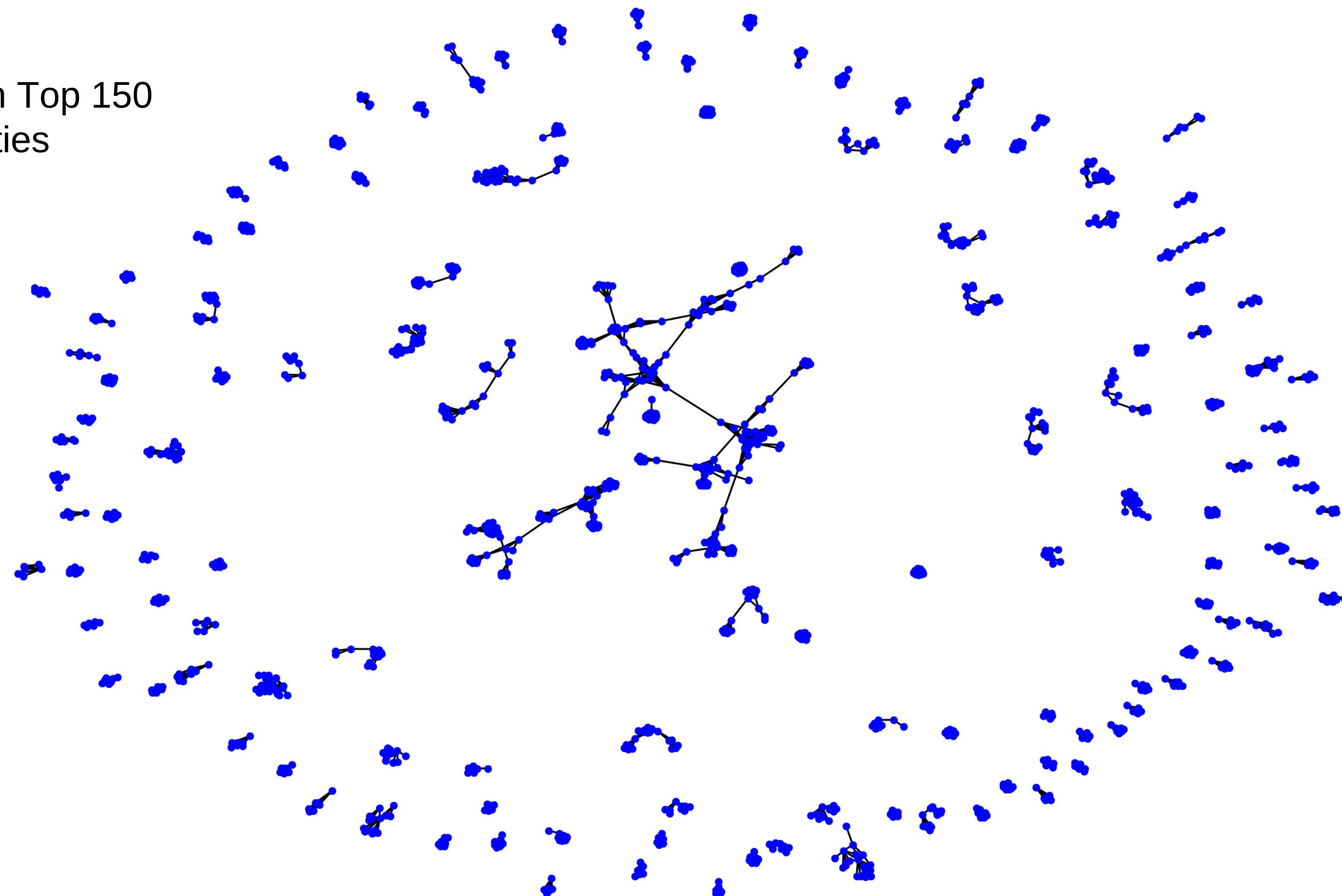
# Amazon Co-Purchase with Top 300 Communities



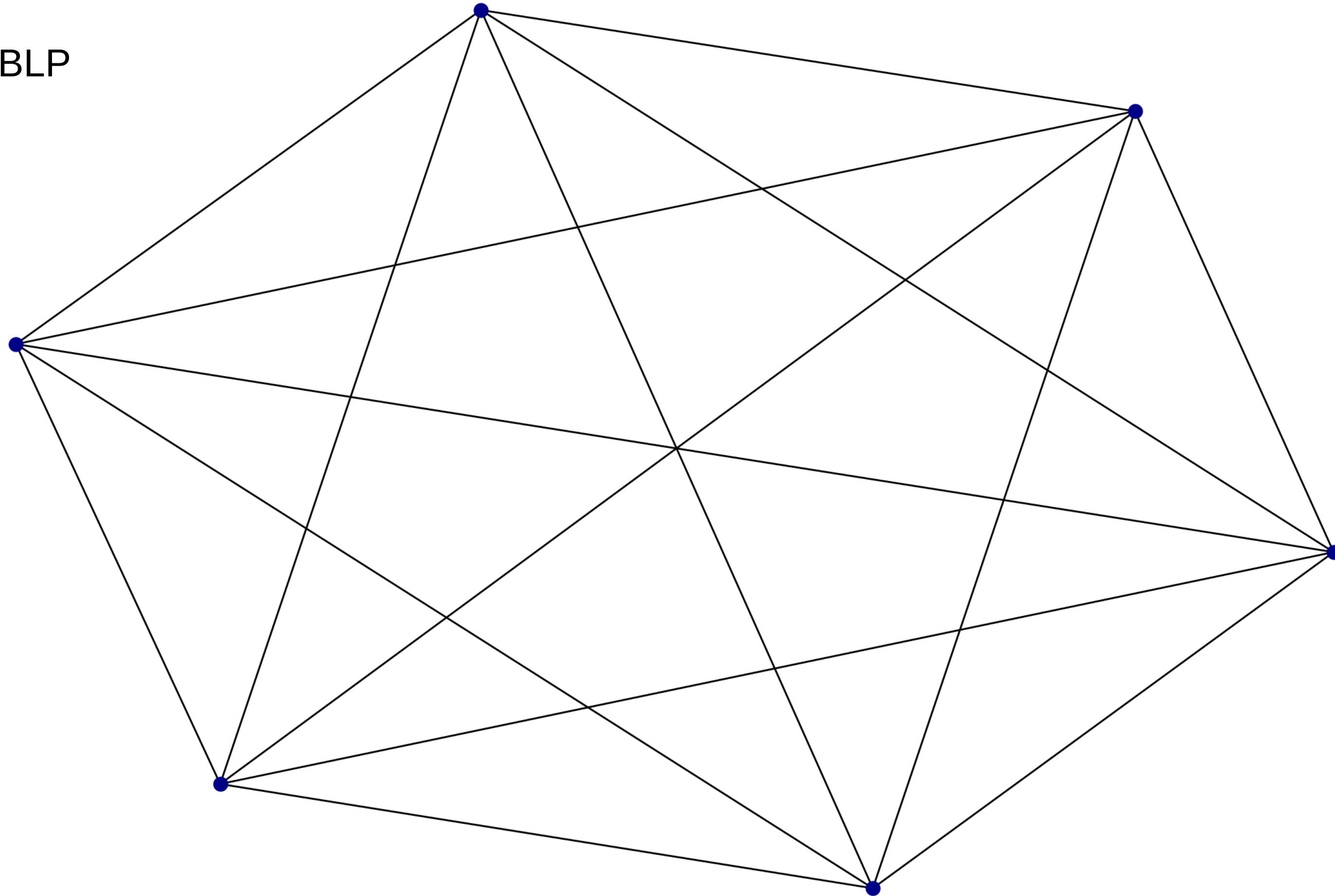
Community 263 in Amazon  
Co-Purchase



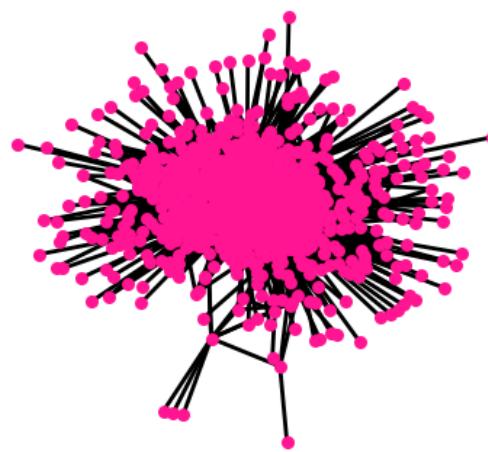
DBLP with Top 150  
Communities



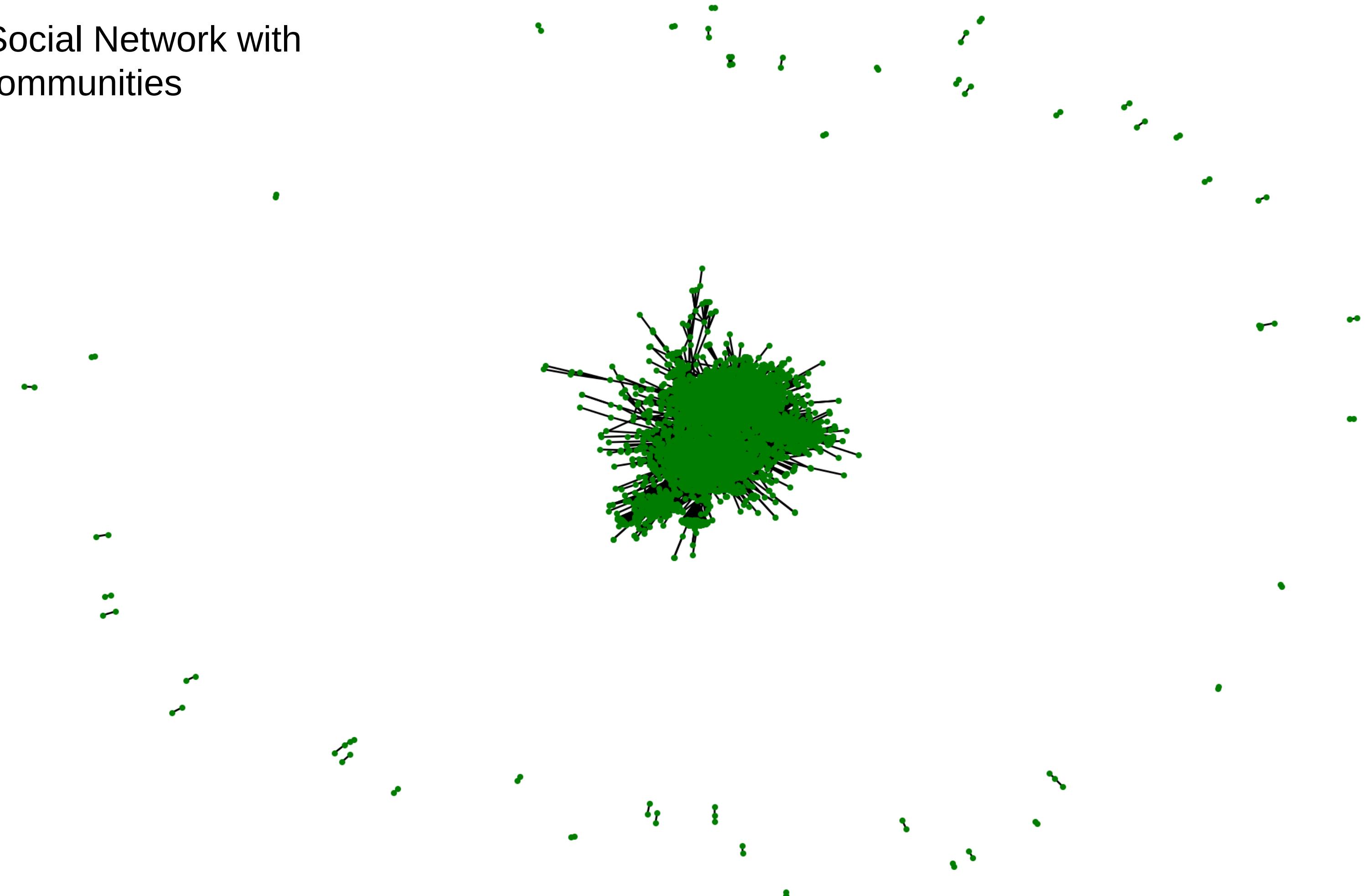
Community 4 in DBLP



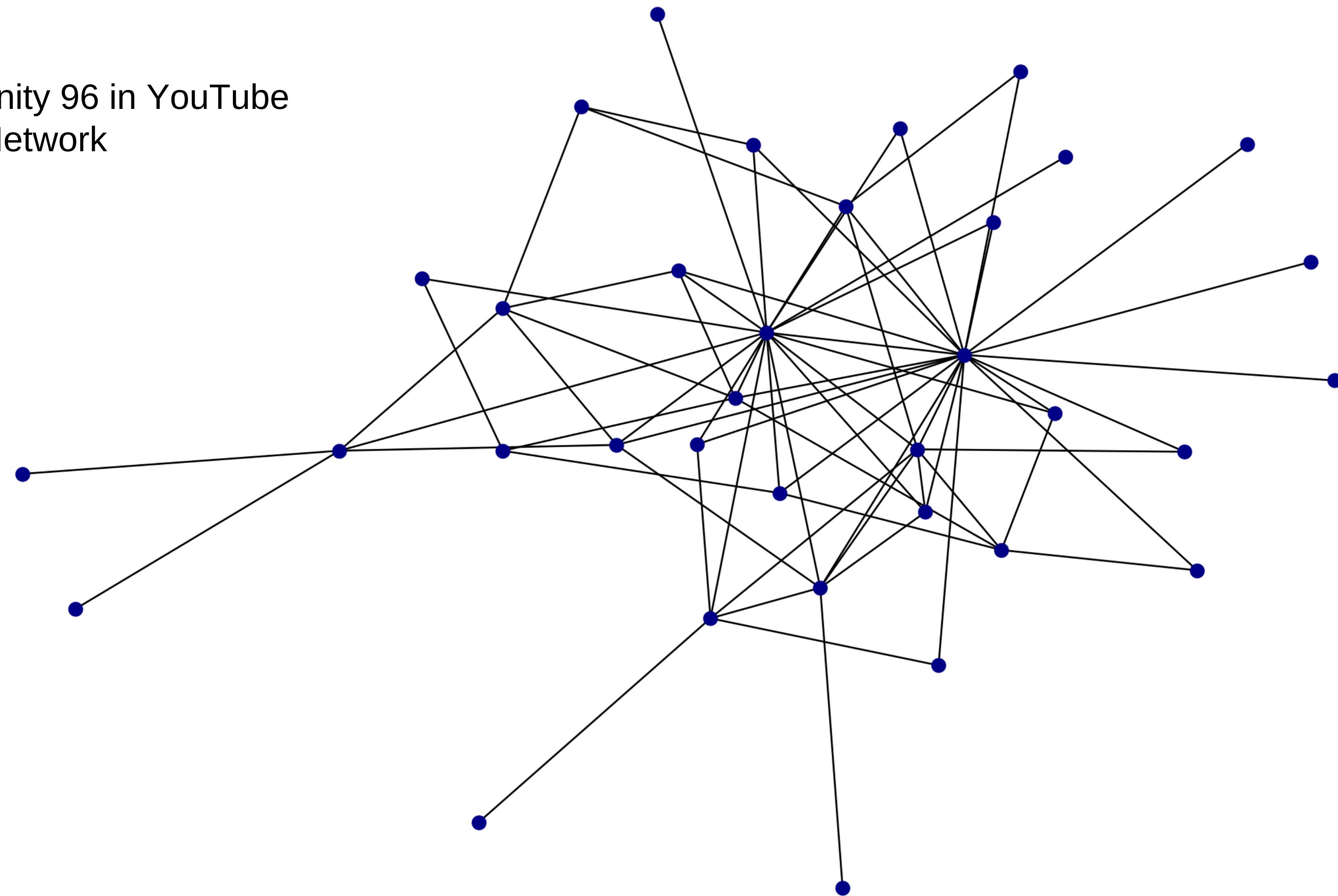
# Email EU Core Network



# YouTube Social Network with Top 100 Communities



# Community 96 in YouTube Social Network



# Community Detection Algorithms Used

1.

Louvain Algorithm

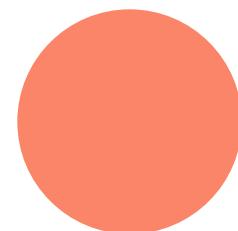
2.

Label Propogation Algorithm

3.

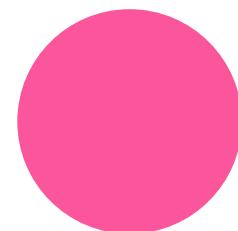
InfoMap Algorithm

# Metrics for comparing Community Quality

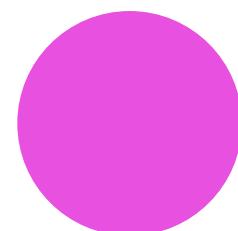


Adjusted Rand Index

$$ARI = \frac{\sum_{ij} \binom{n_{ij}}{2} - [\sum_i \binom{a_i}{2} \sum_j \binom{b_j}{2}] / \binom{n}{2}}{\frac{1}{2} [\sum_i \binom{a_i}{2} + \sum_j \binom{b_j}{2}] - [\sum_i \binom{a_i}{2} \sum_j \binom{b_j}{2}] / \binom{n}{2}}$$

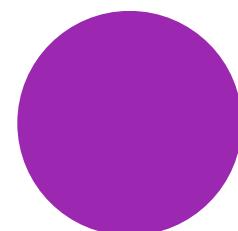


Normalized Mutual Information



Modularity

$$Q(\mathcal{C}) = \frac{1}{2m} \sum_{C \in \mathcal{C}} \sum_{u \in C, v \in C} \left( A_{u,v} - \frac{d_u d_v}{2m} \right)$$

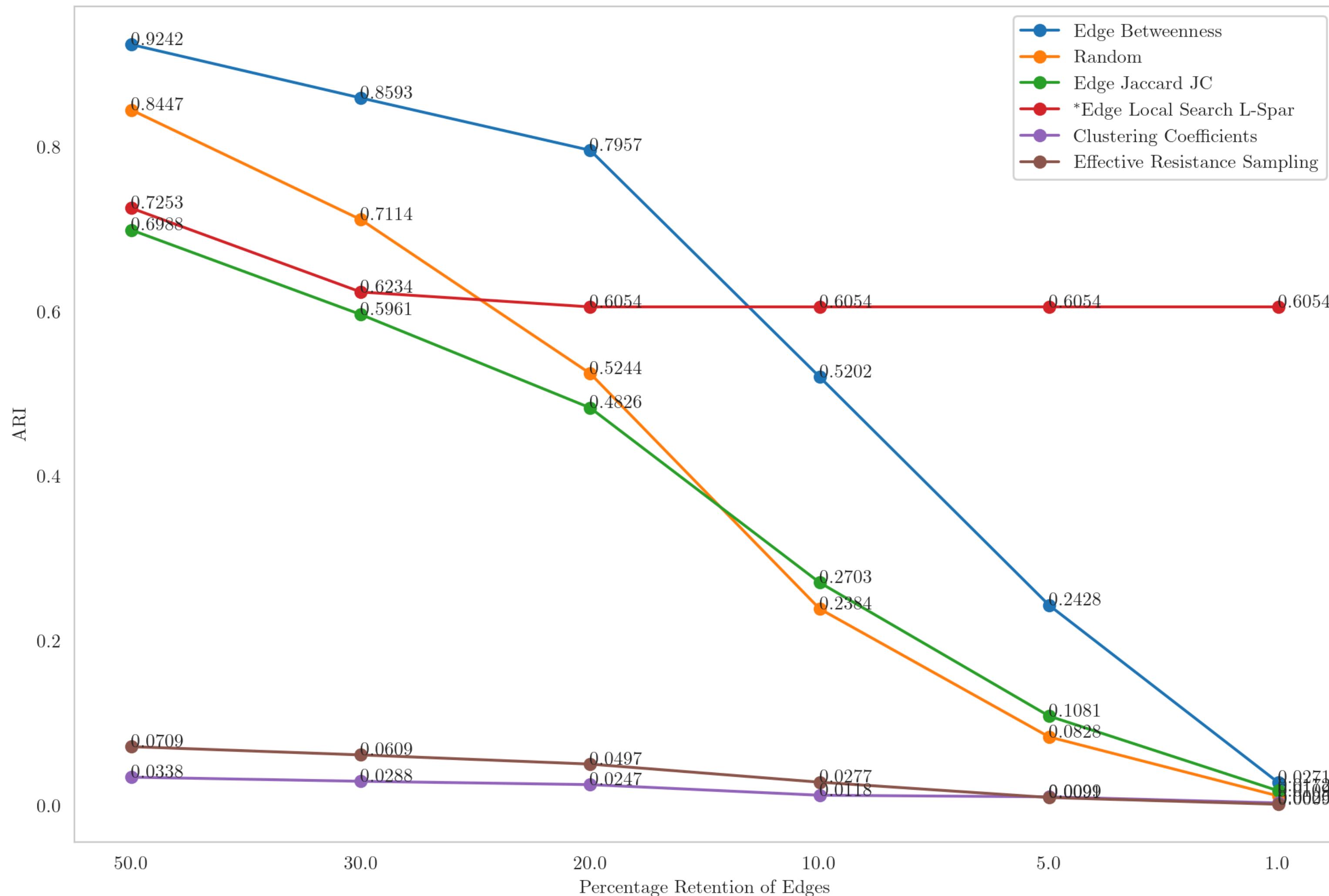


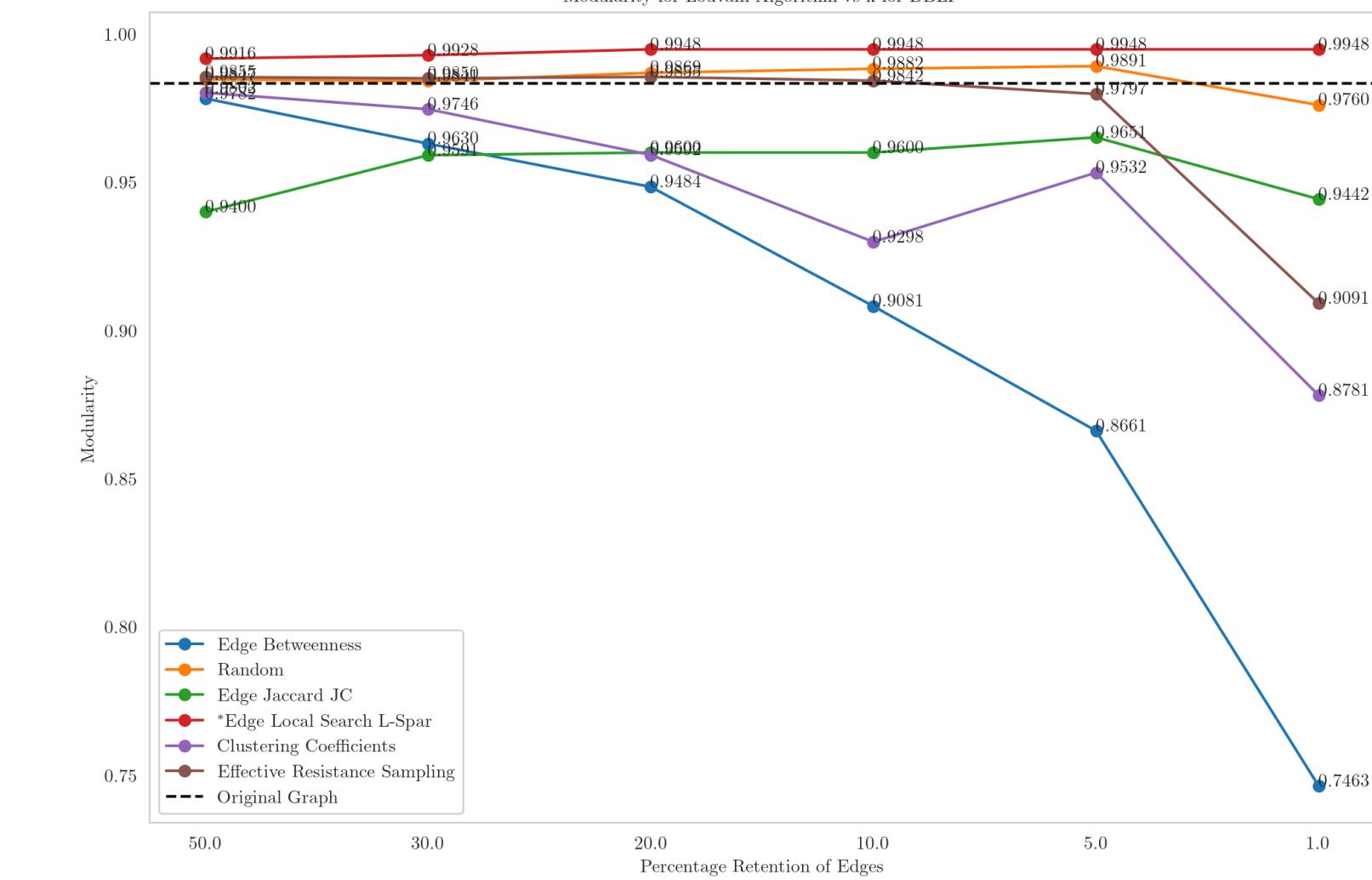
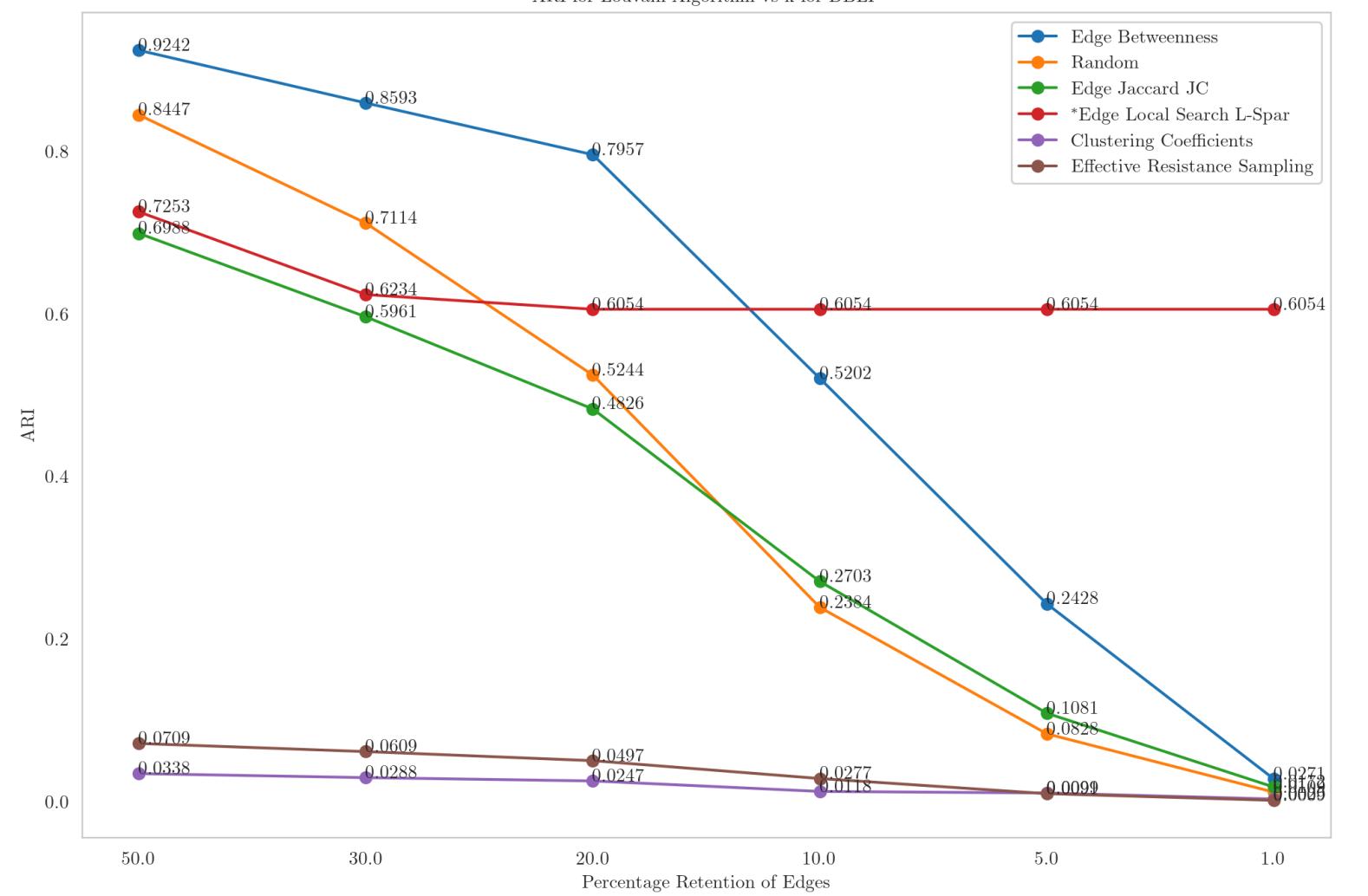
Clustering Coefficient

$$GCC(G) = \frac{|\{<u, v, w> | (u, v), (v, w), (w, u) \in E\}|/3}{|\{<u, v, w> | (u, v), (v, w) \in E\}|/2}$$

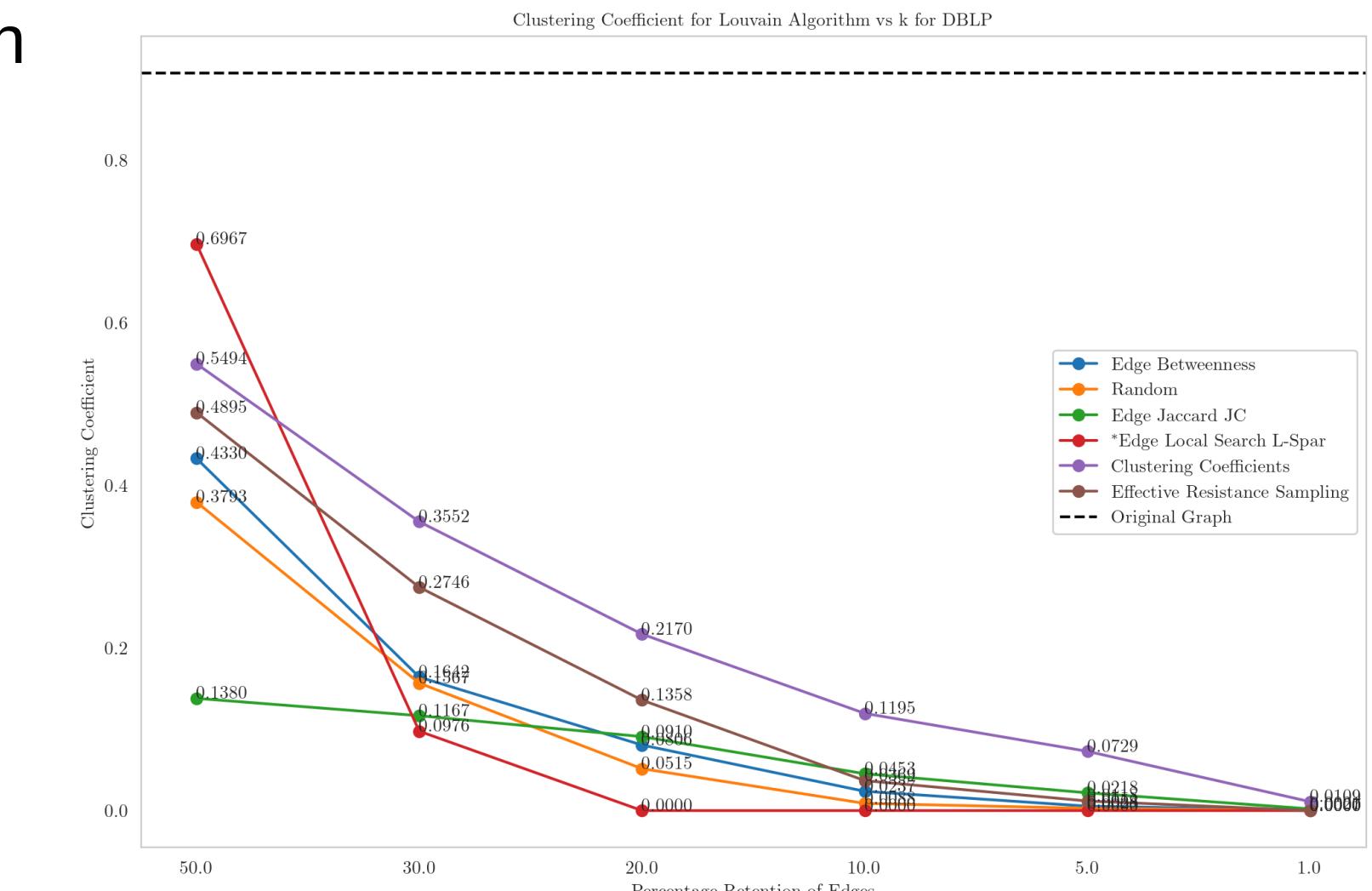
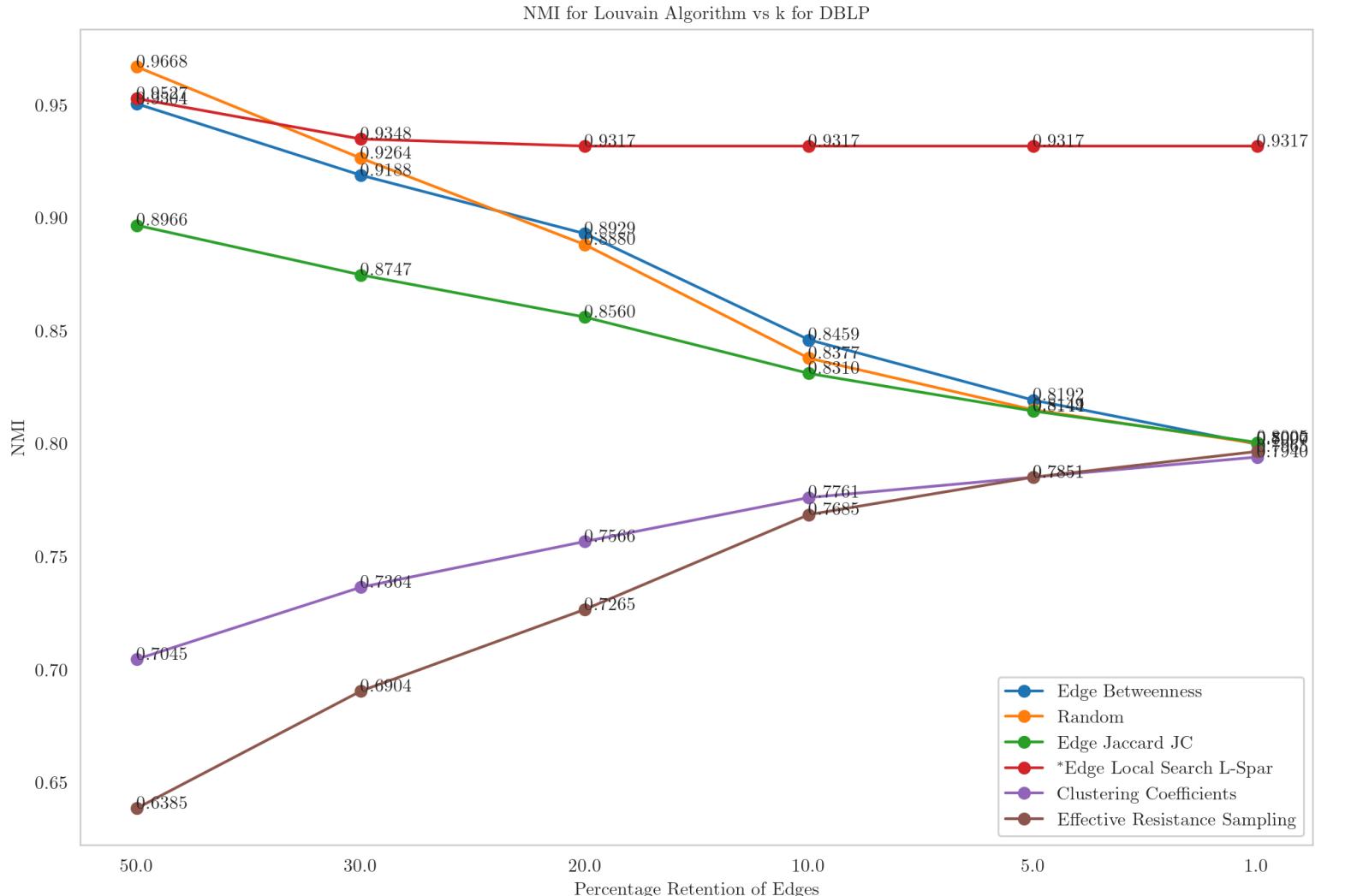
# Results for DBLP Network

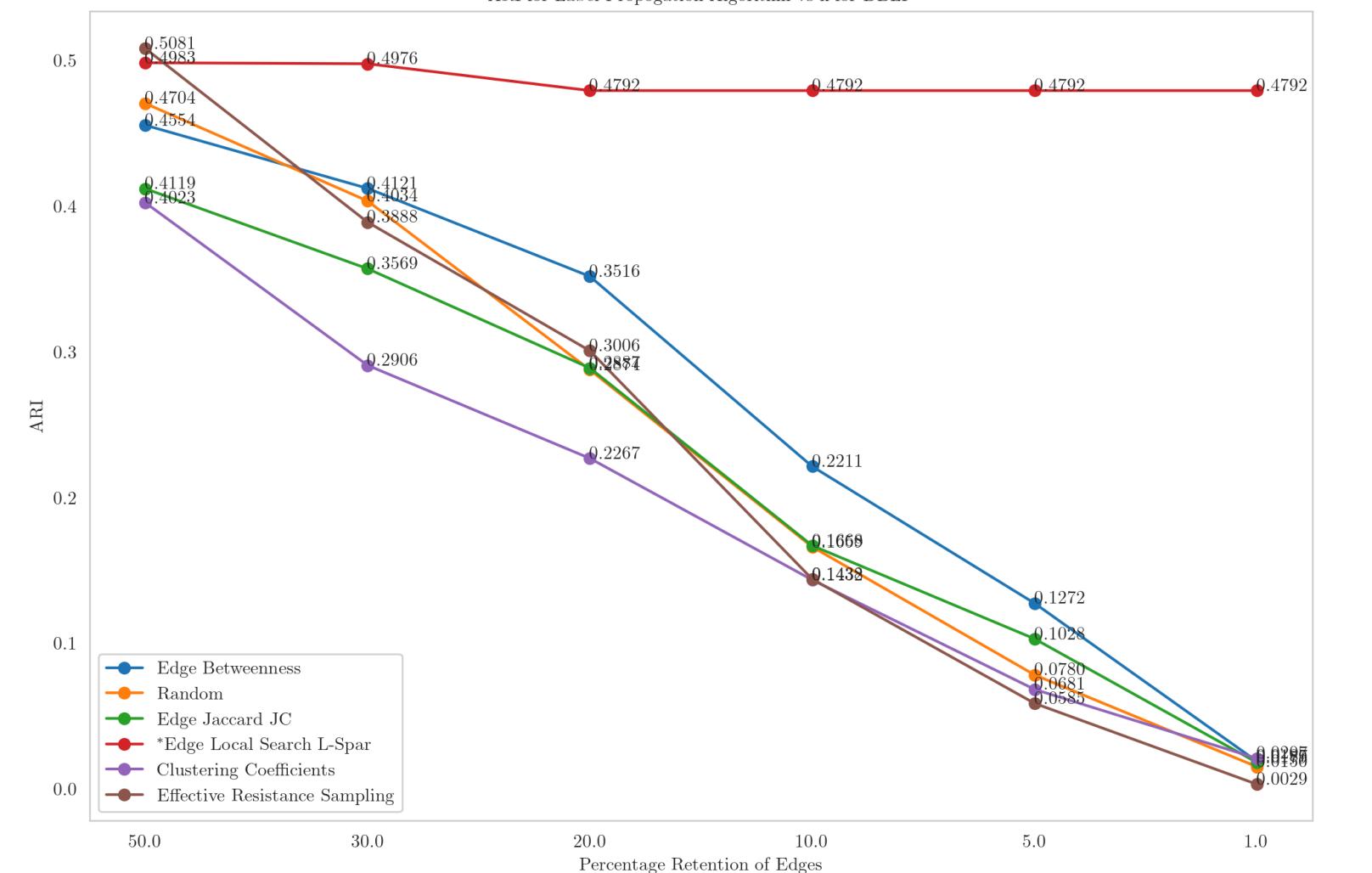
ARI for Louvain Algorithm vs k for DBLP



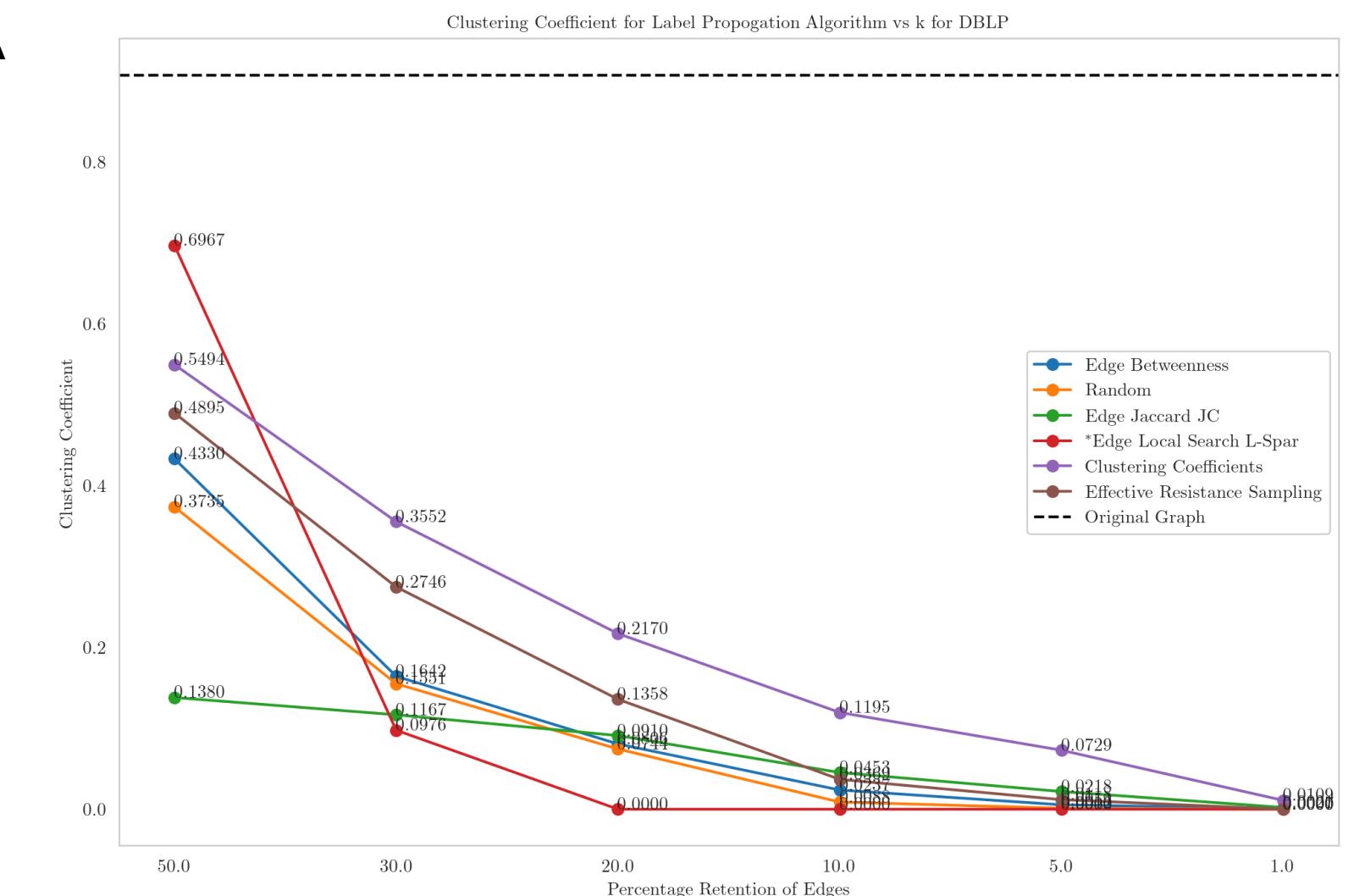
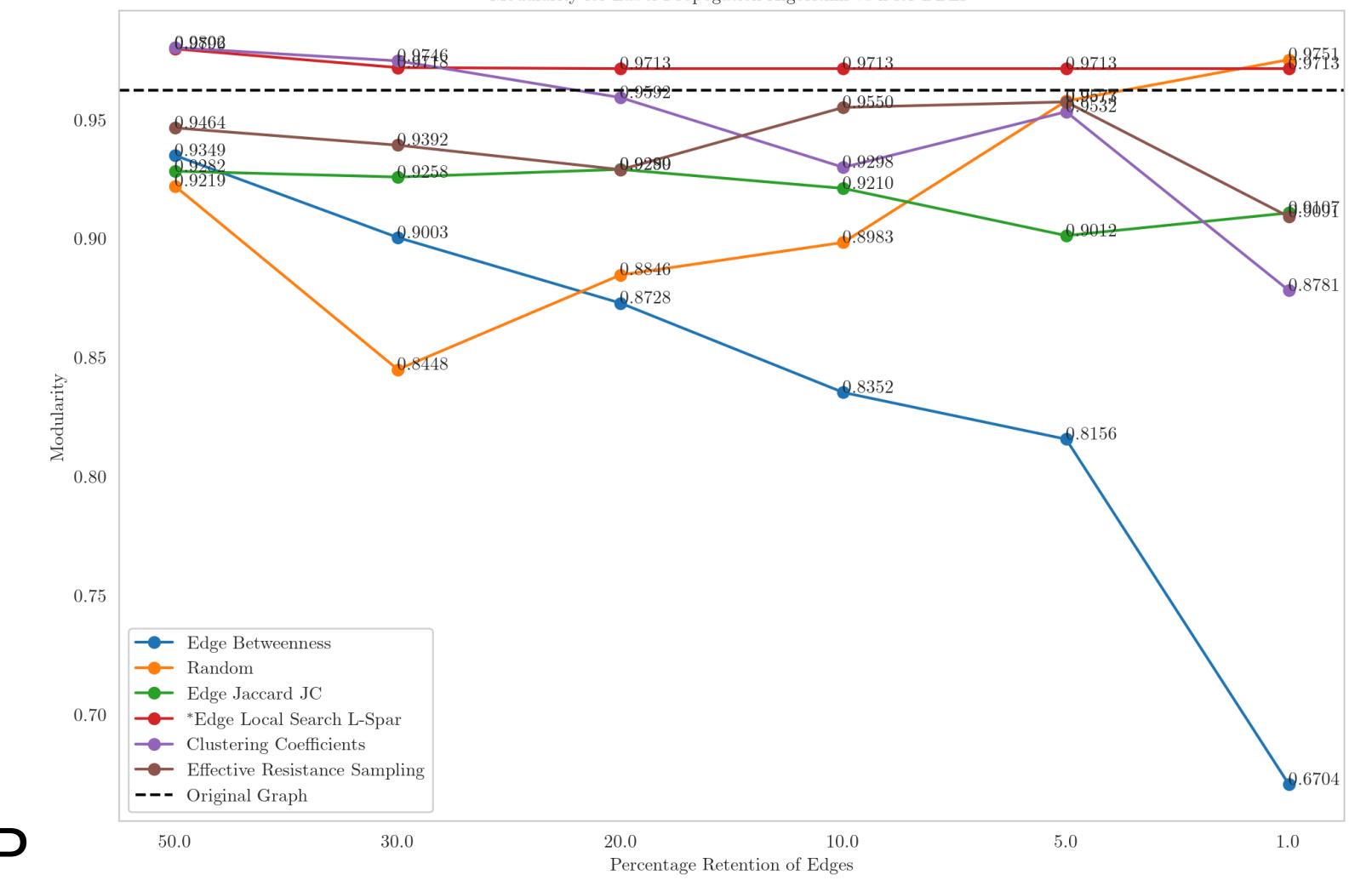
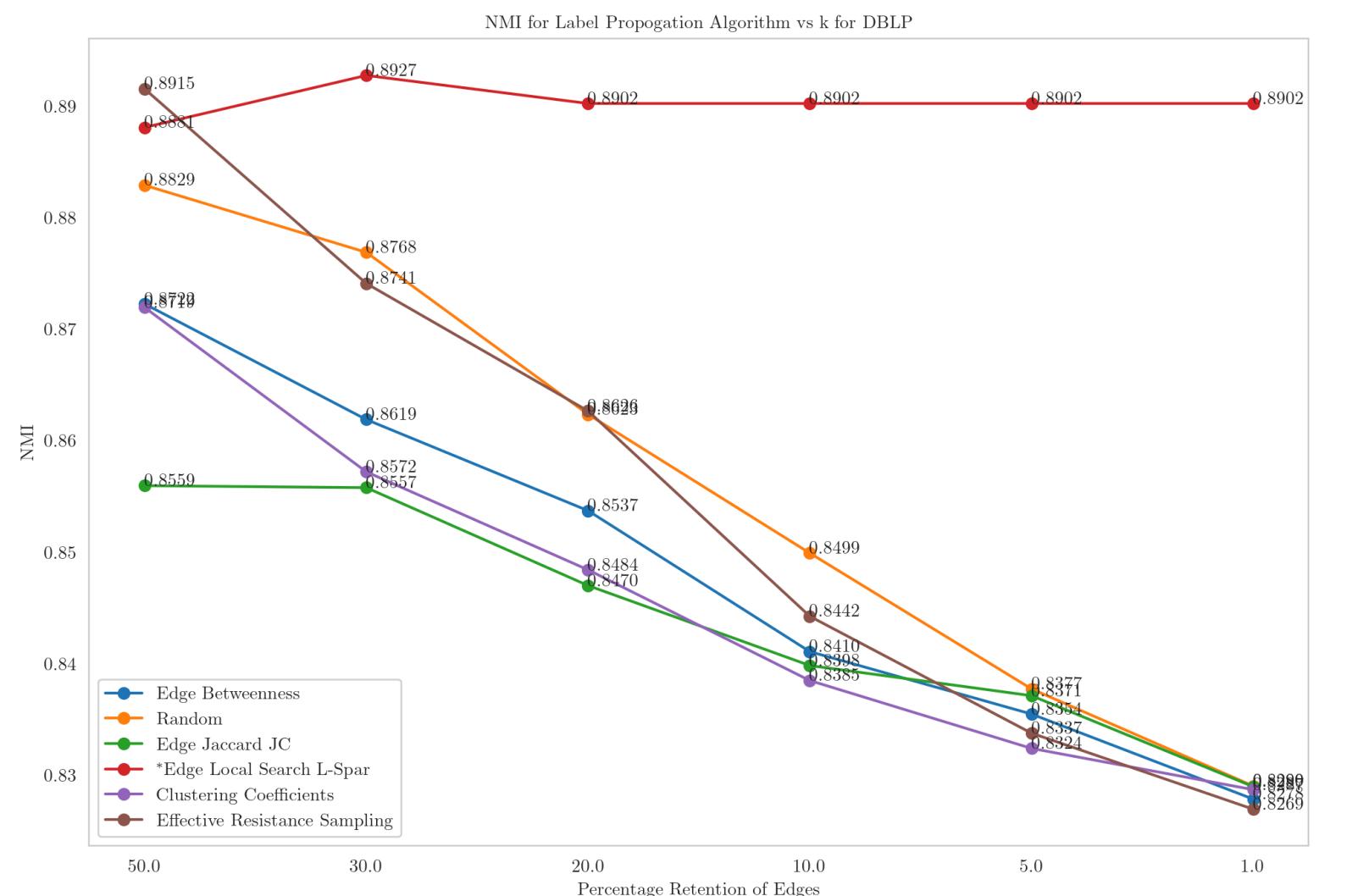


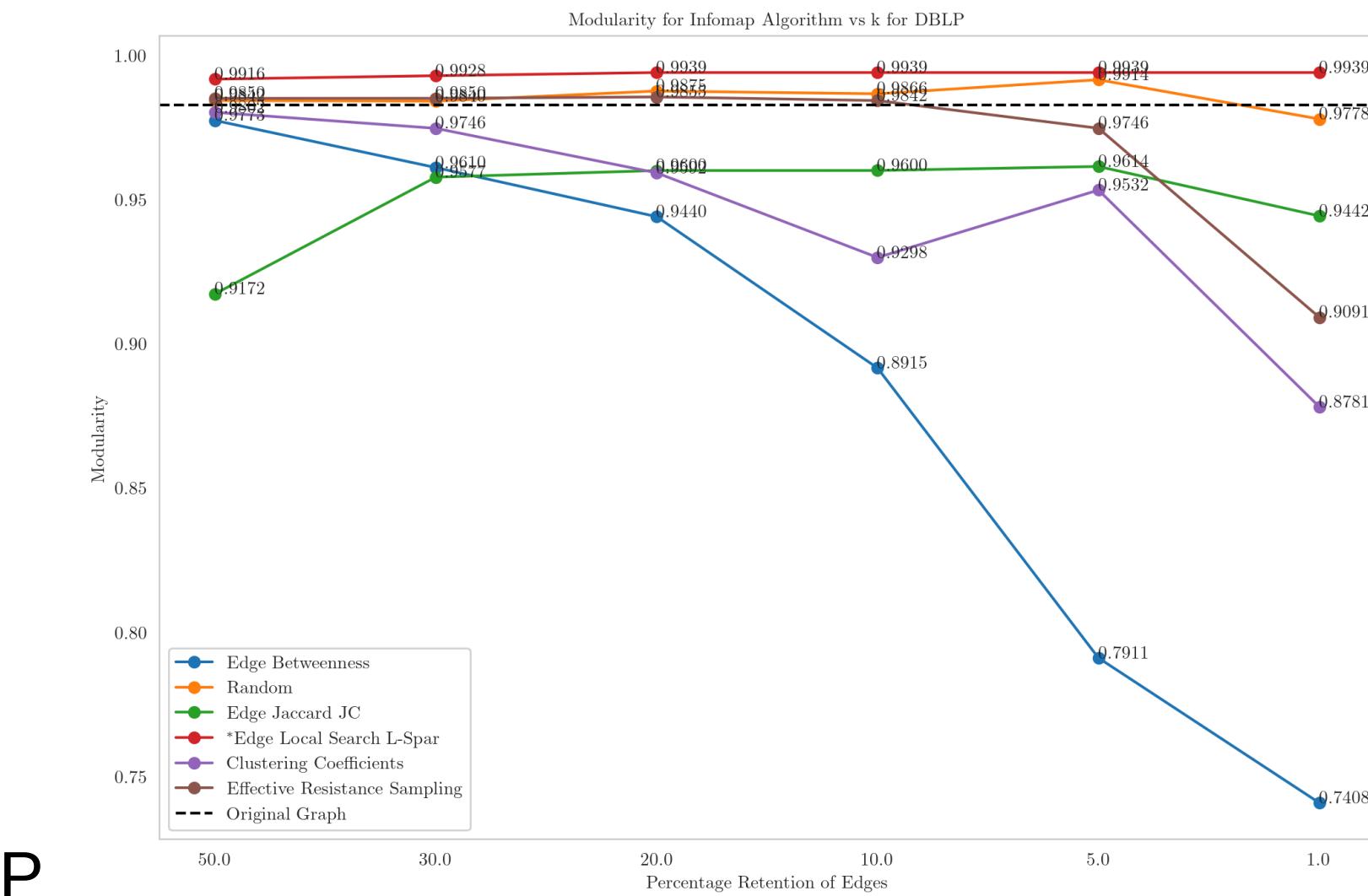
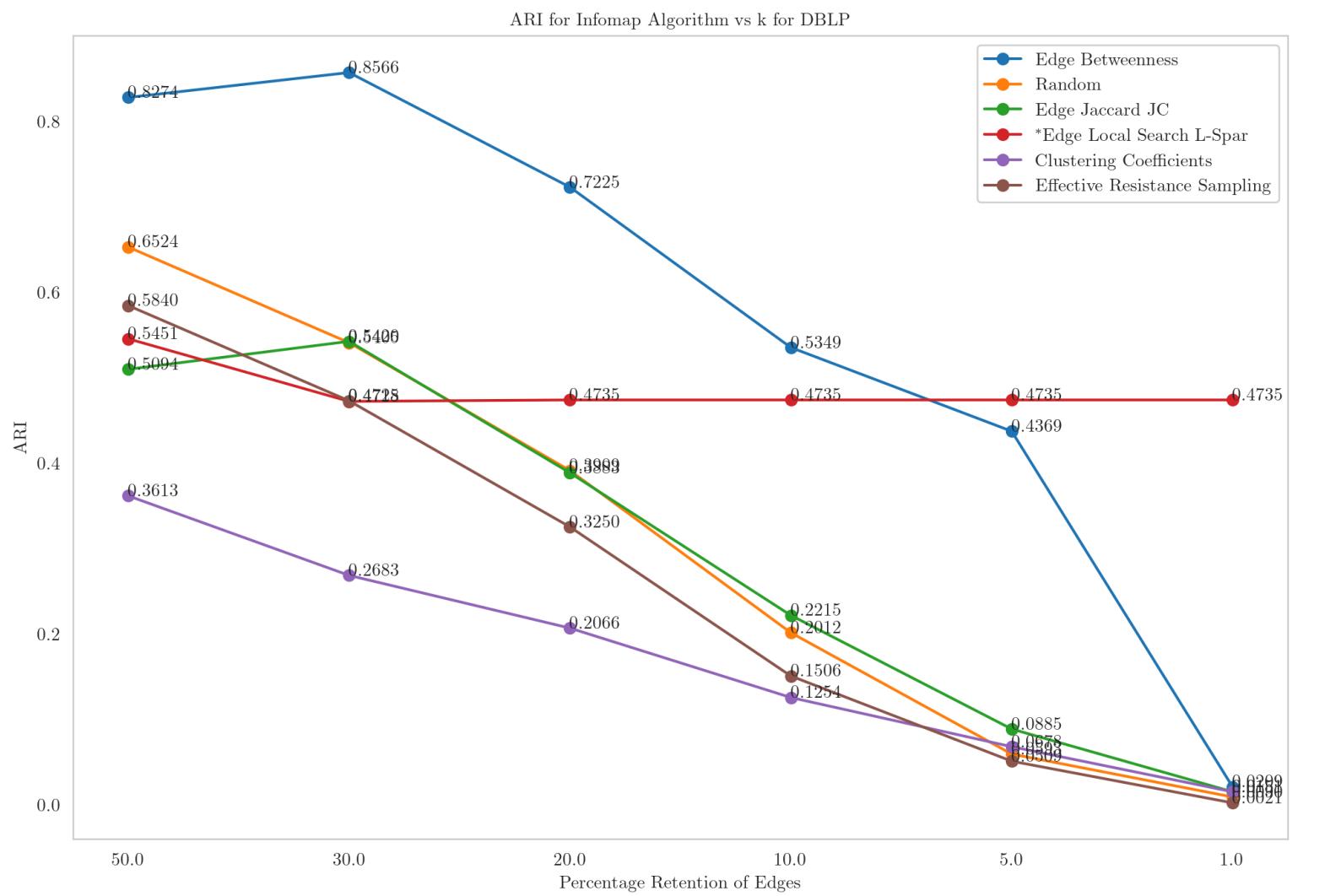
DBLP  
Louvain



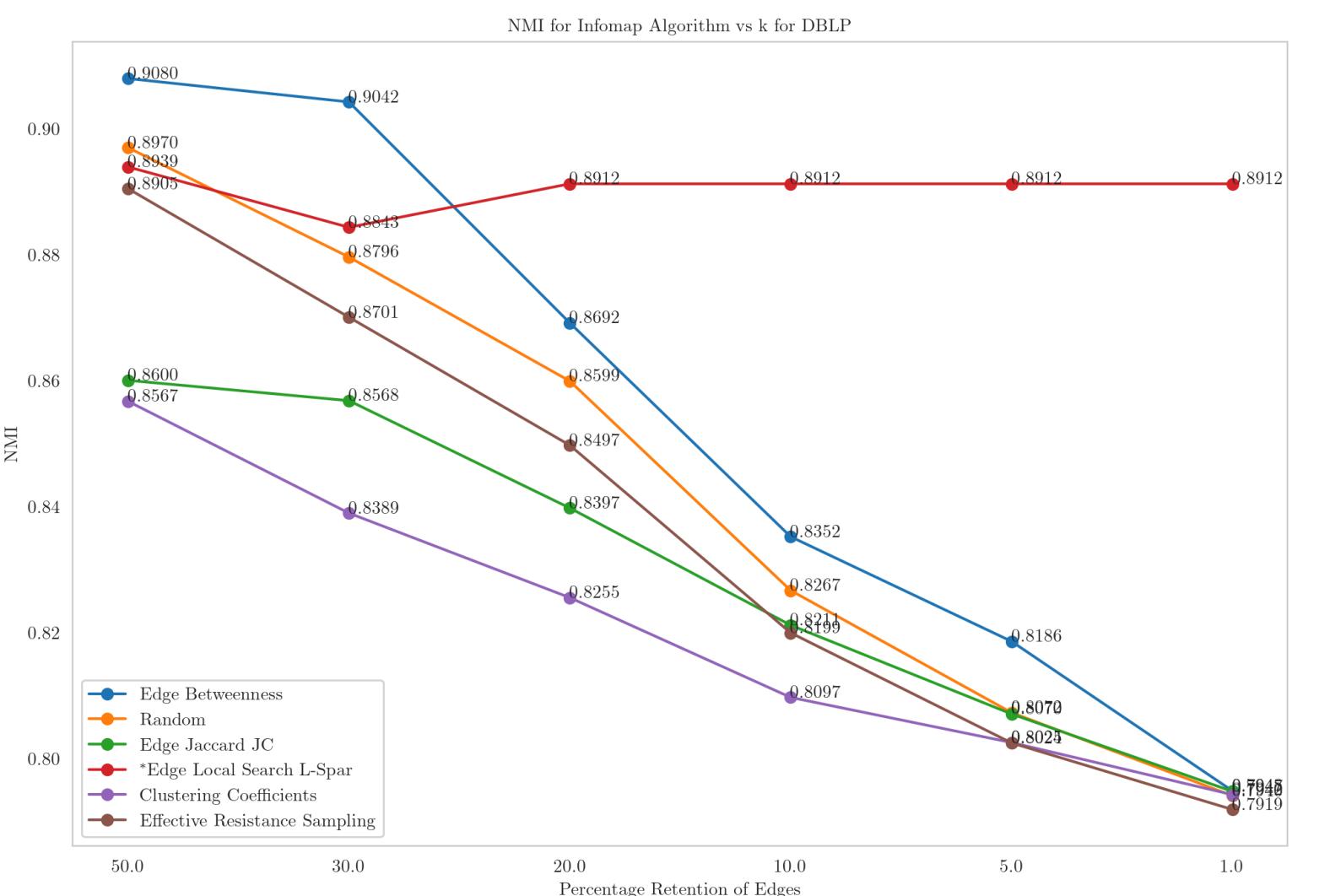
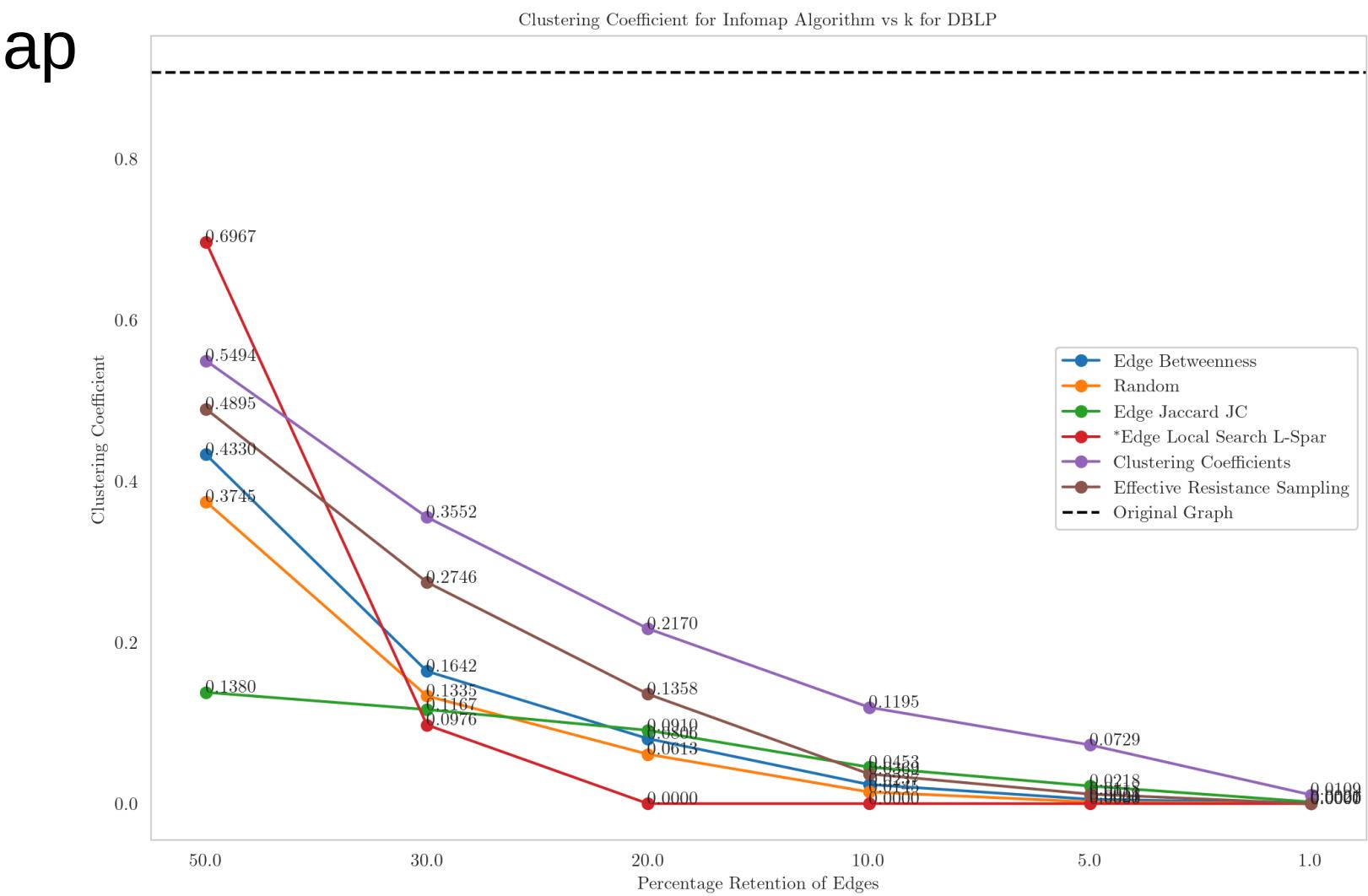


**DBL**  
**LPA**



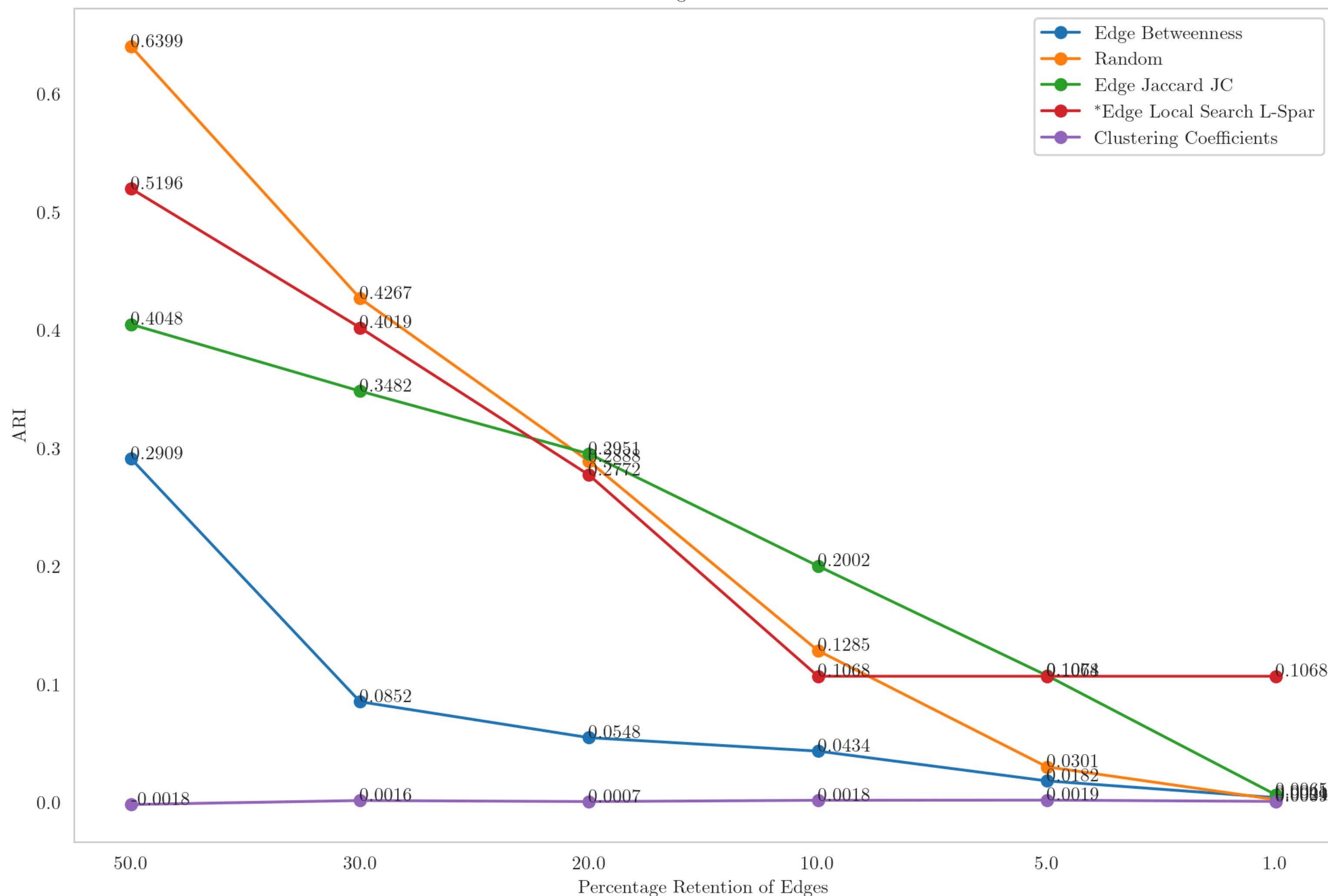


# DBLP InfoMap

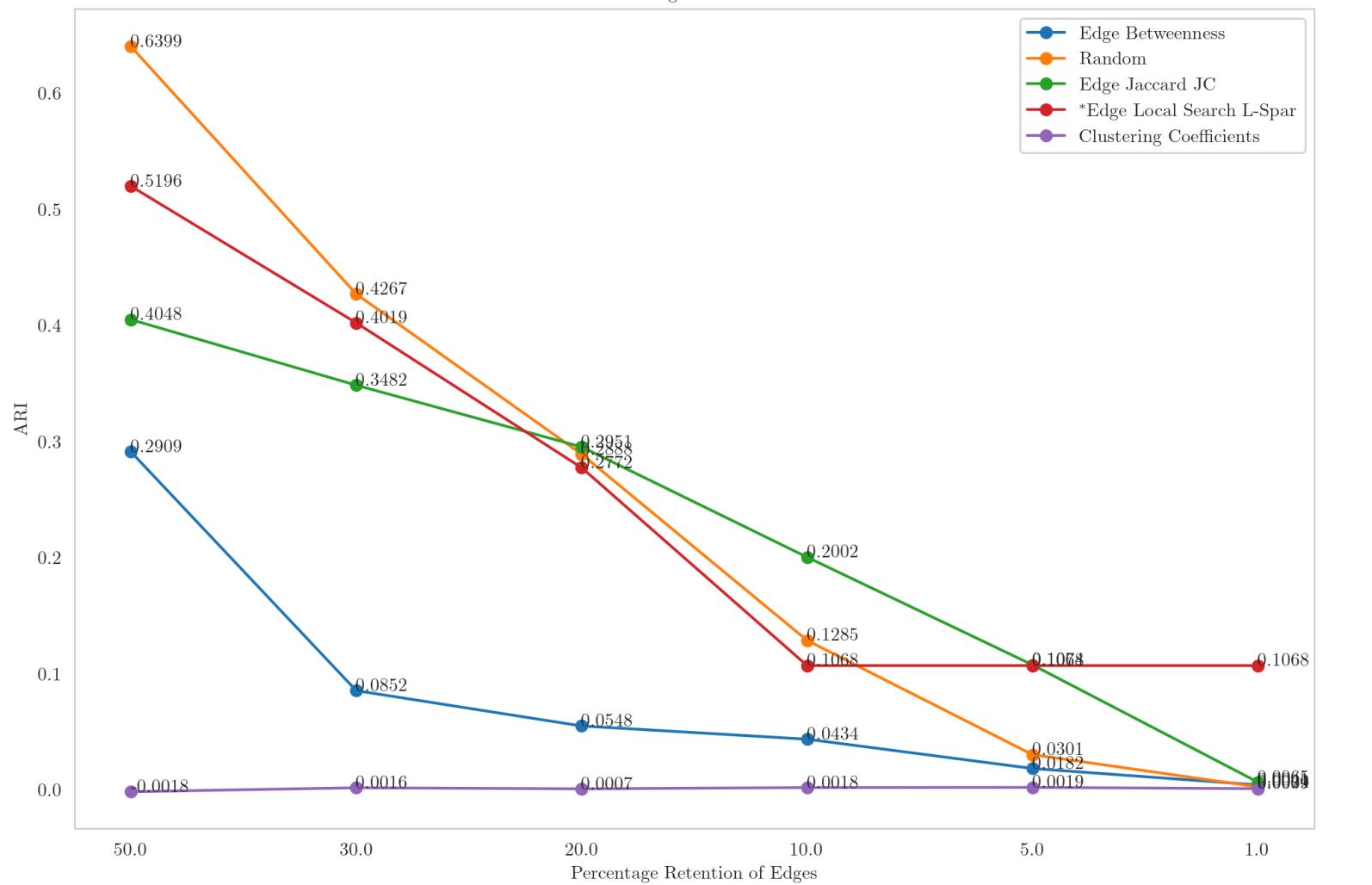


# **Results for Email EU Core Network**

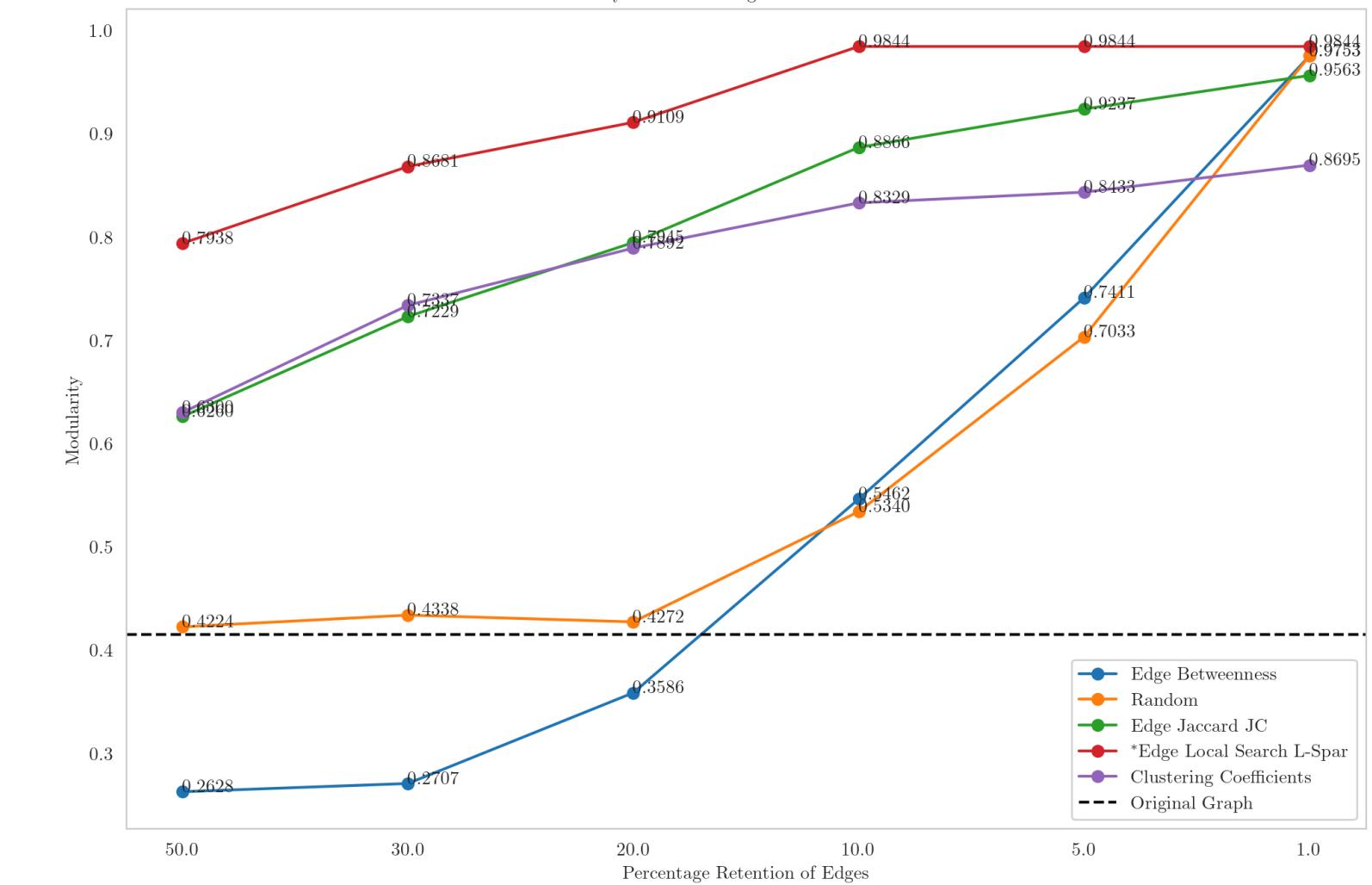
ARI for Louvain Algorithm vs k for EmailEU



ARI for Louvain Algorithm vs k for EmailEU

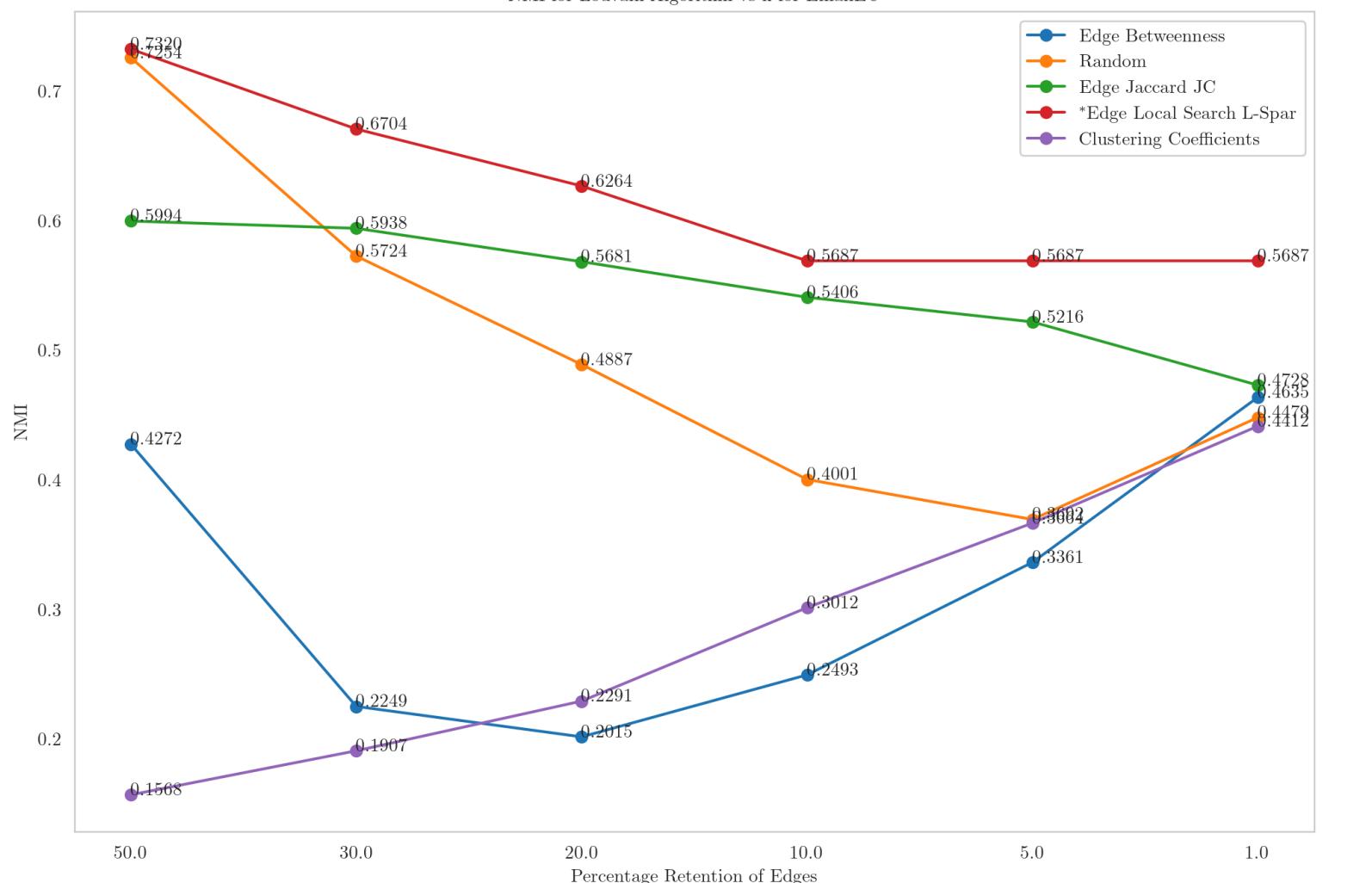


Modularity for Louvain Algorithm vs k for EmailEU

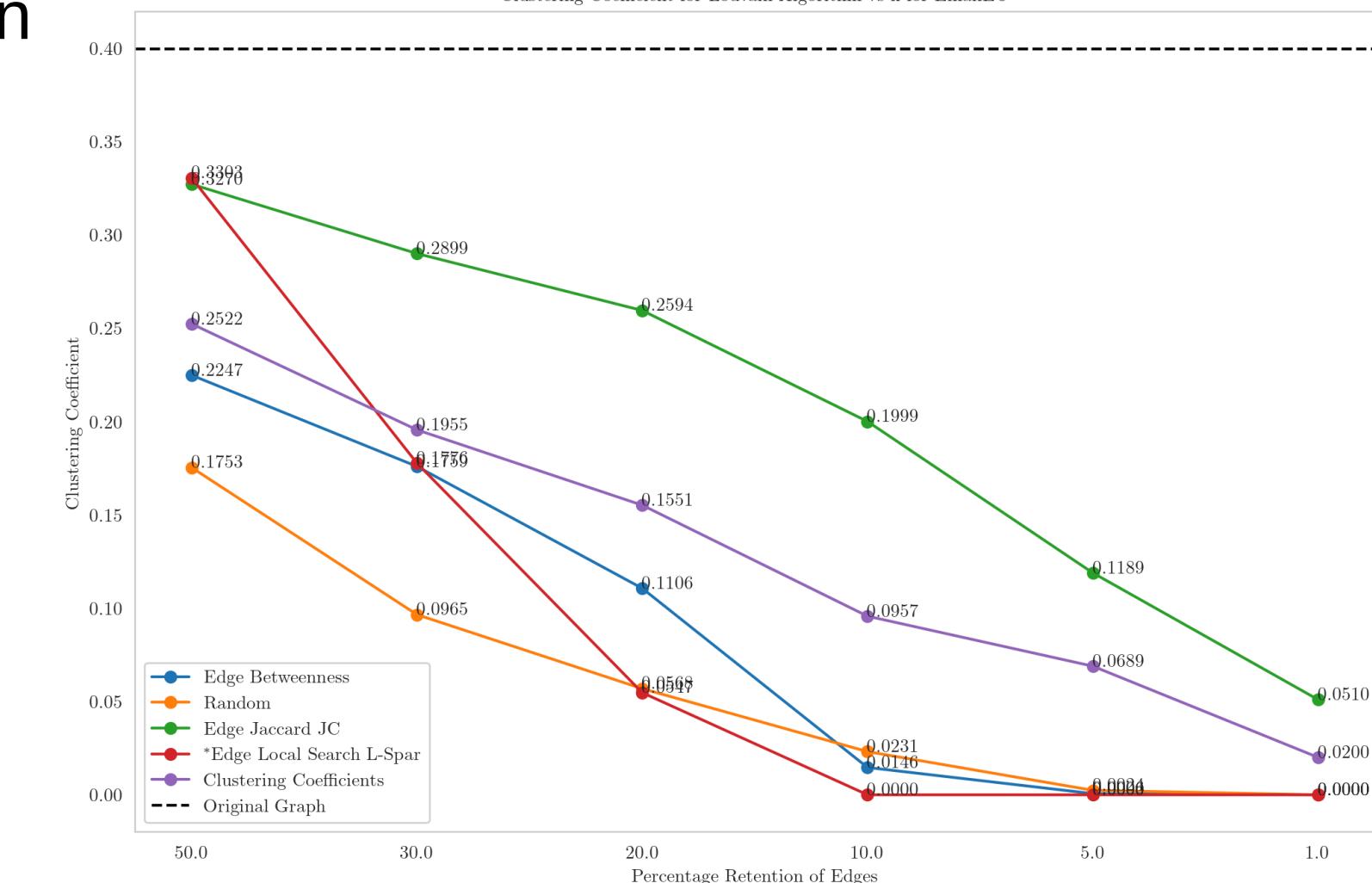


# Email Louvain

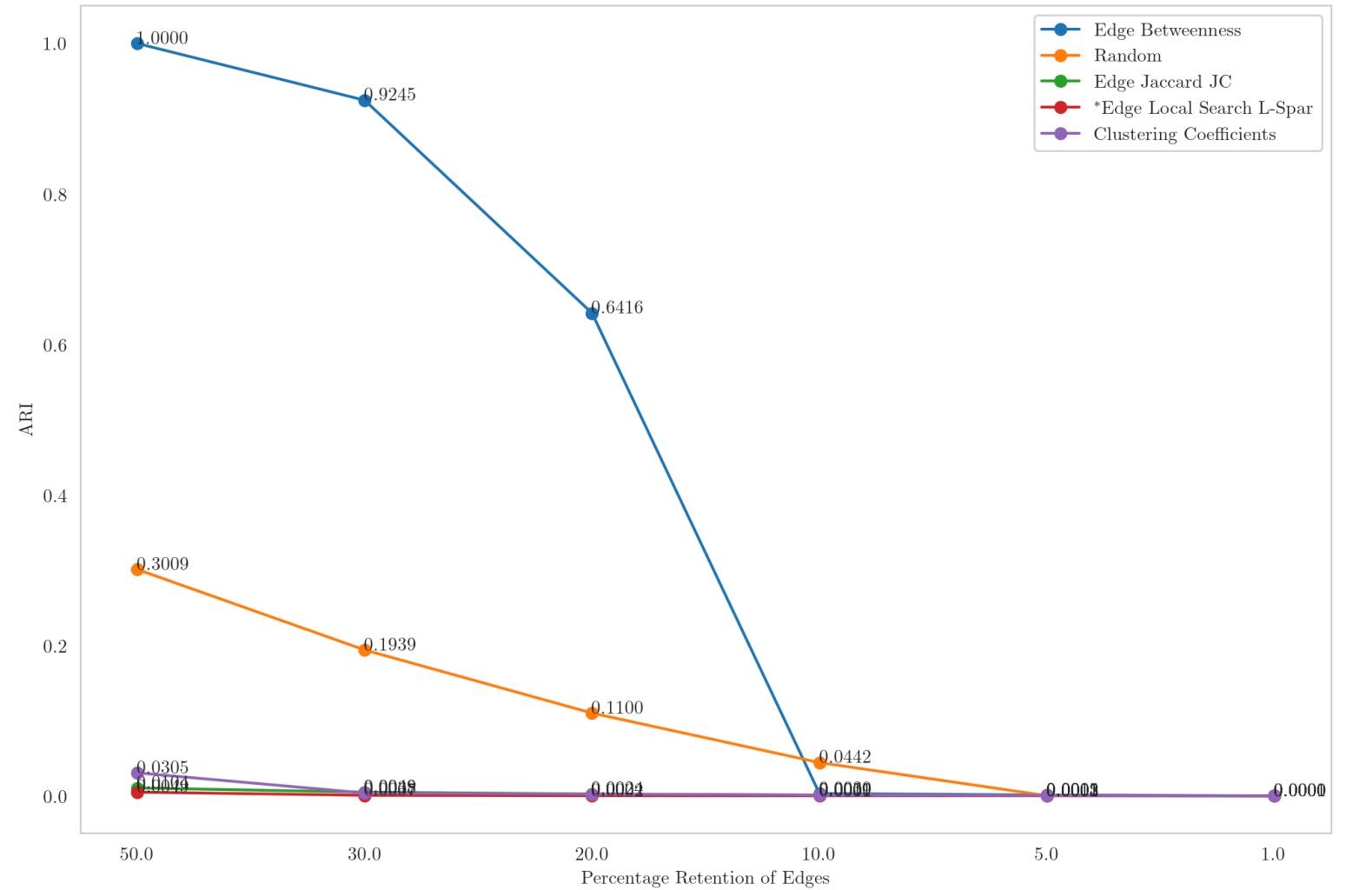
NMI for Louvain Algorithm vs k for EmailEU



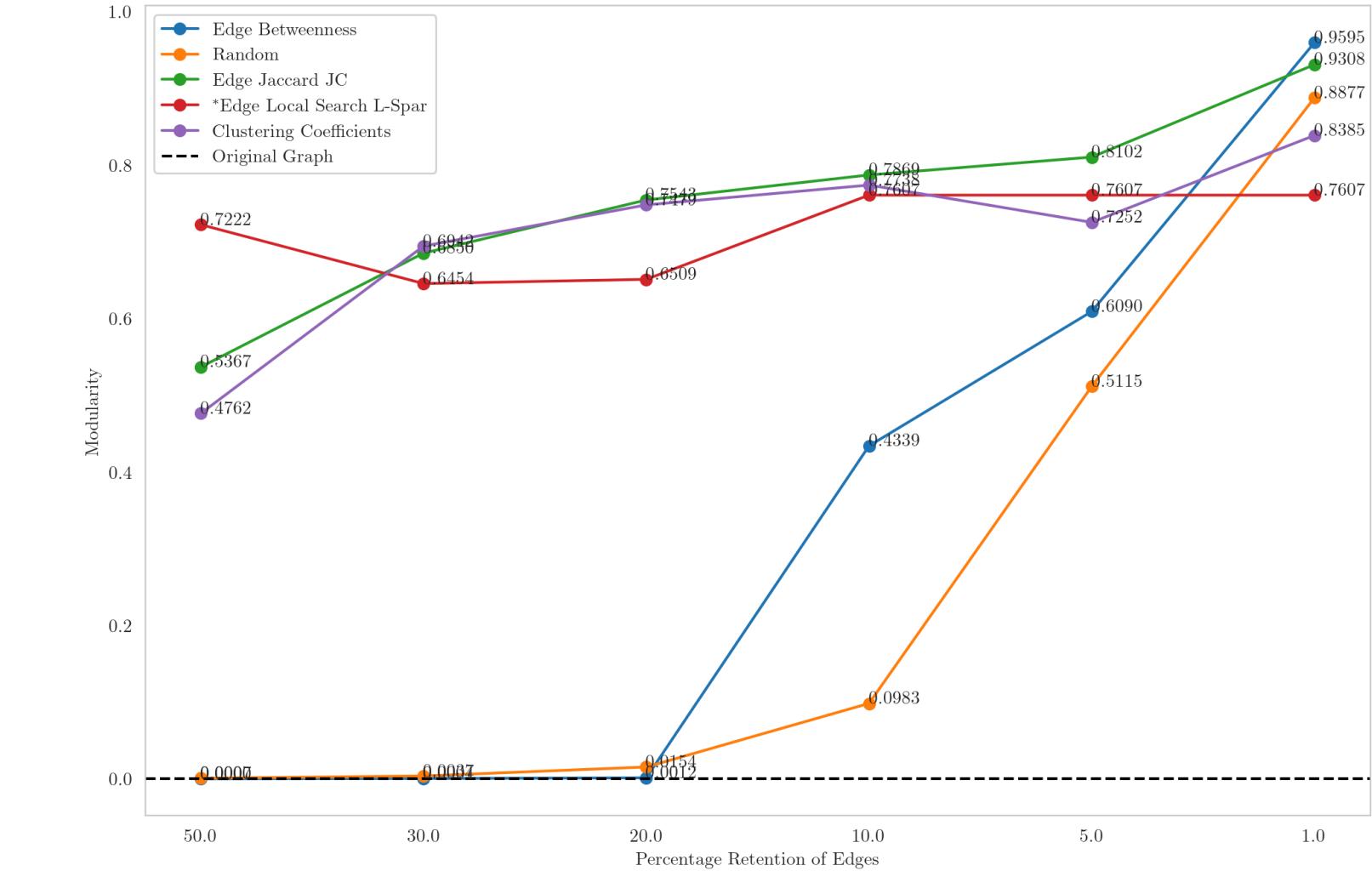
Clustering Coefficient for Louvain Algorithm vs k for EmailEU



ARI for Label Propogation Algorithm vs k for EmailEU

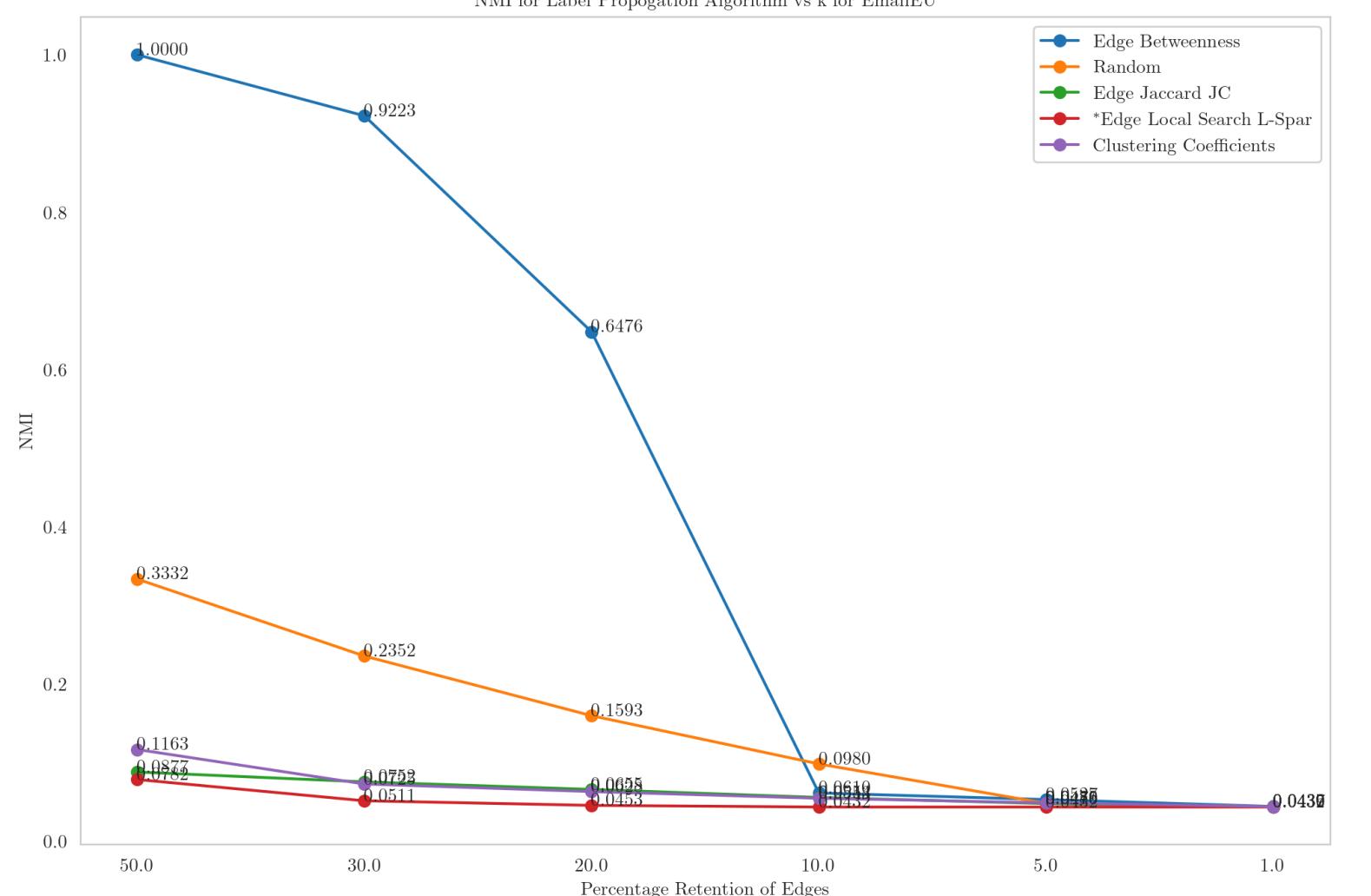


Modularity for Label Propogation Algorithm vs k for EmailEU

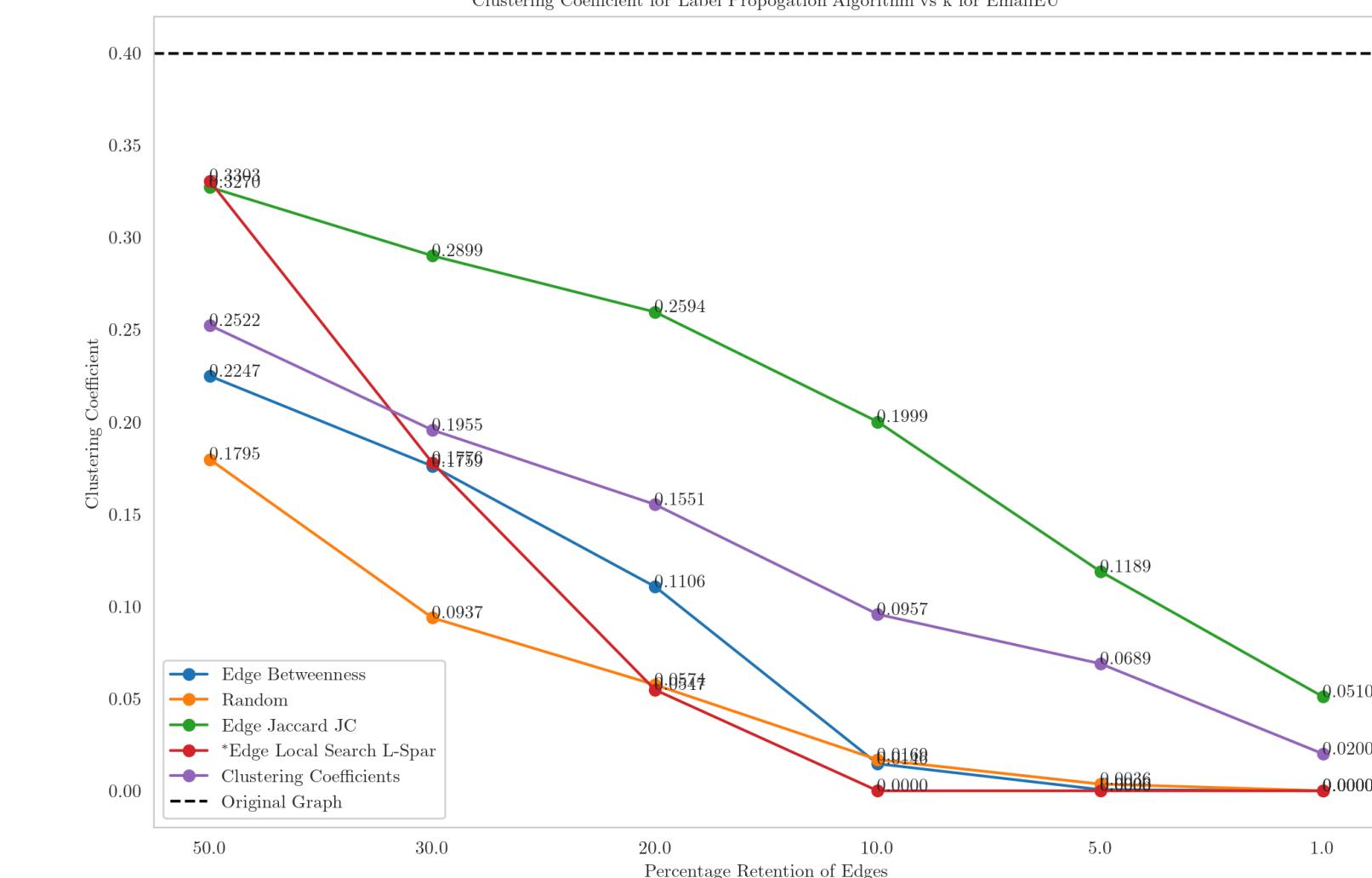


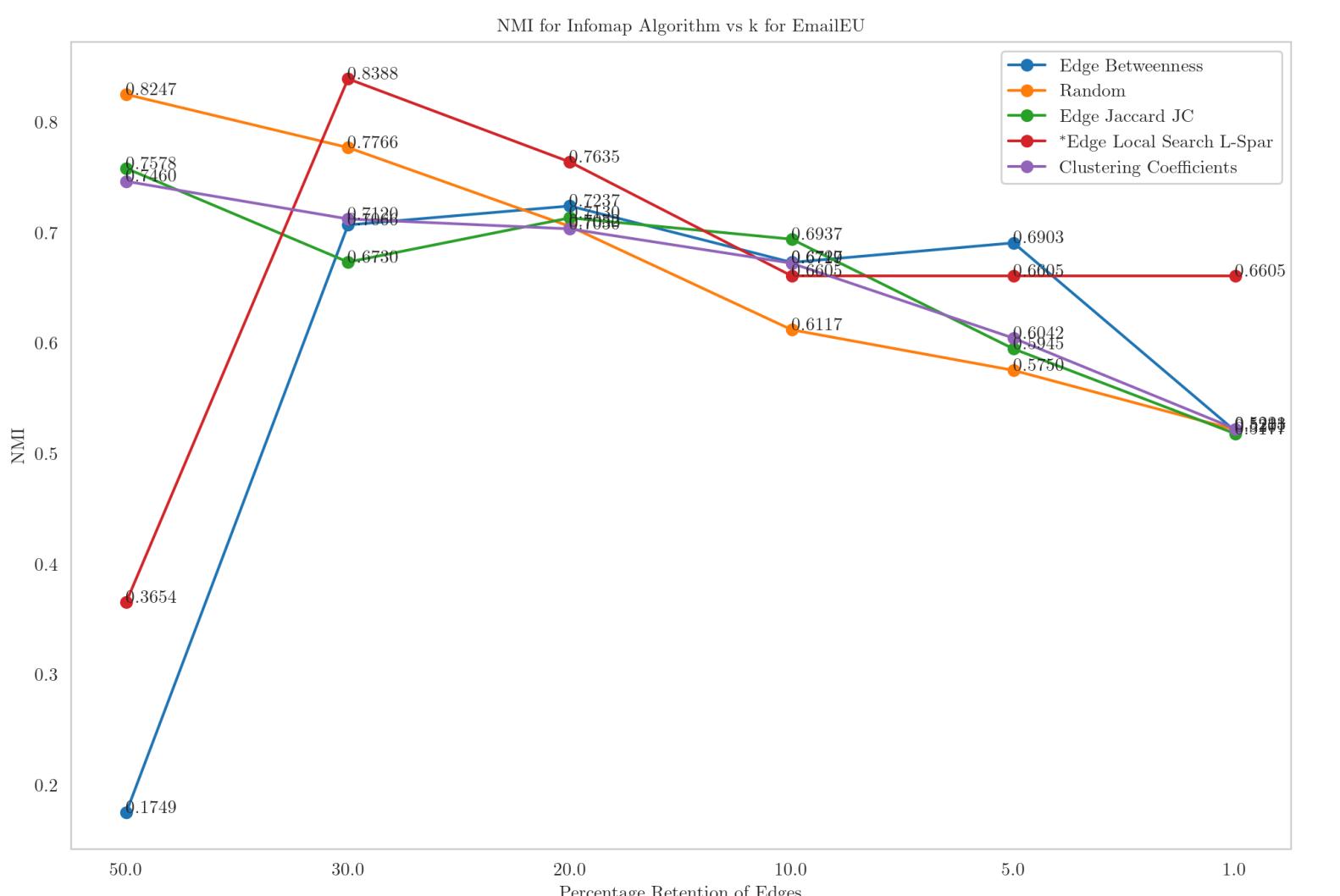
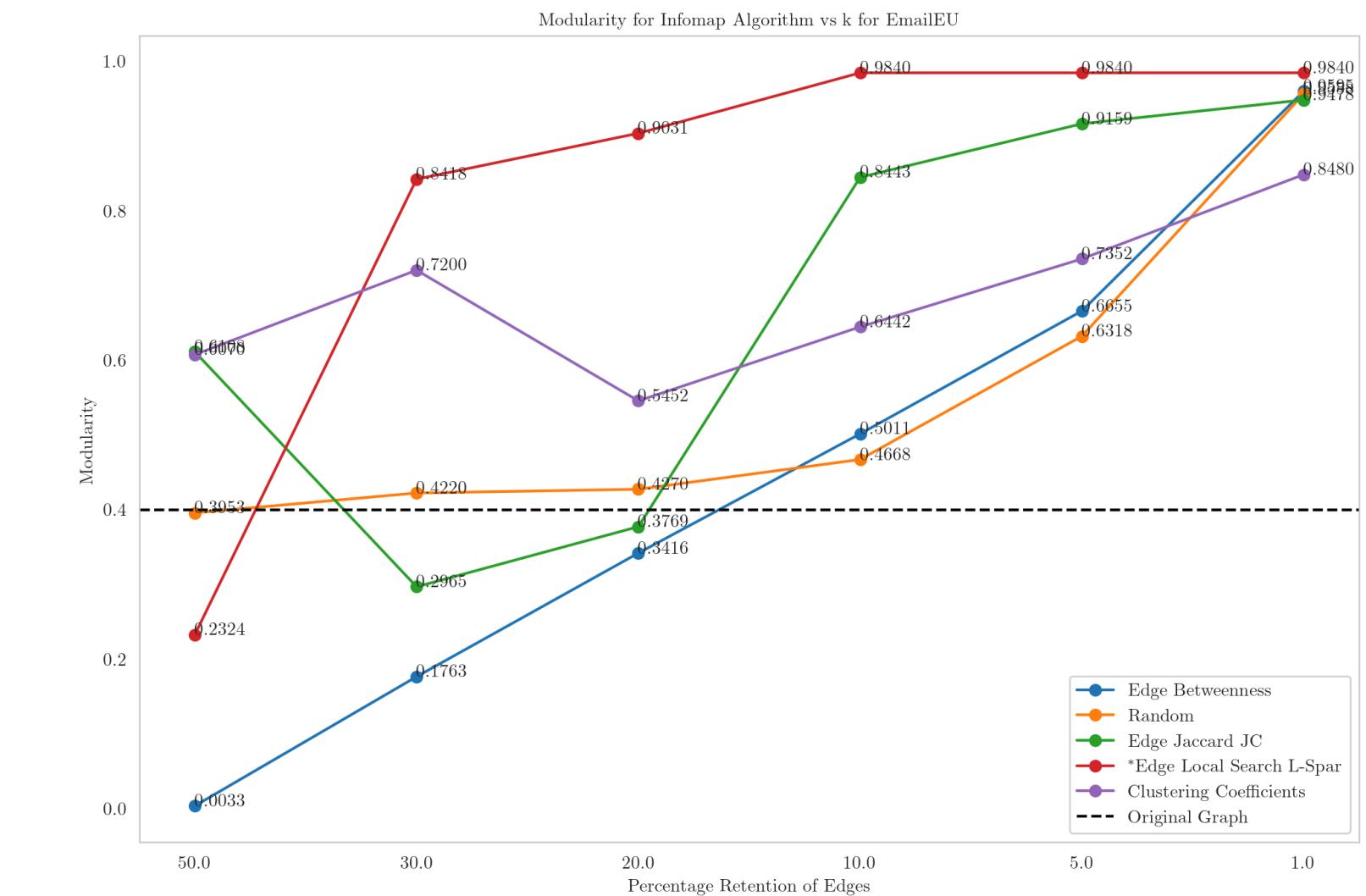
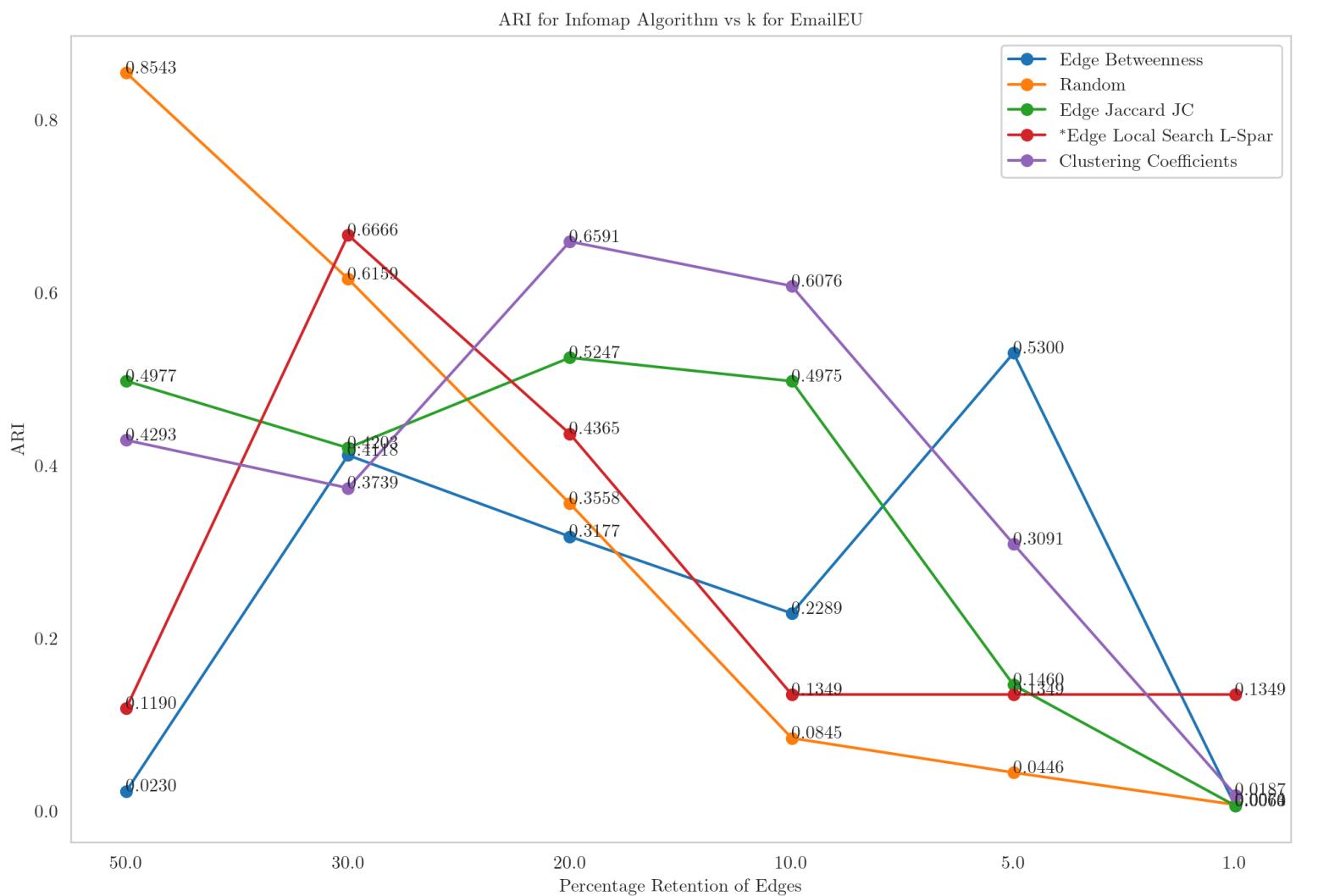
# Email LPA

NMI for Label Propogation Algorithm vs k for EmailEU

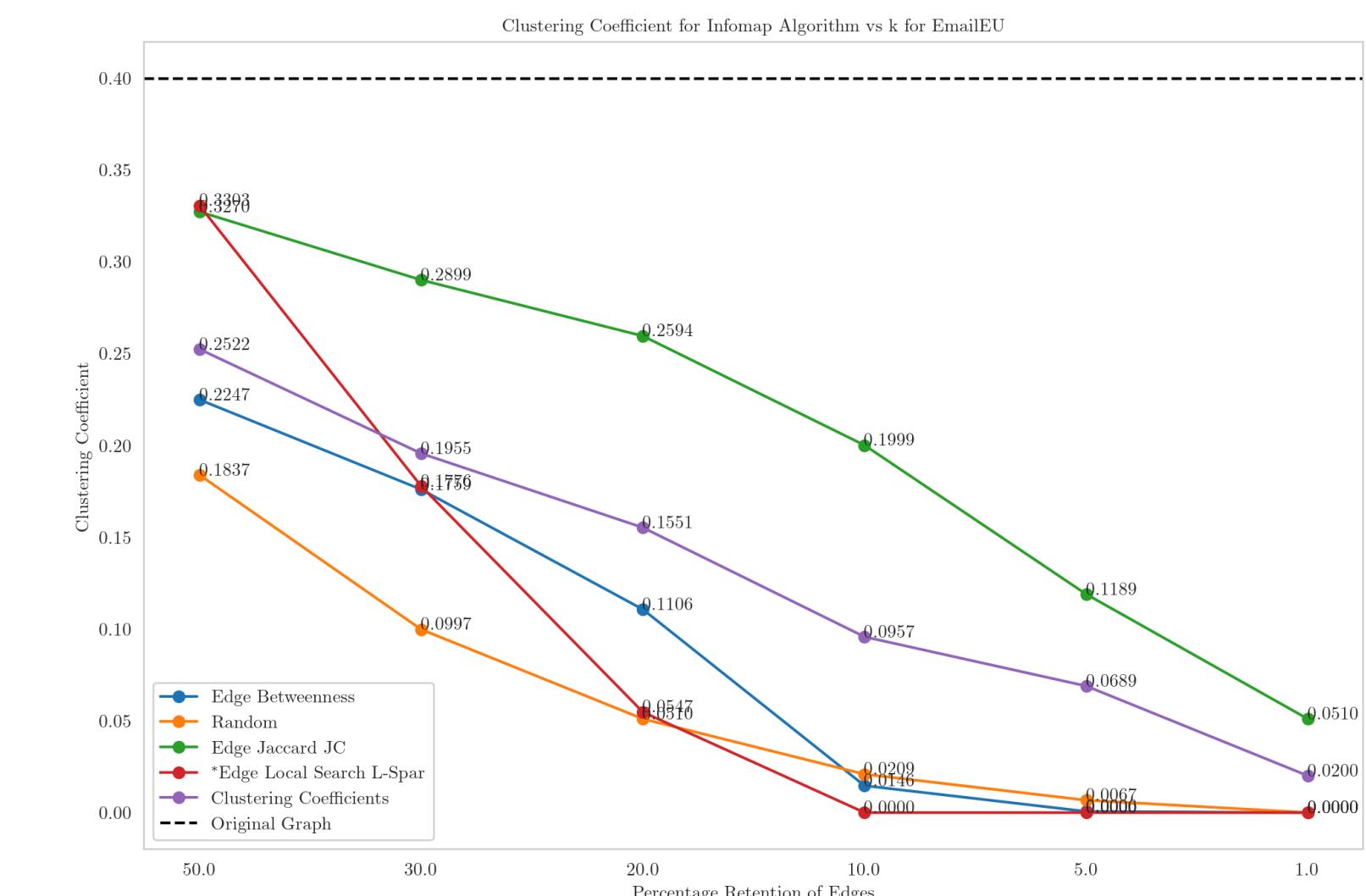


Clustering Coefficient for Label Propogation Algorithm vs k for EmailEU



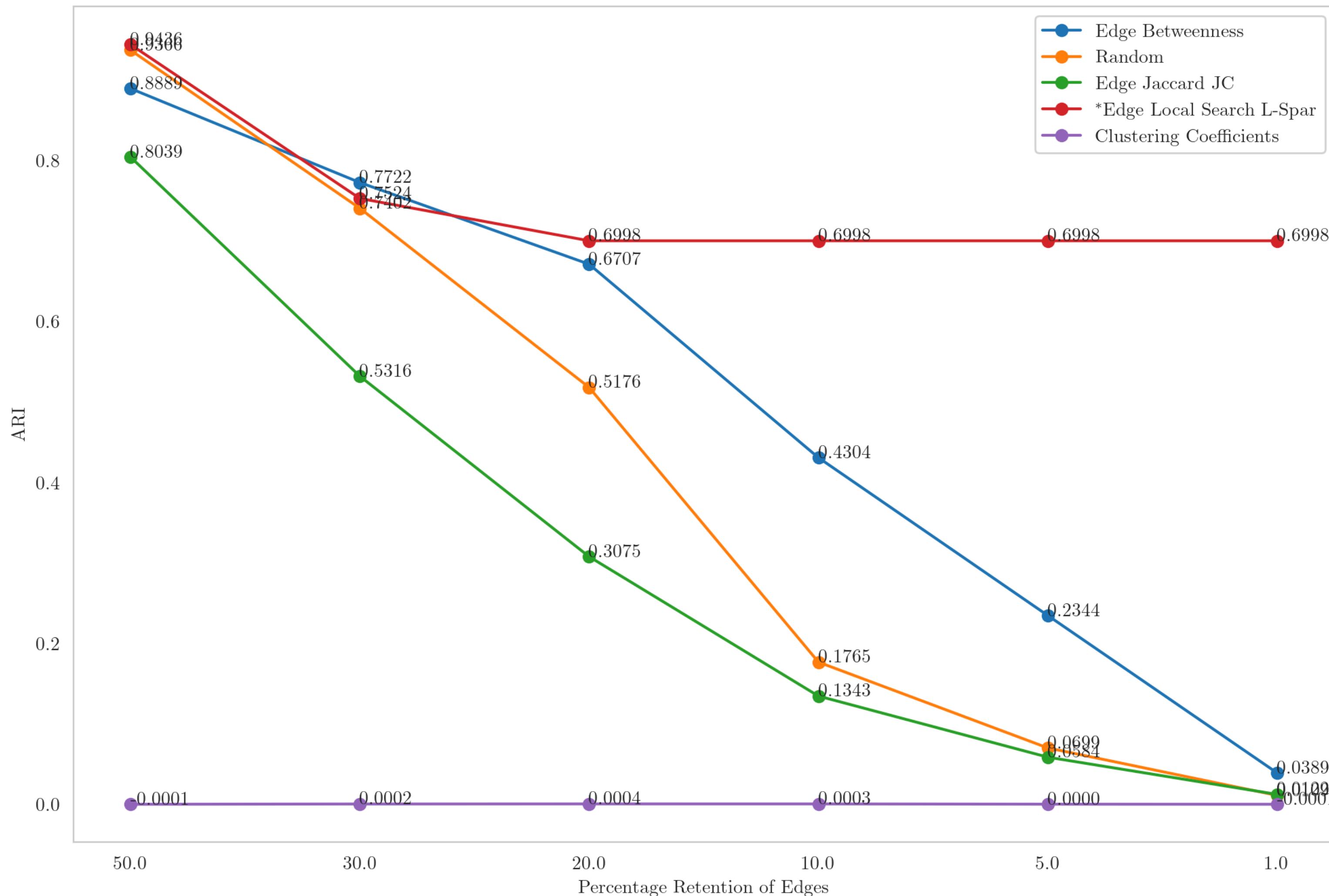


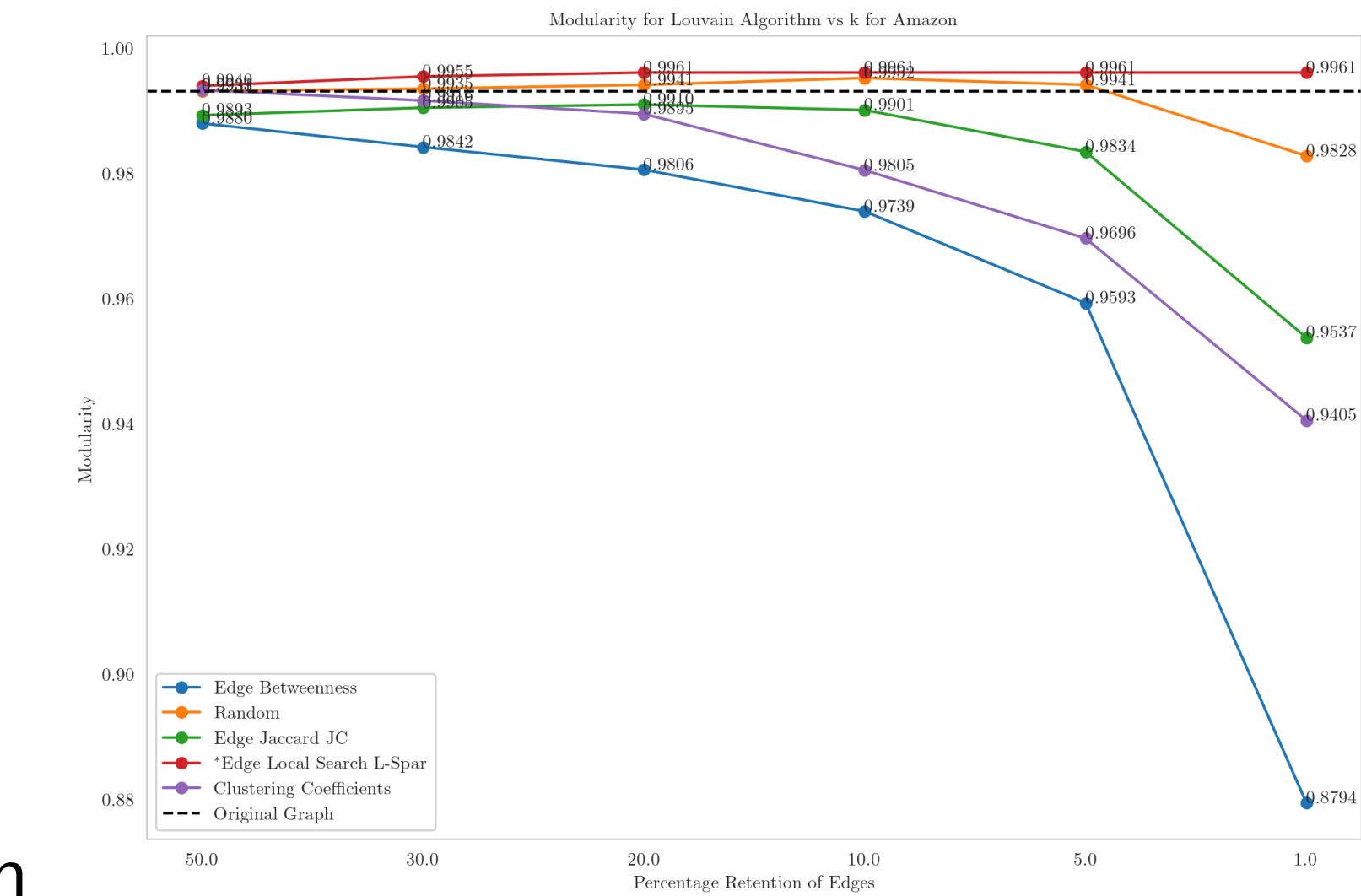
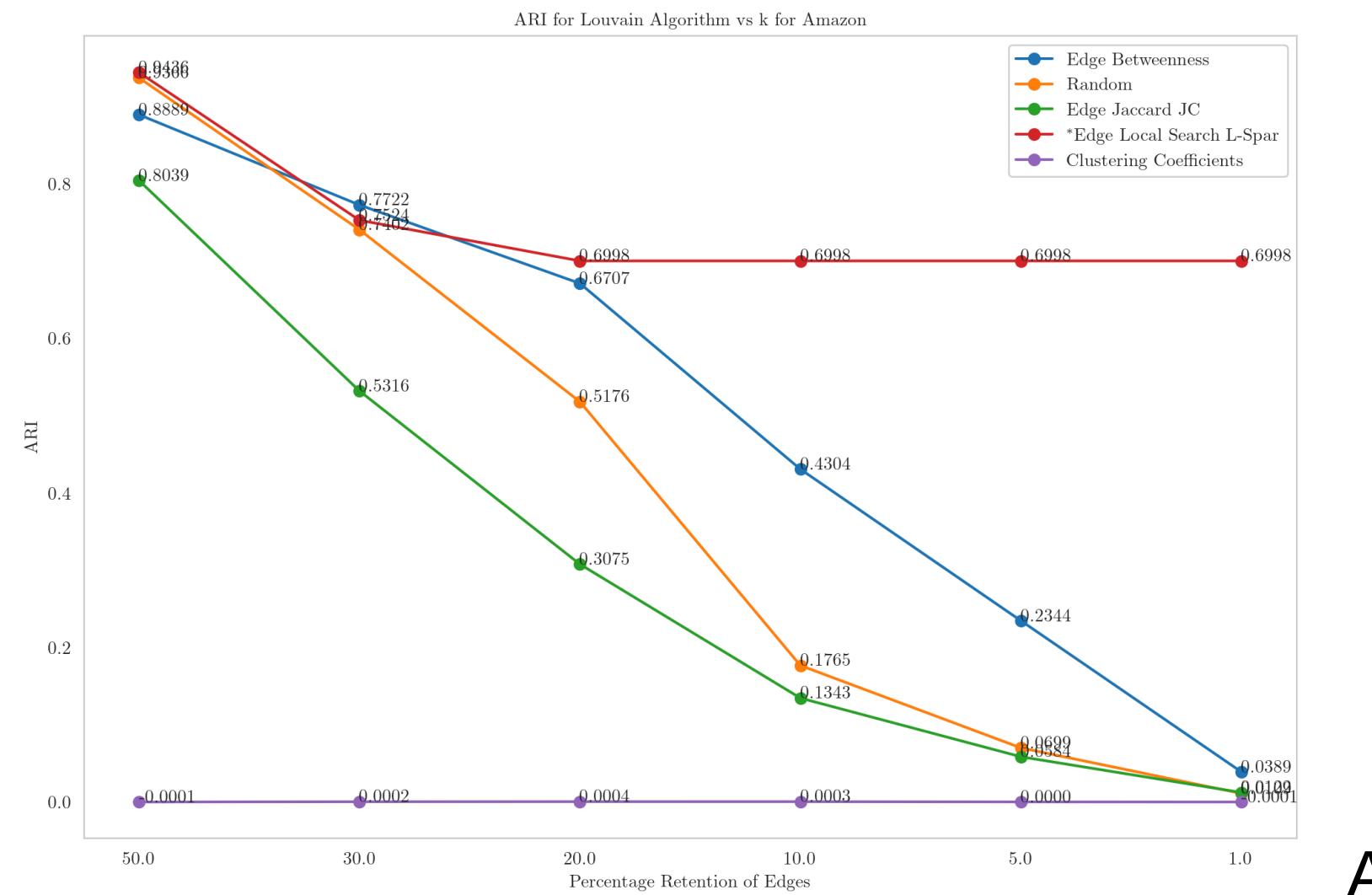
# Email InfoMap



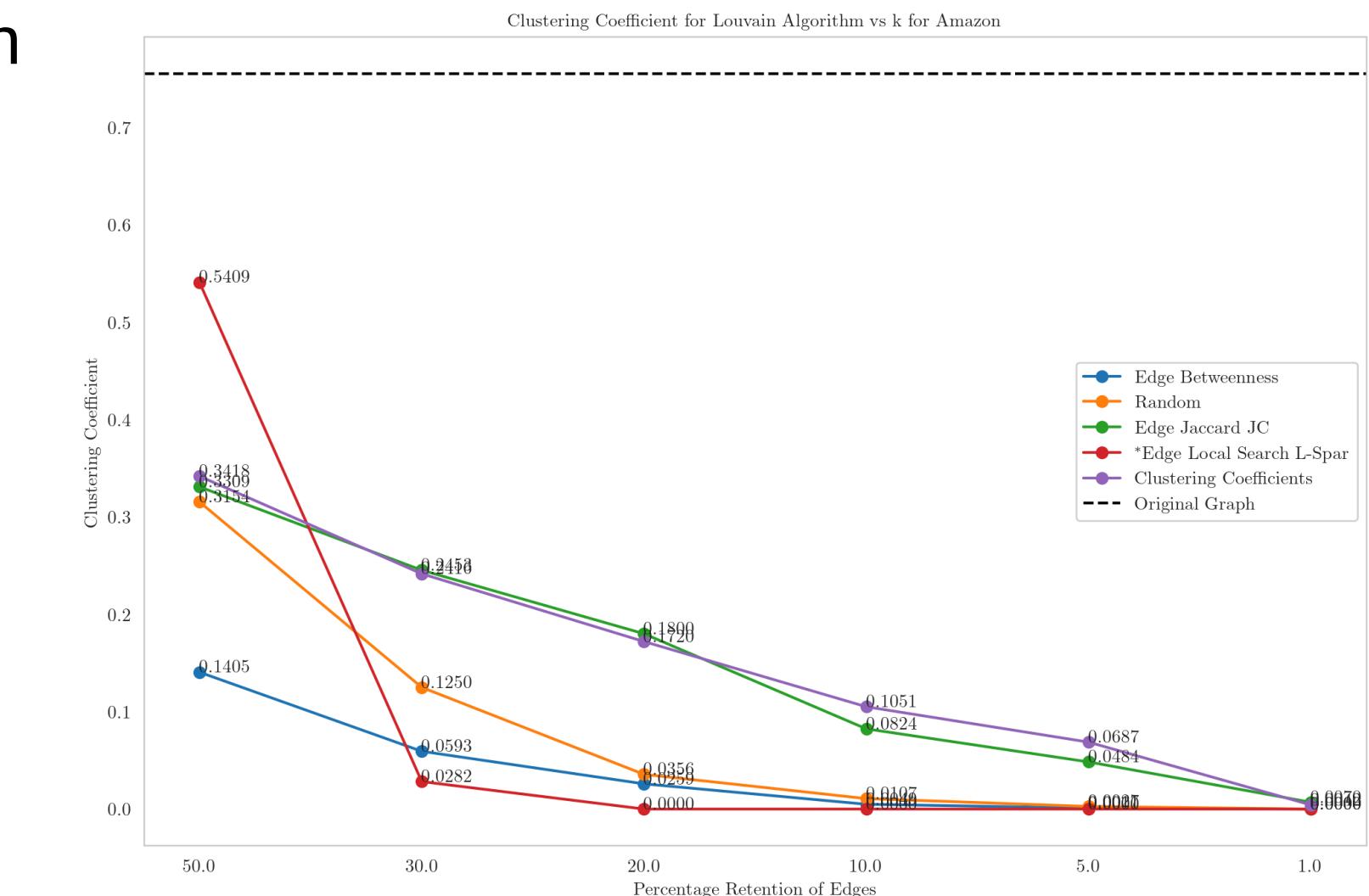
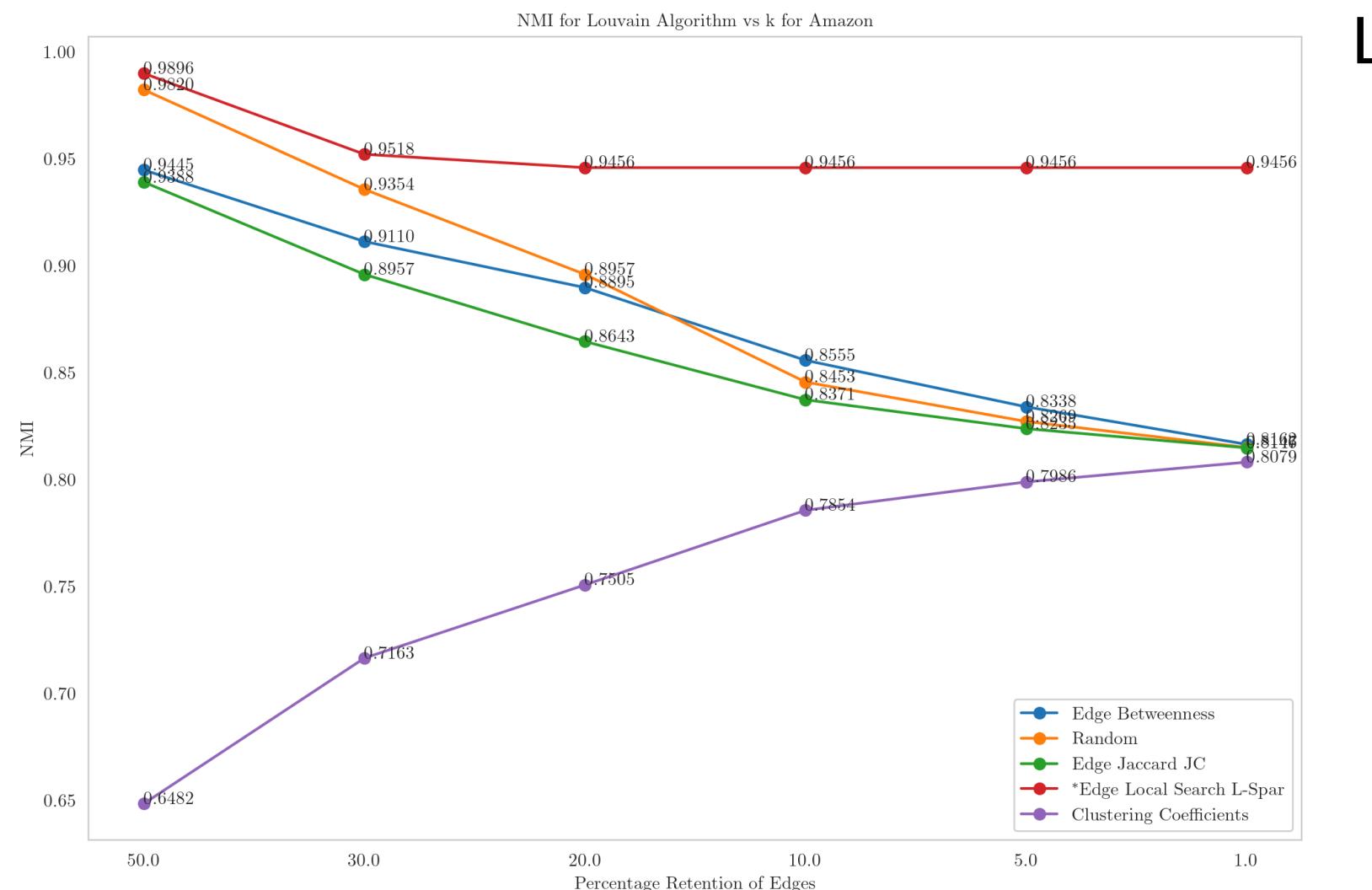
# Results for Amazon Co-Purchase Network

ARI for Louvain Algorithm vs k for Amazon

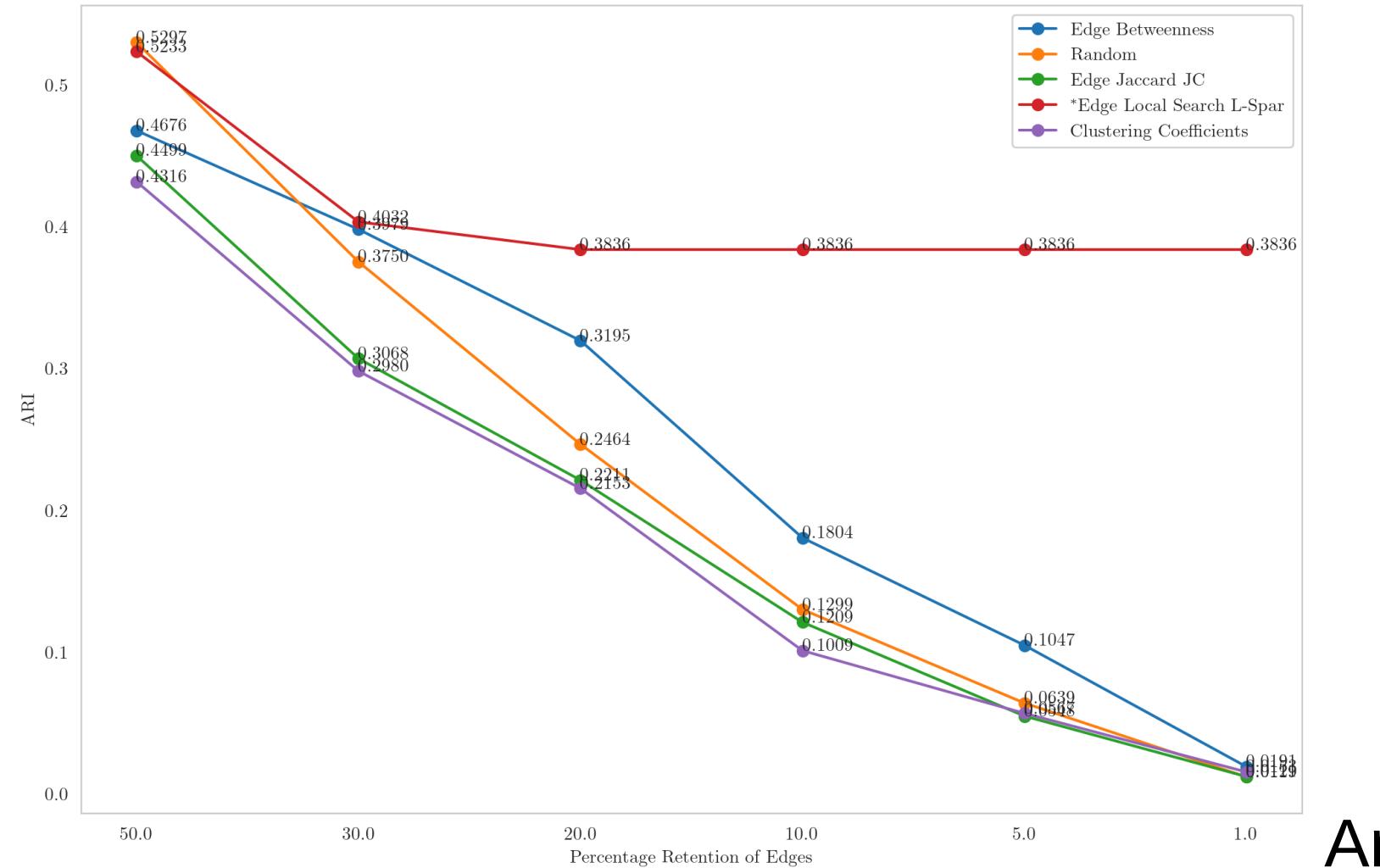




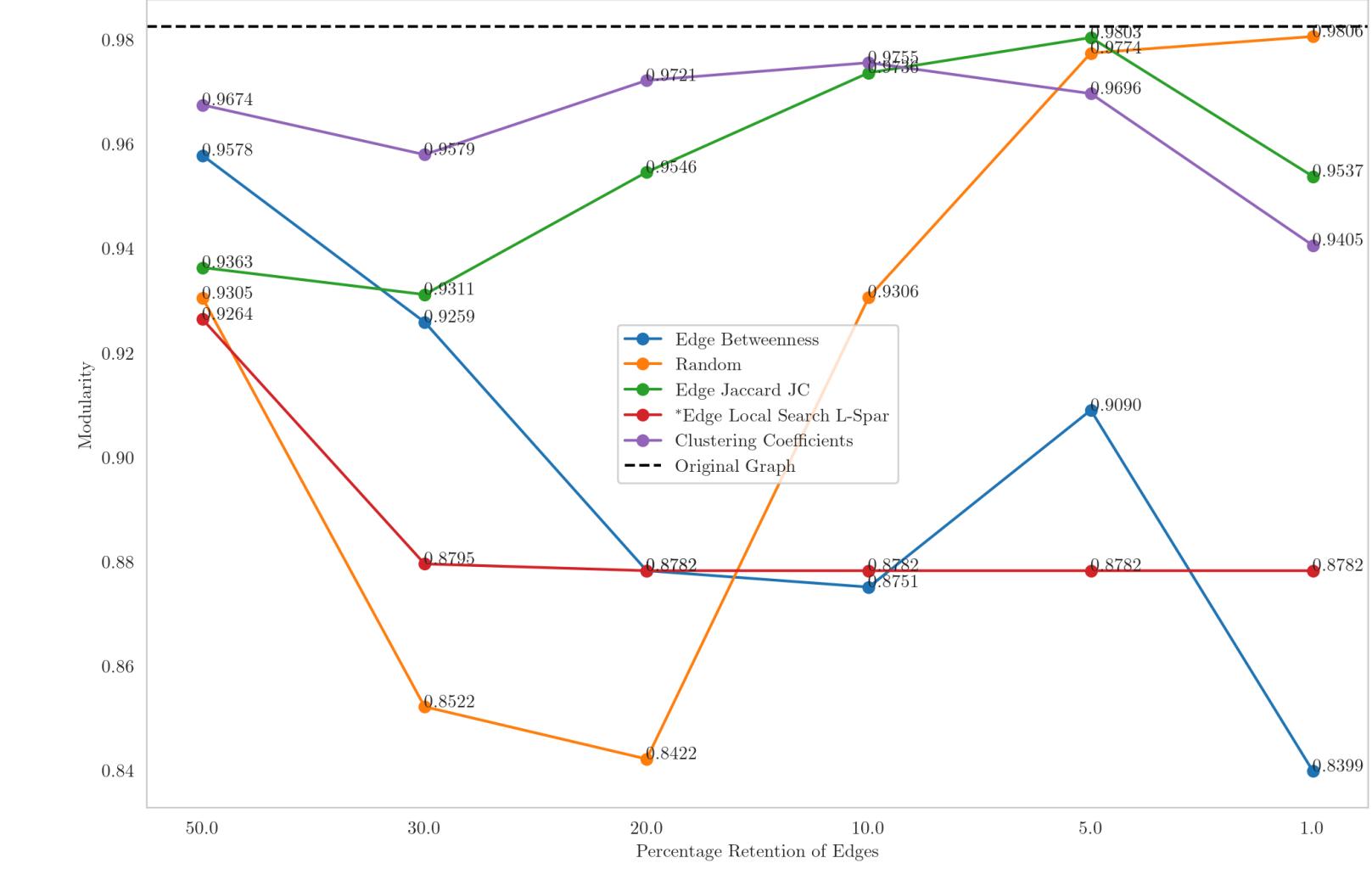
# Amazon Louvain



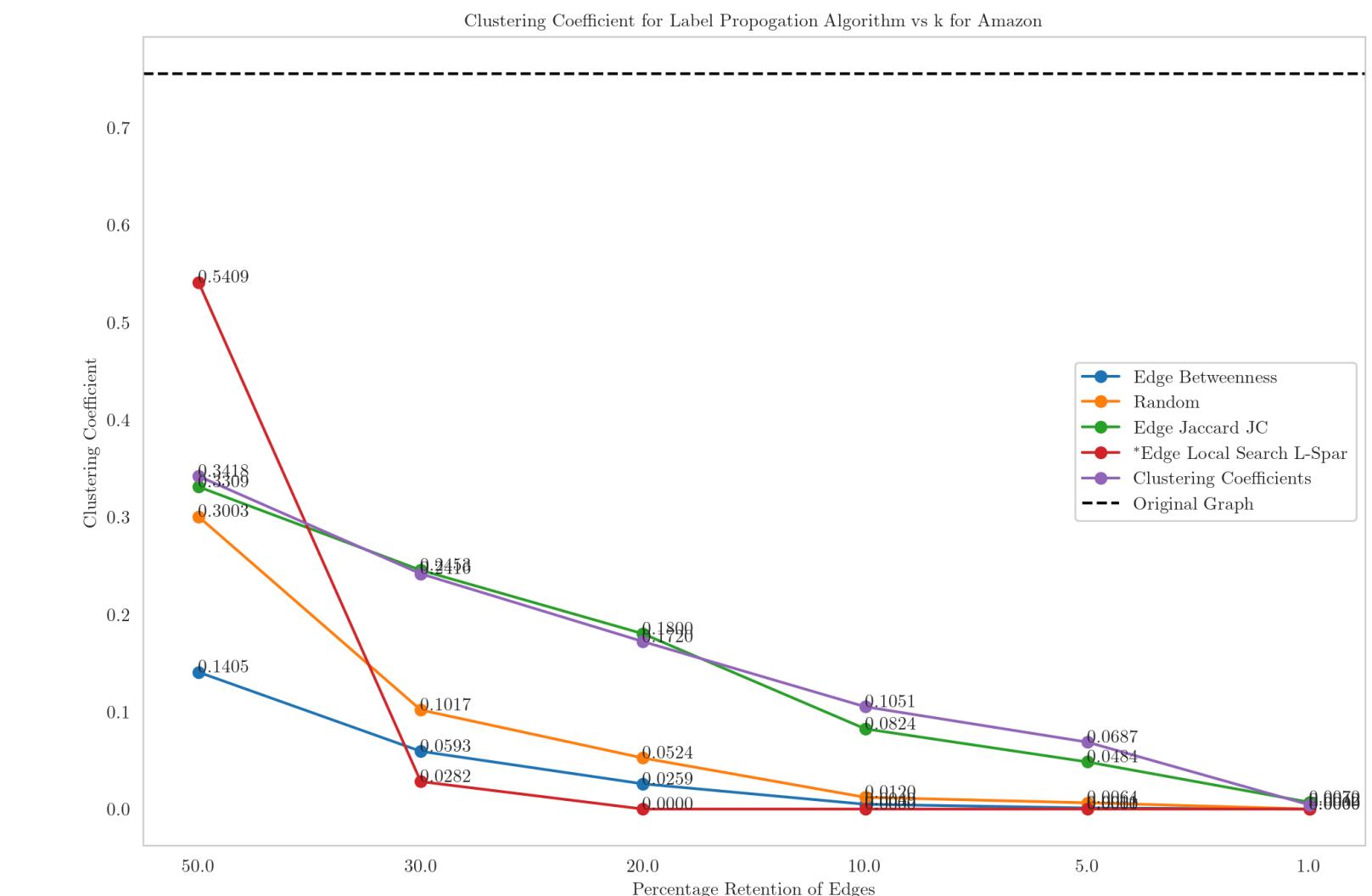
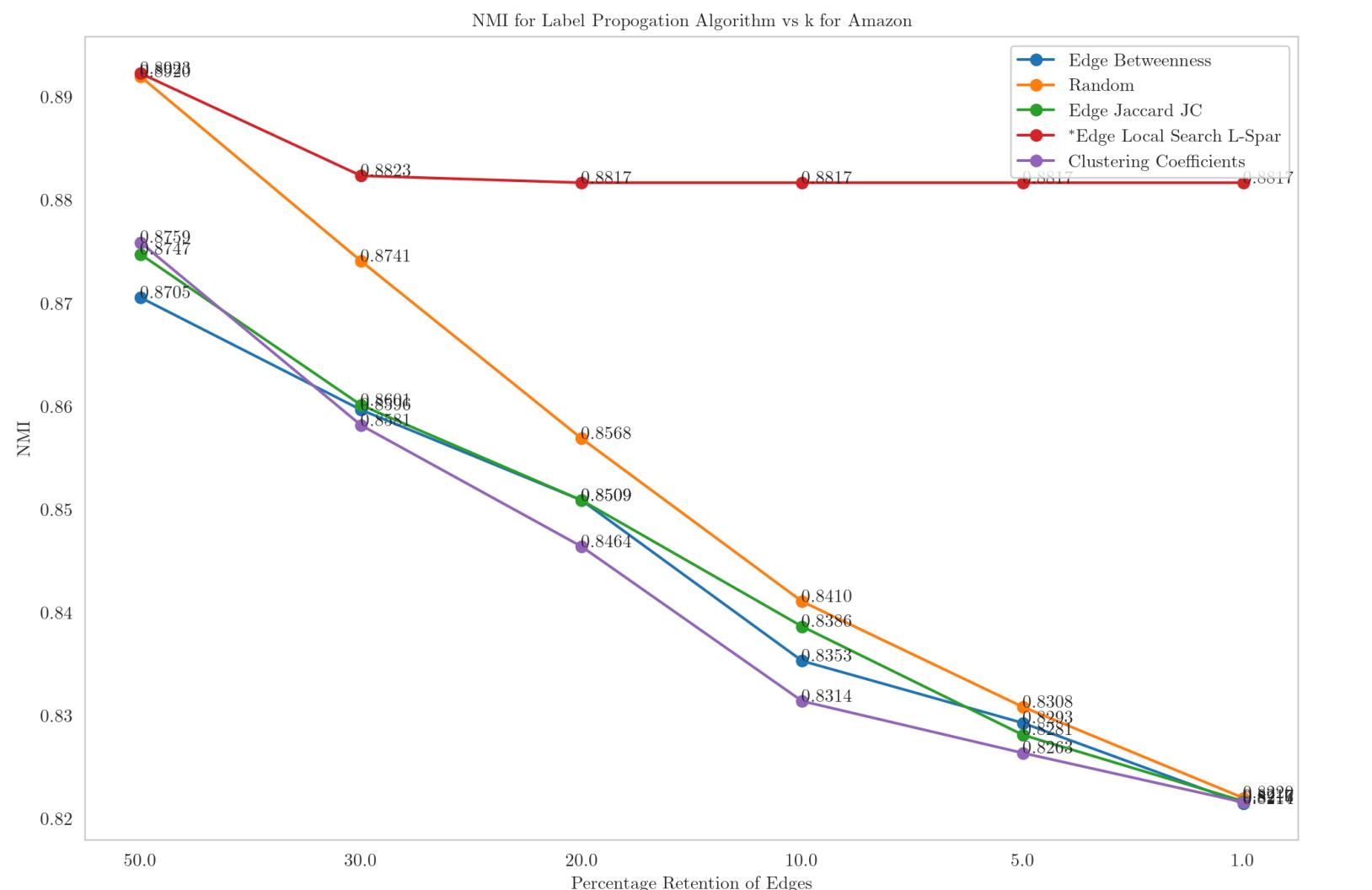
ARI for Label Propogation Algorithm vs k for Amazon

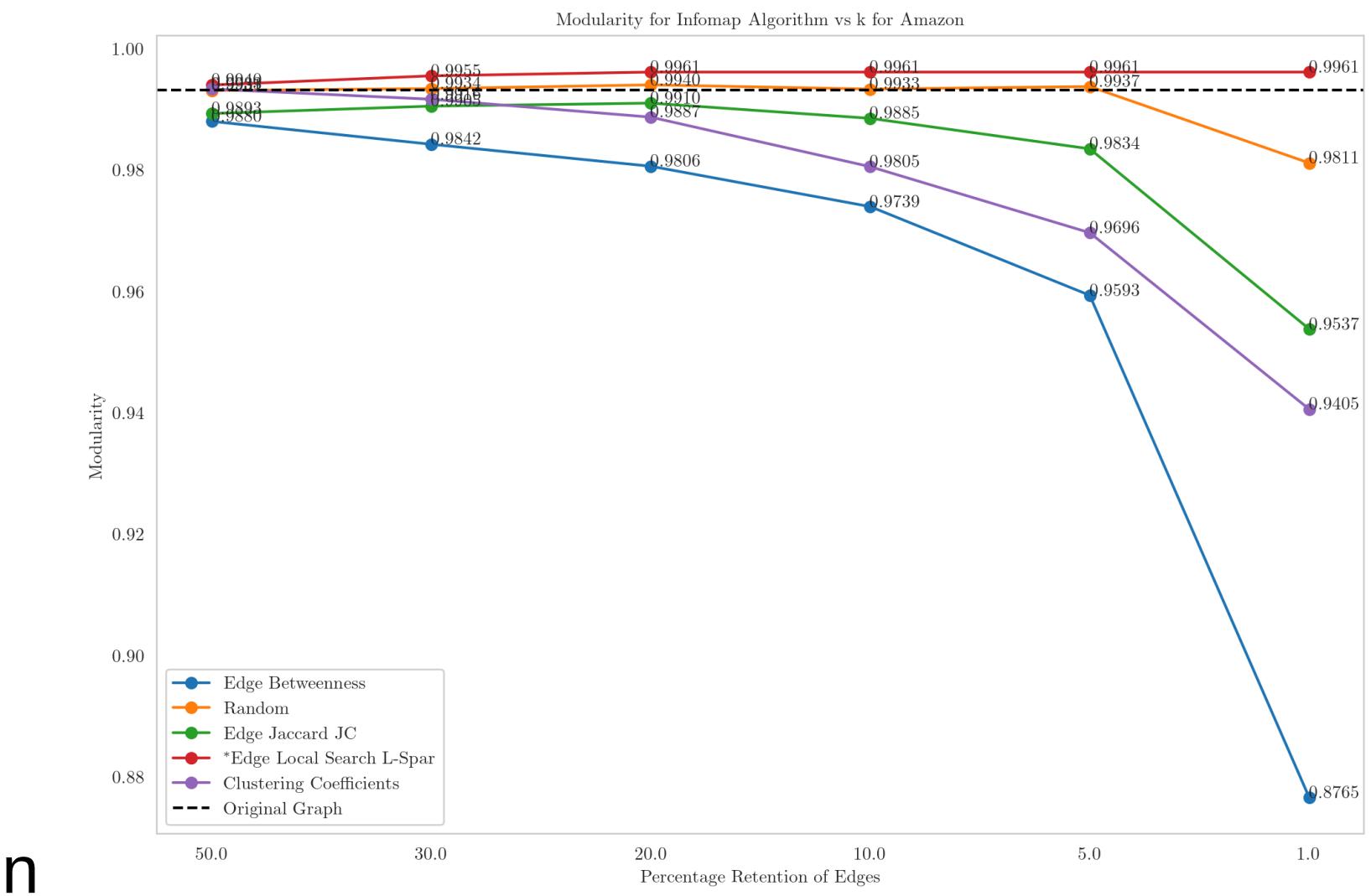
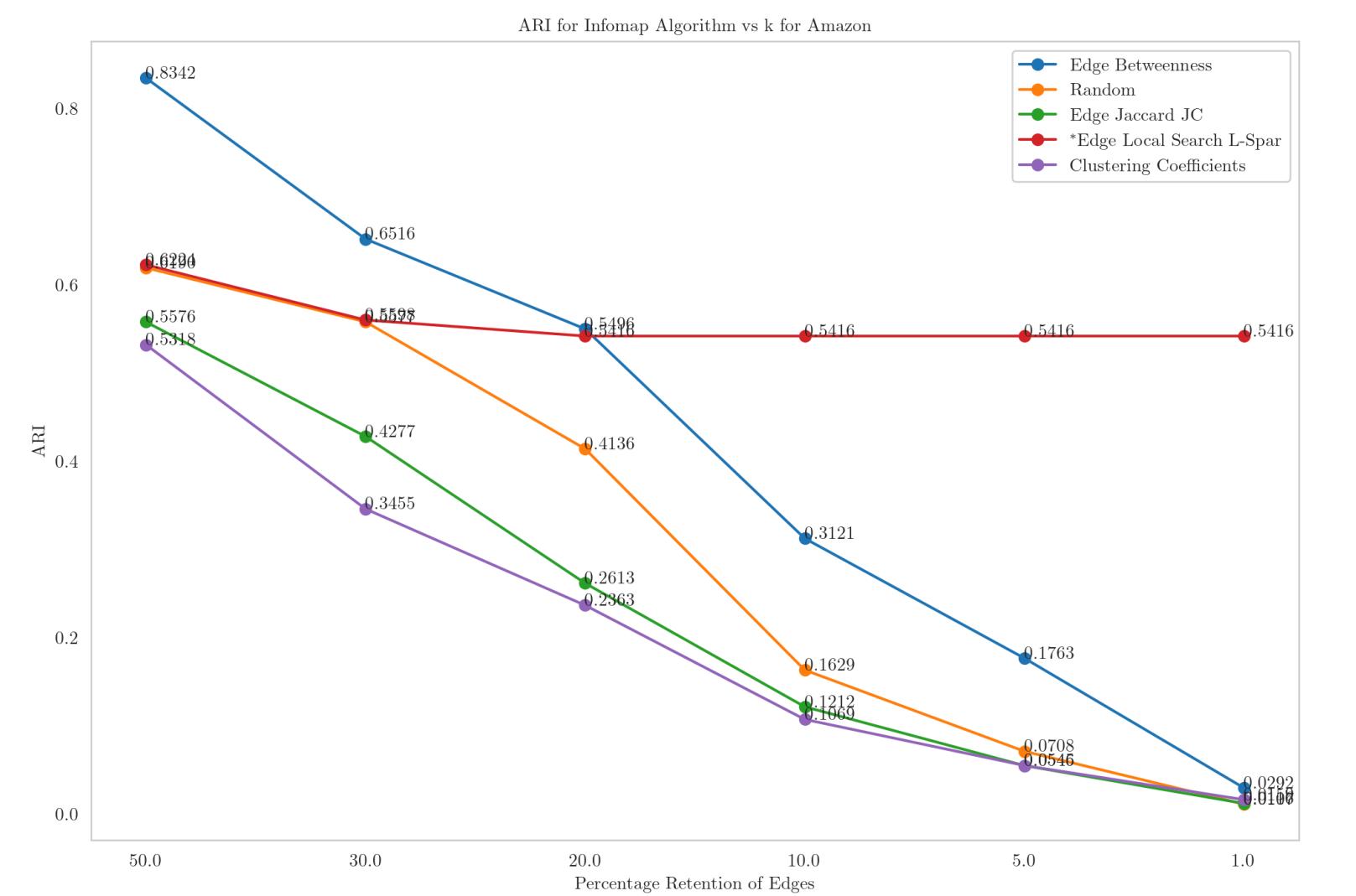


Modularity for Label Propogation Algorithm vs k for Amazon

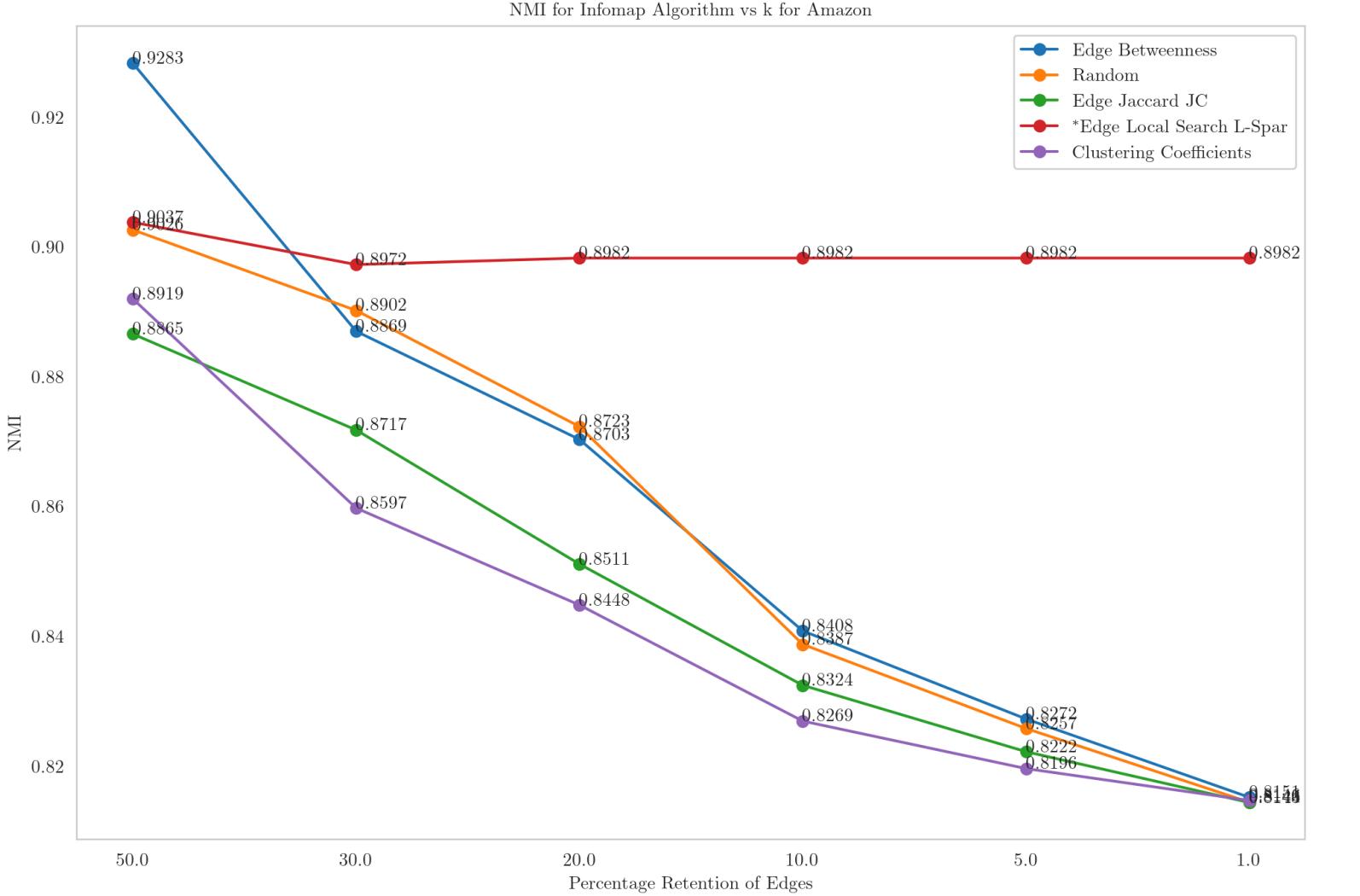
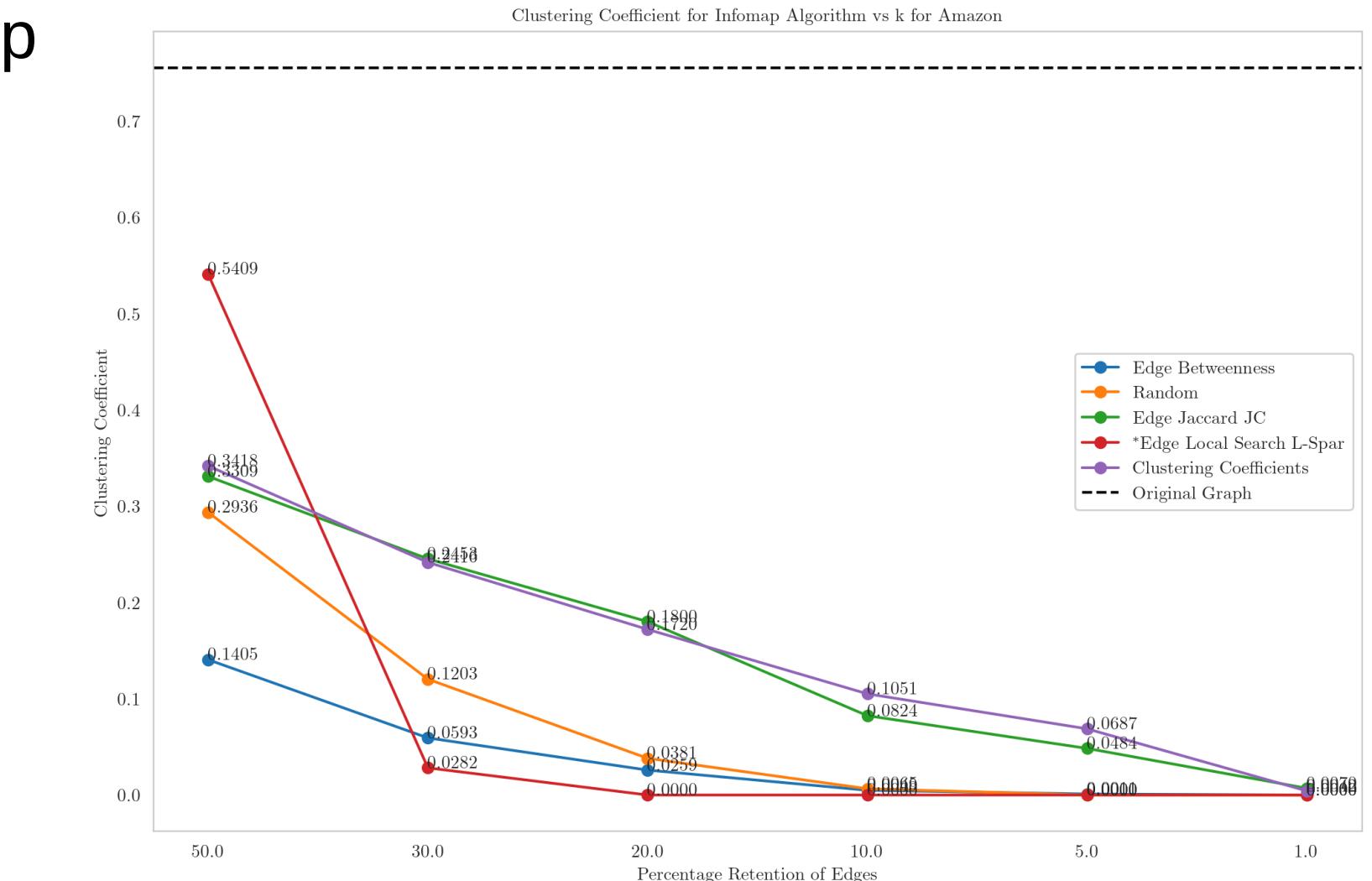


# Amazon LPA



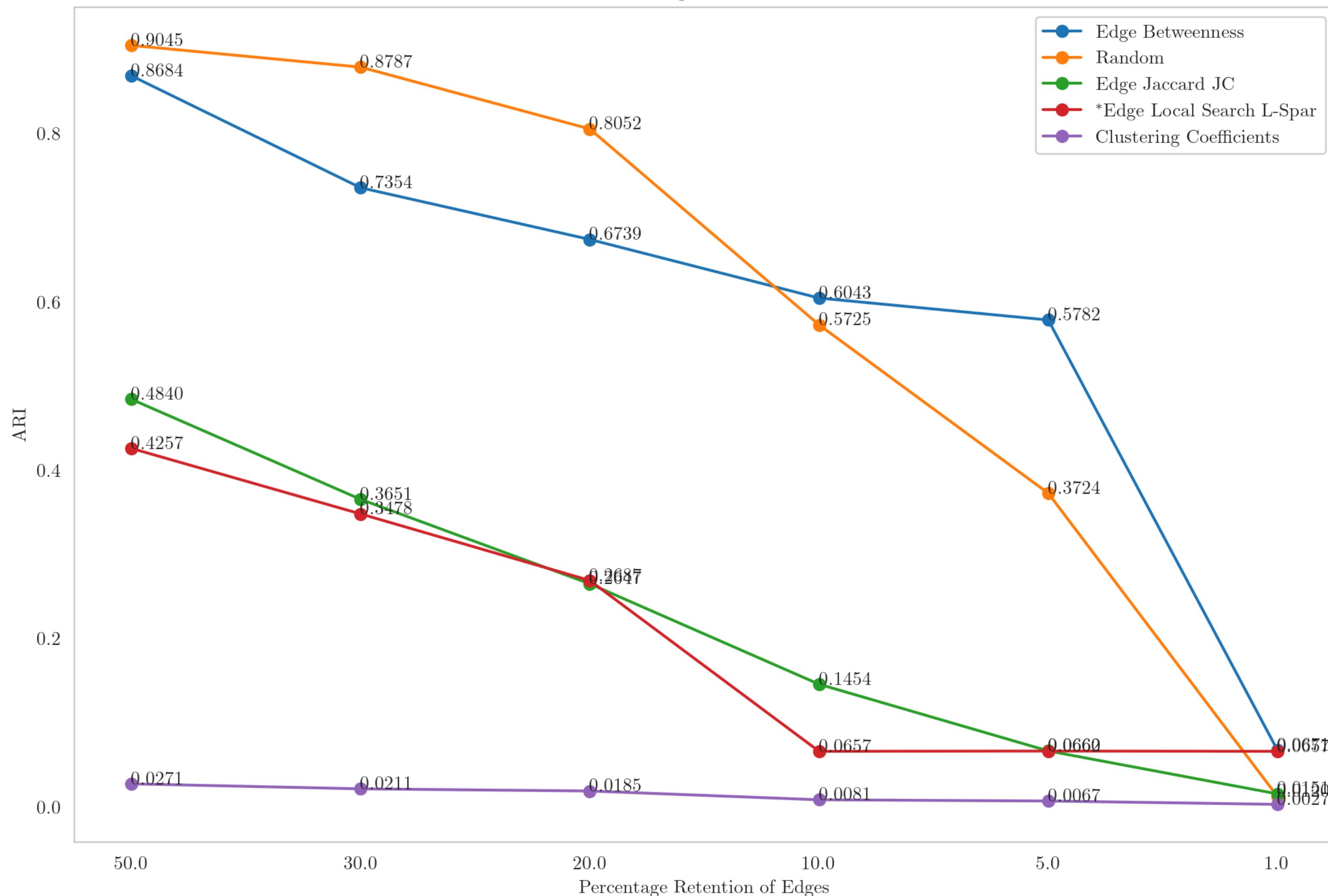


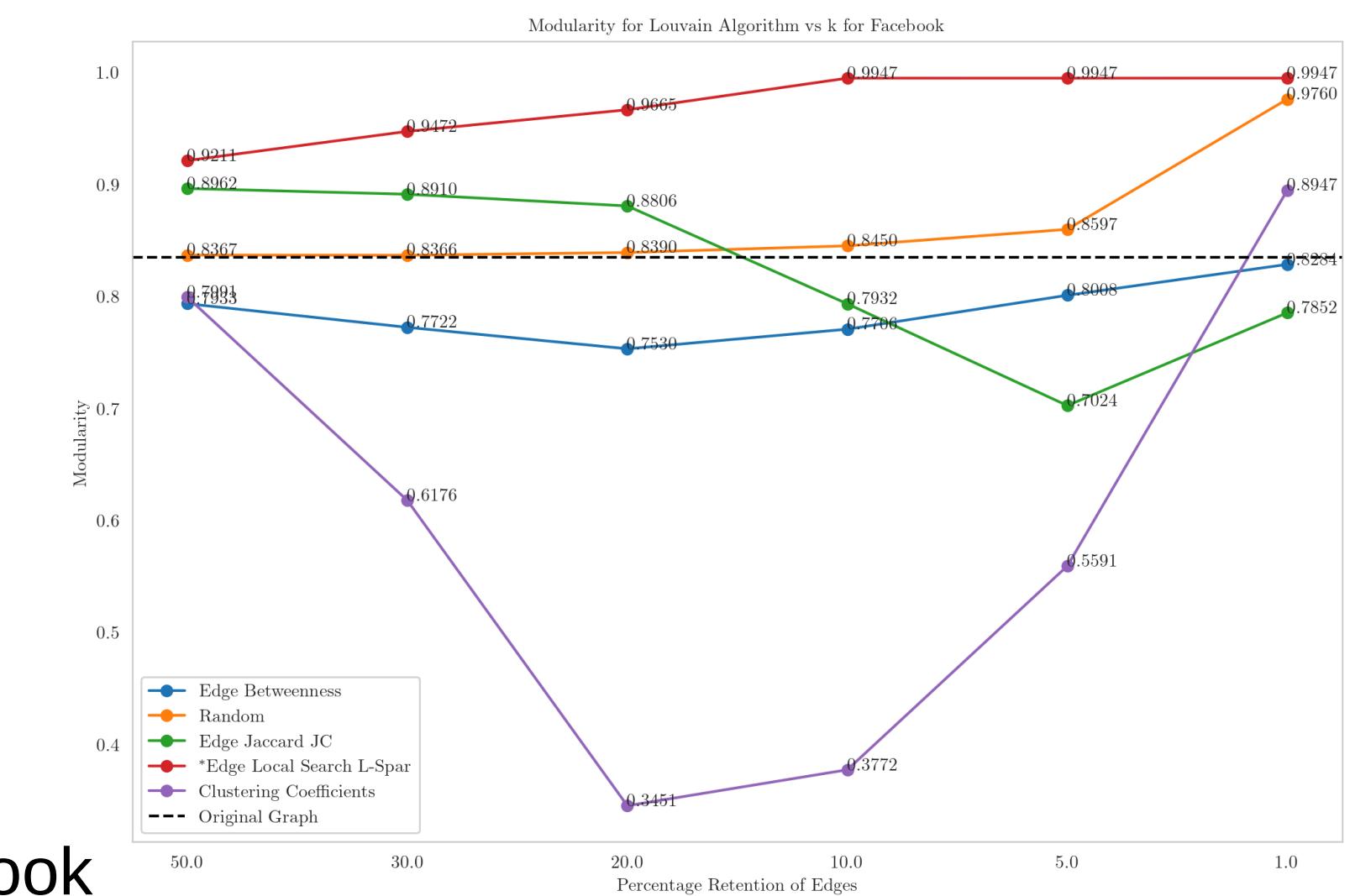
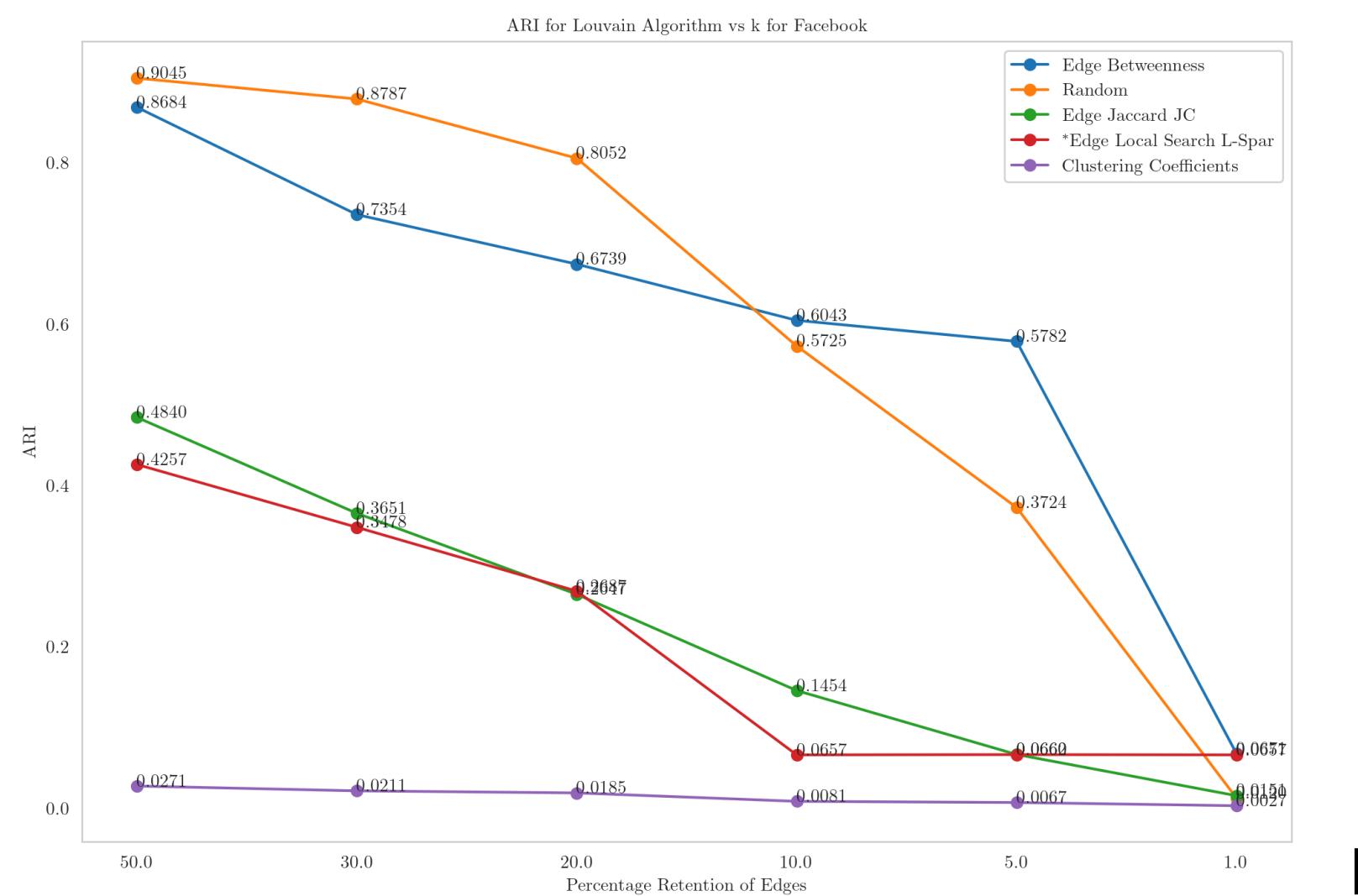
# Amazon InfoMap



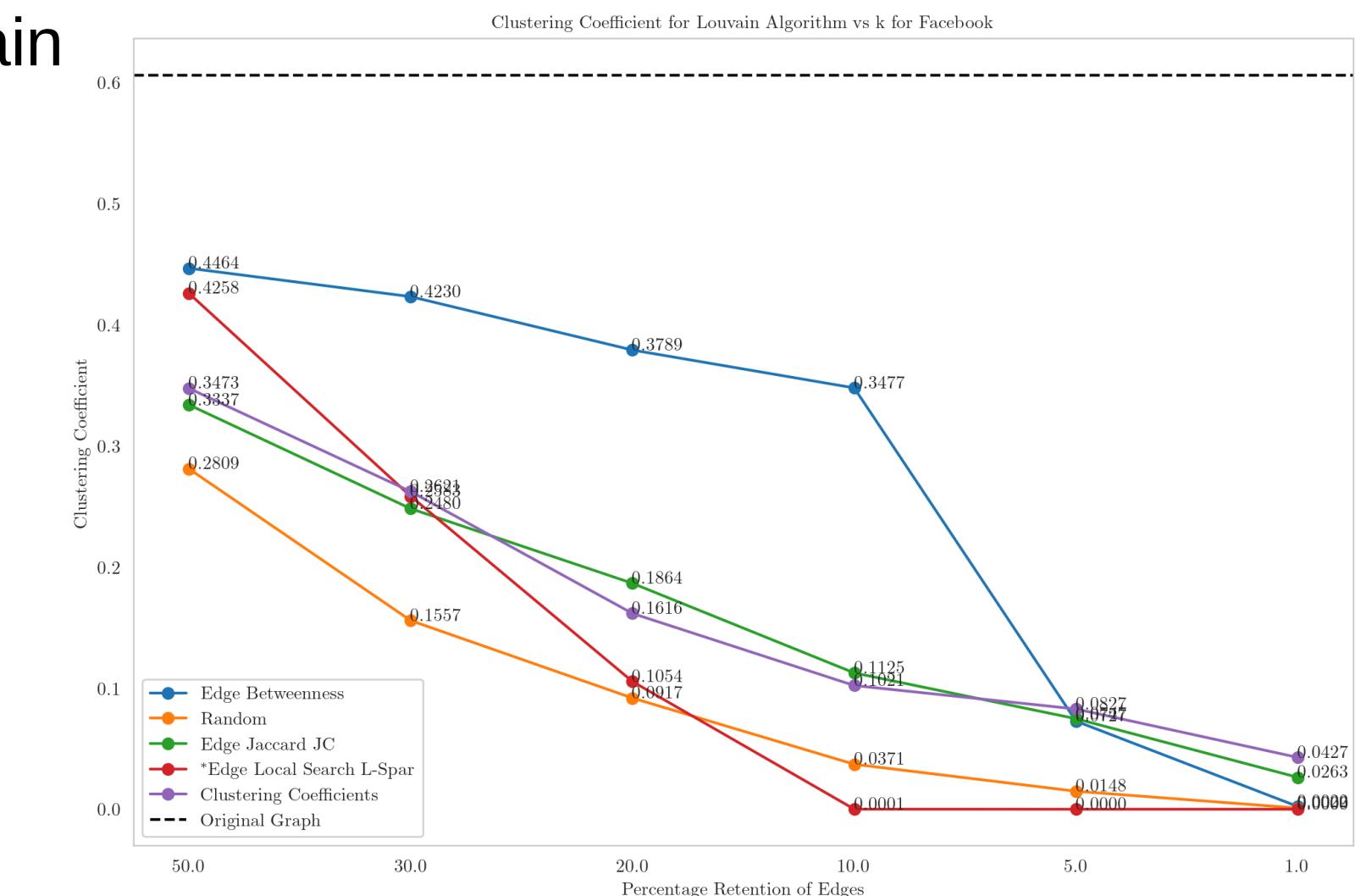
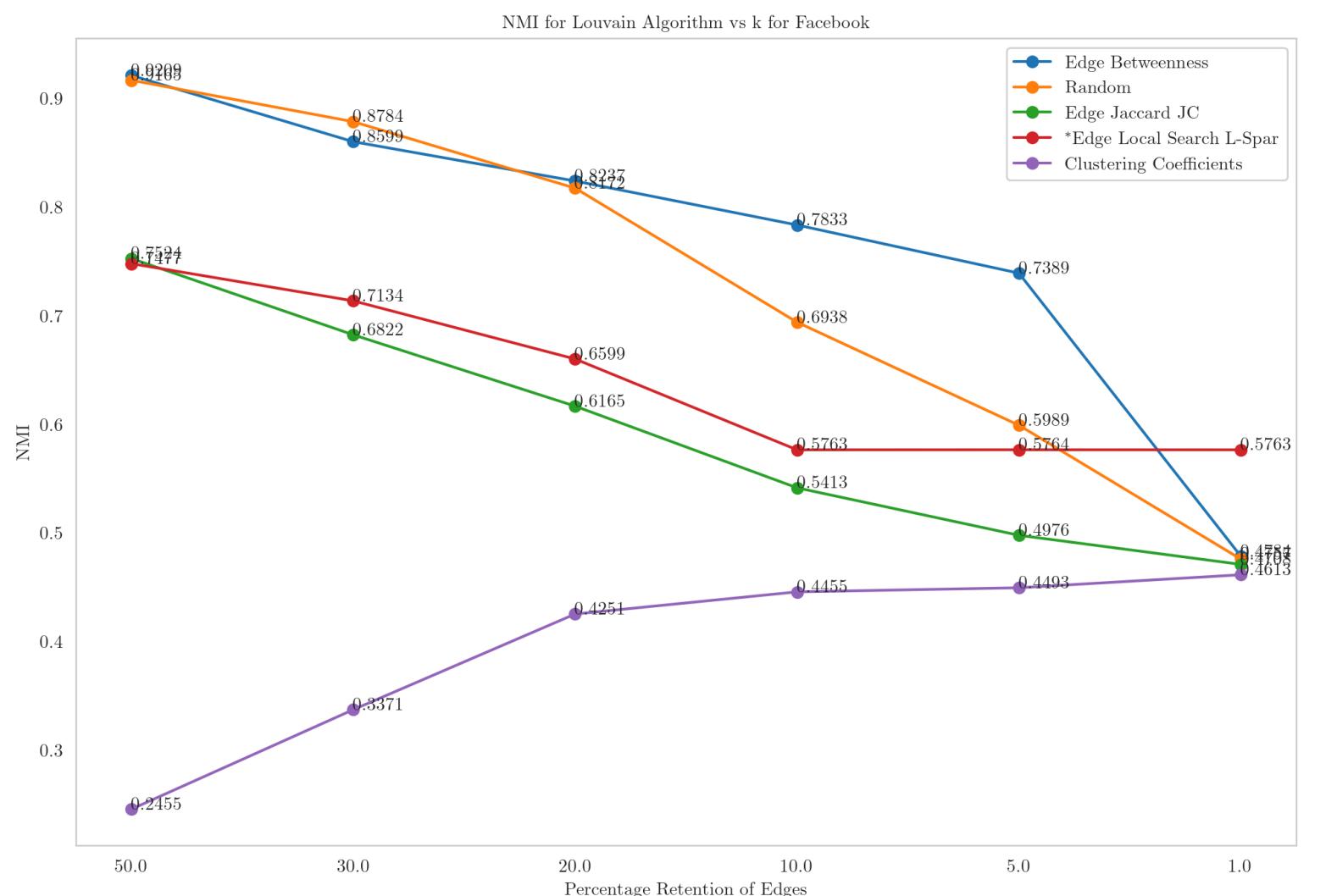
# Results for Facebook Social Network

ARI for Louvain Algorithm vs k for Facebook

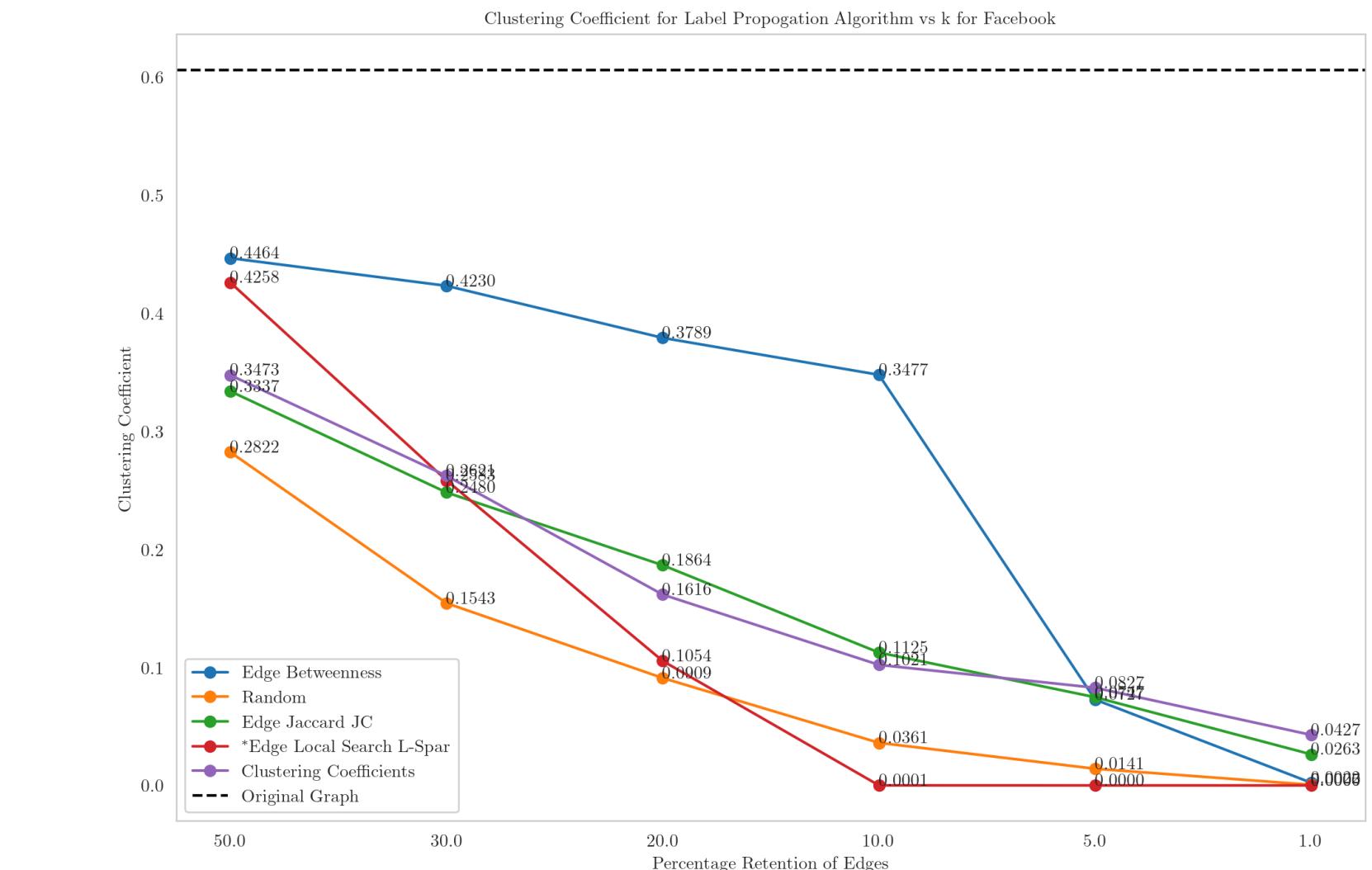
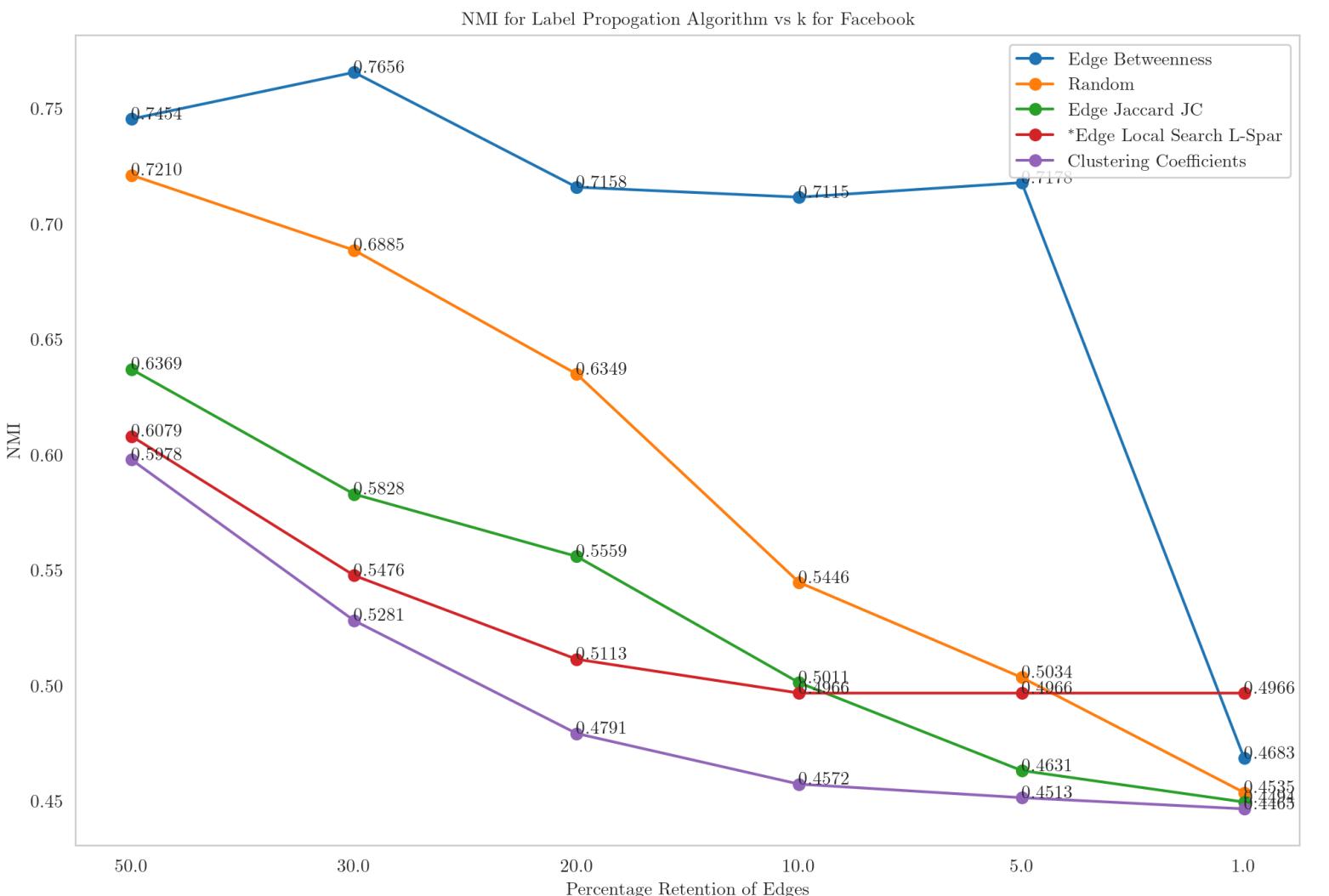
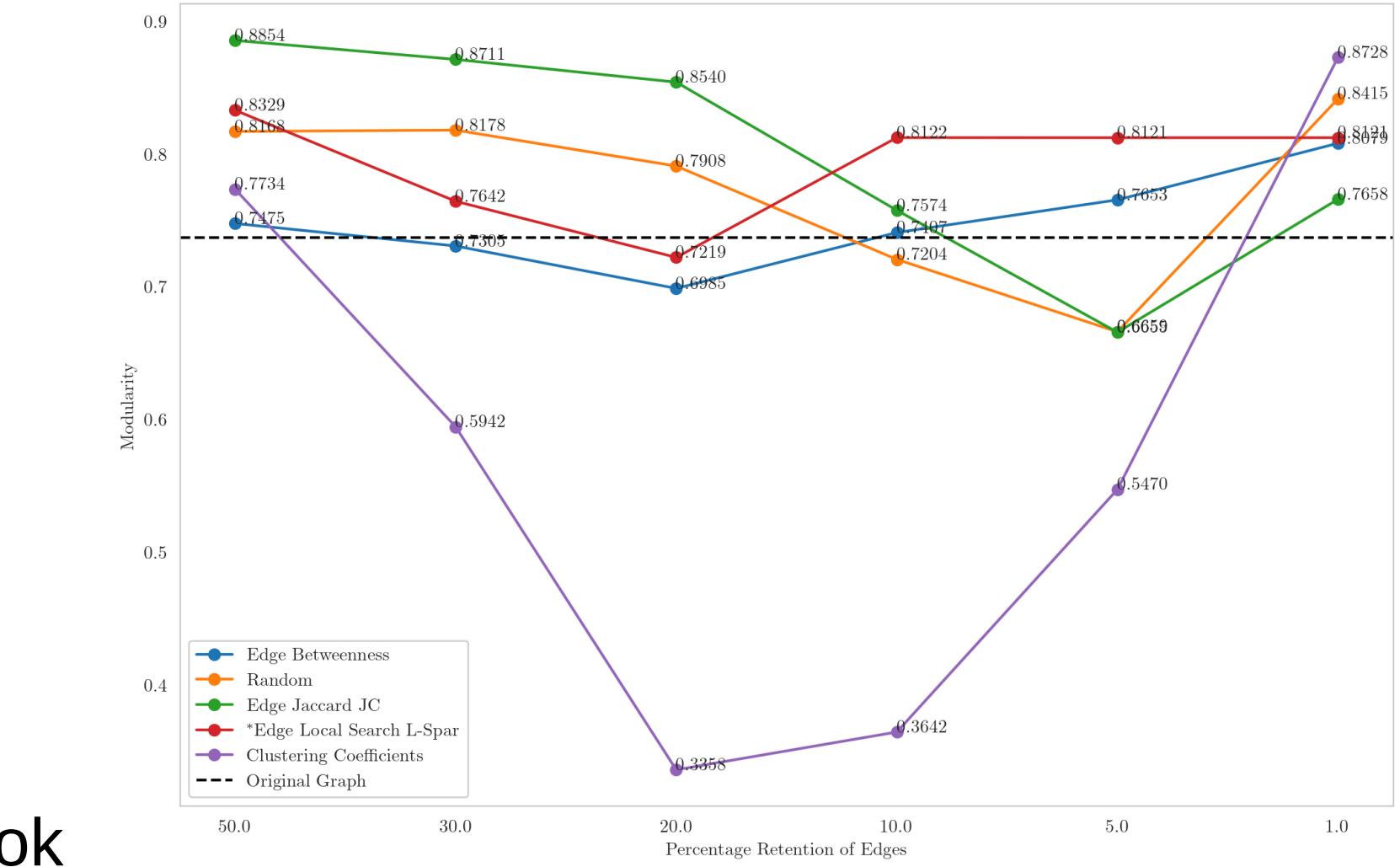
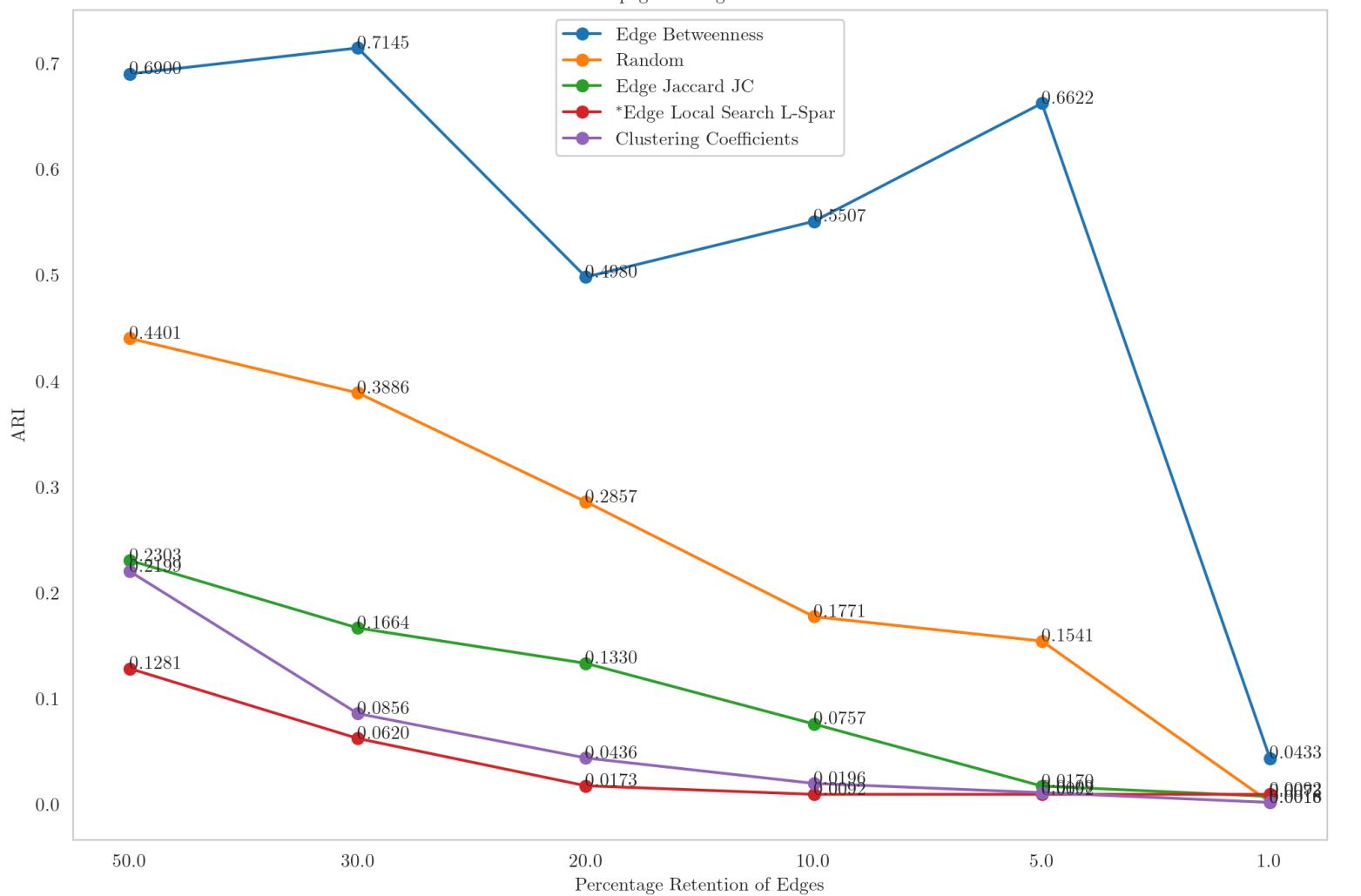




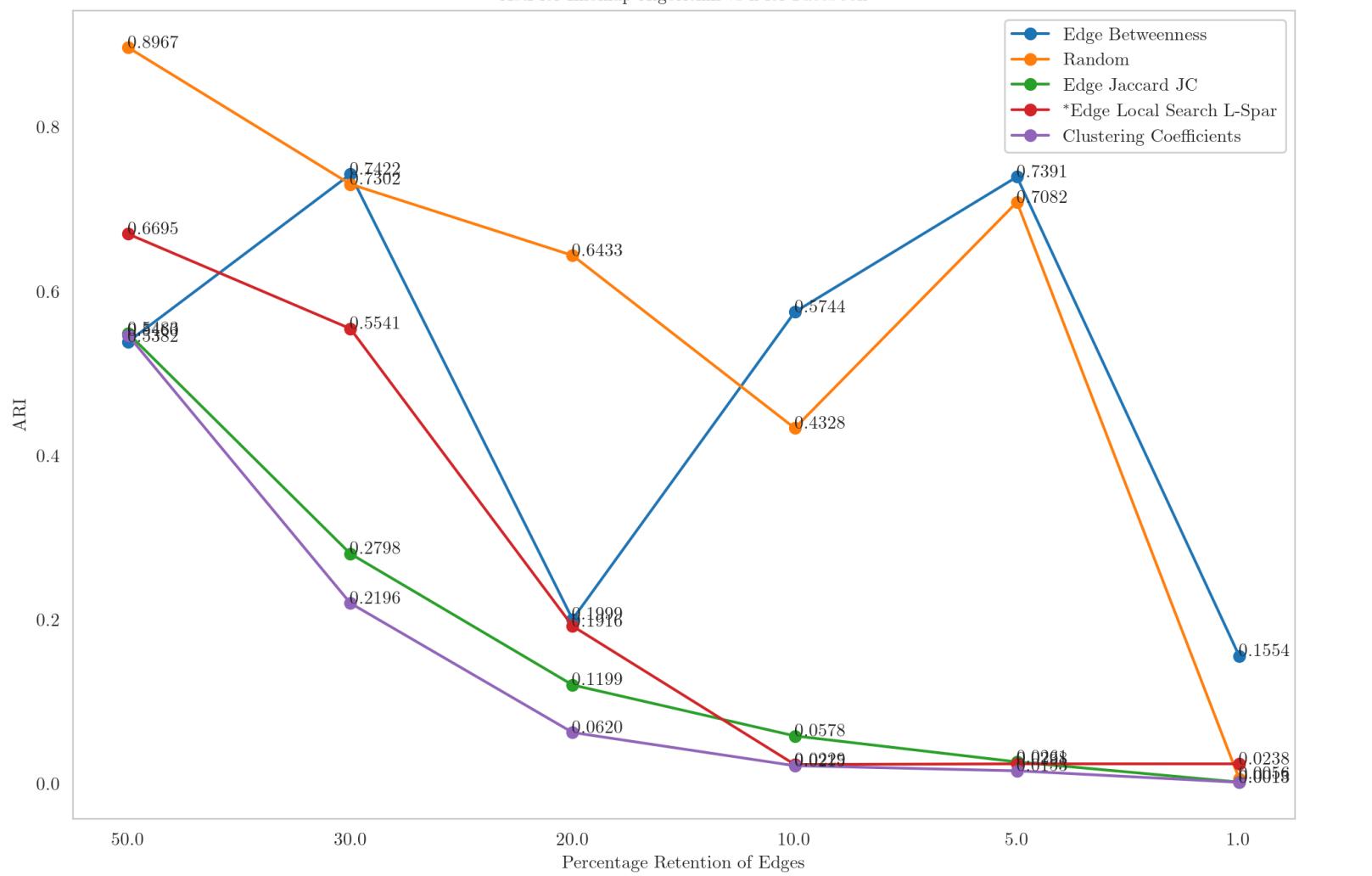
# Facebook Louvain



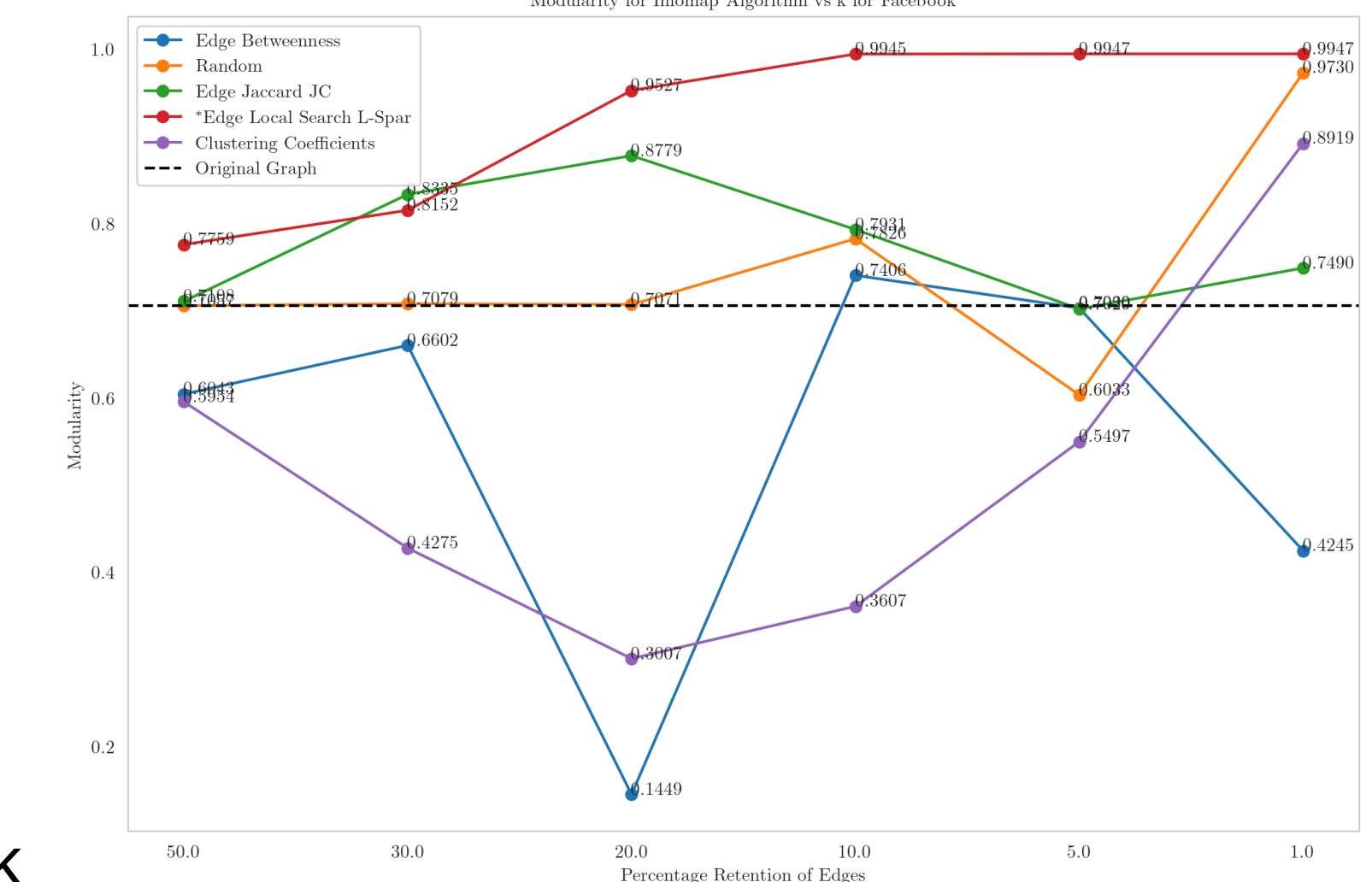
# Facebook LPA



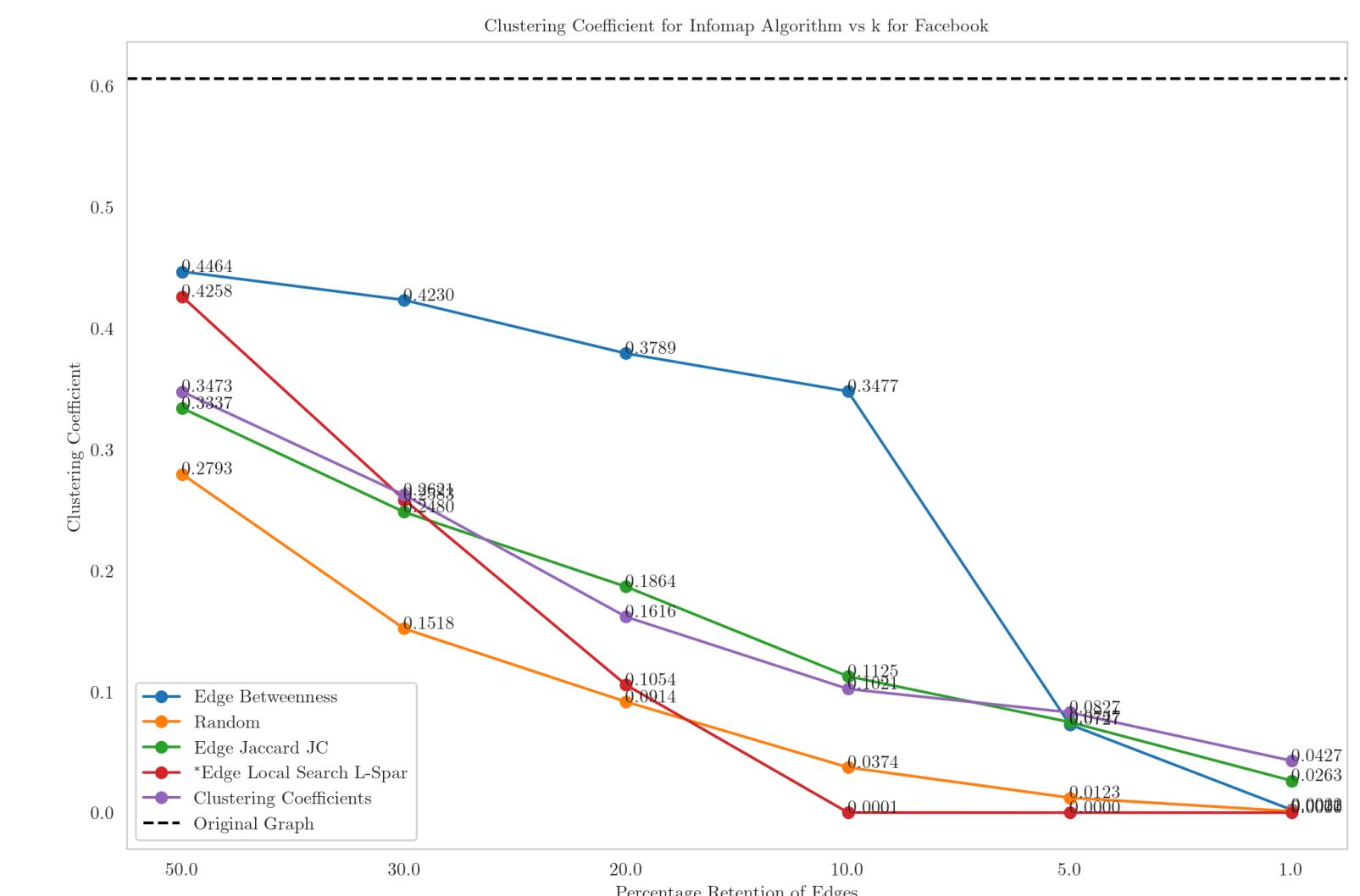
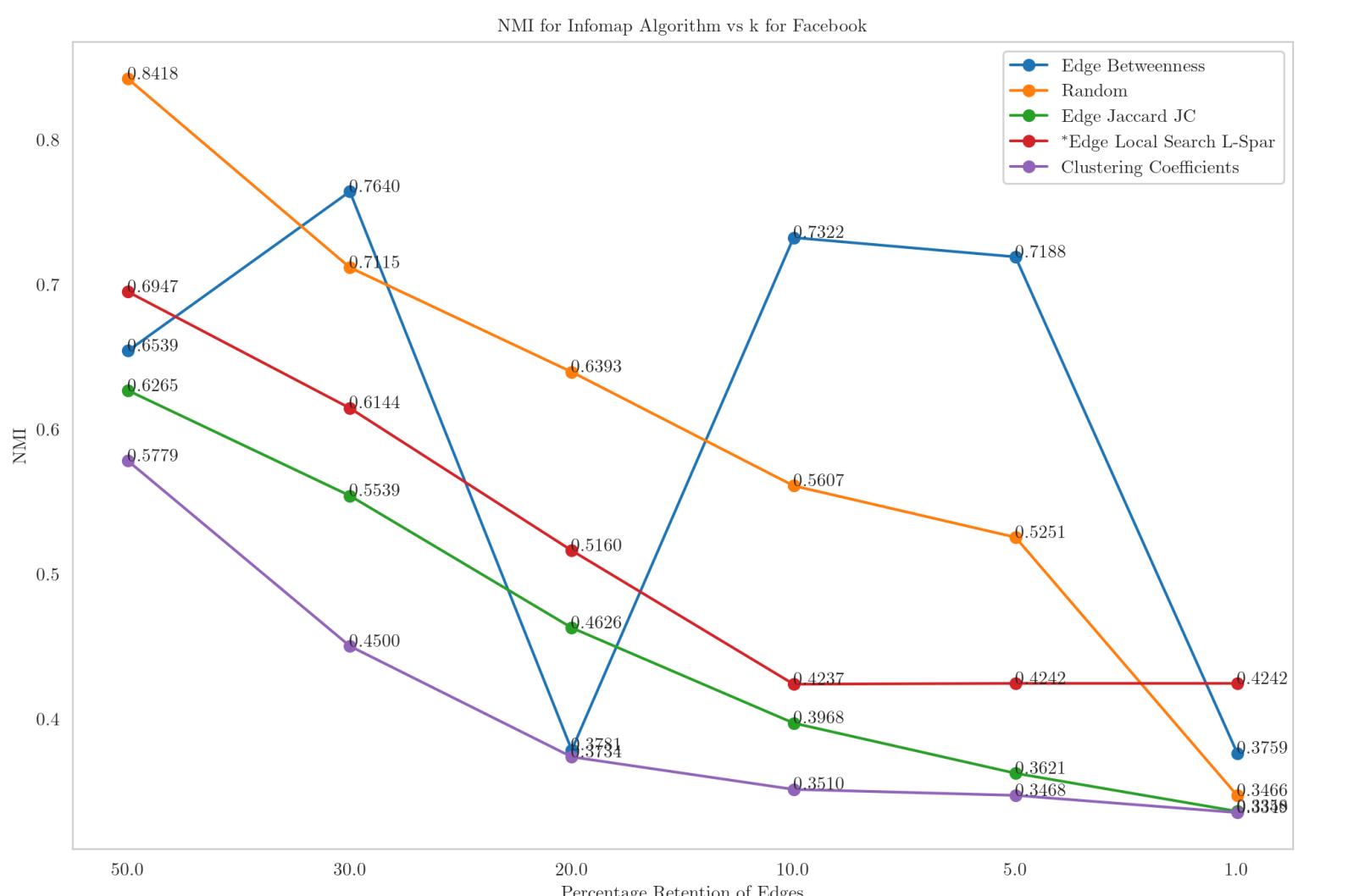
ARI for Infomap Algorithm vs k for Facebook



Modularity for Infomap Algorithm vs k for Facebook



# Facebook InfoMap



# Results for YouTube Social Network



YouTube  
Louvain

YouTube  
LPA

YouTube  
InfoMap



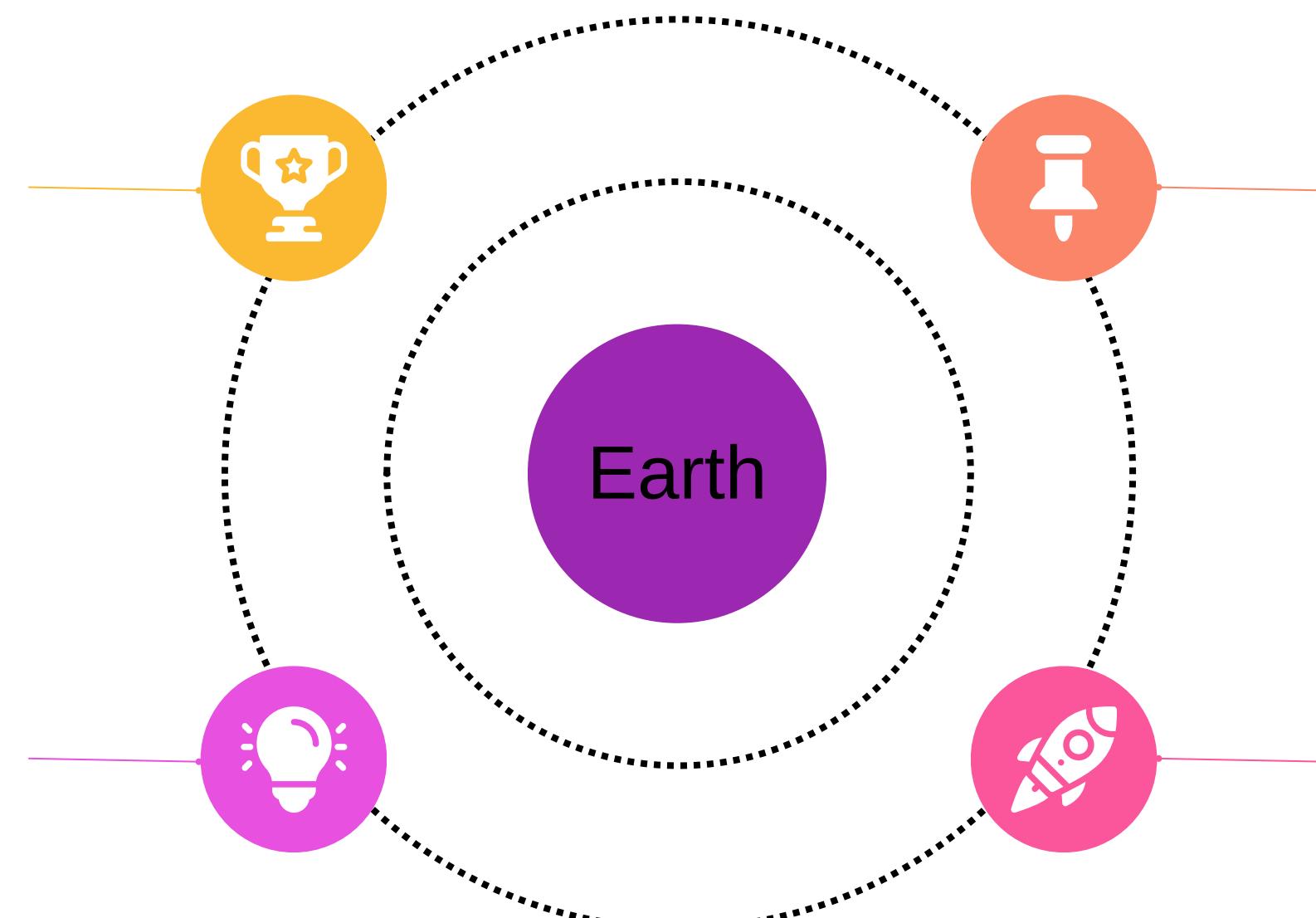
# Project Management Infographics

## Mercury

Mercury is the closest planet to the Sun and the smallest one

## Mars

Despite being red, Mars is a cold place full of iron oxide dust



## Neptune

Neptune is the farthest planet from the Sun and the fourth-largest one

## Earth

Earth is the third planet from the Sun and the only one that harbors life

# Project Management Infographics



Neptune is the farthest planet from the Sun and a gas giant



Despite being red, Mars is actually a cold place



Earth is the third planet from the Sun

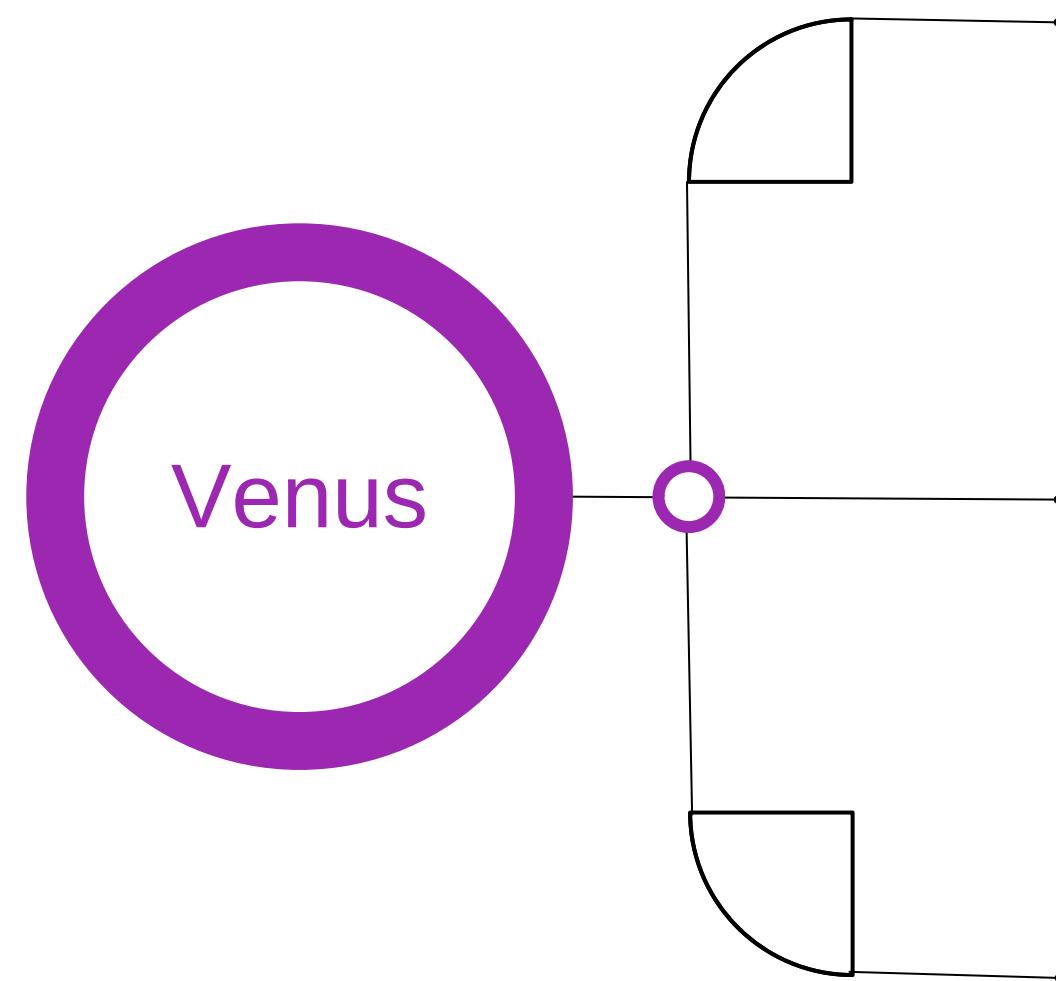


Venus has a nice name and is the second



Jupiter is a gas giant and the biggest planet of them all

# Project Management Infographics



Mercury

Jupiter

Saturn

Mercury is the smallest planet in the Solar System

Jupiter is a gas giant and also the biggest planet

Saturn is a gas giant made of hydrogen and helium

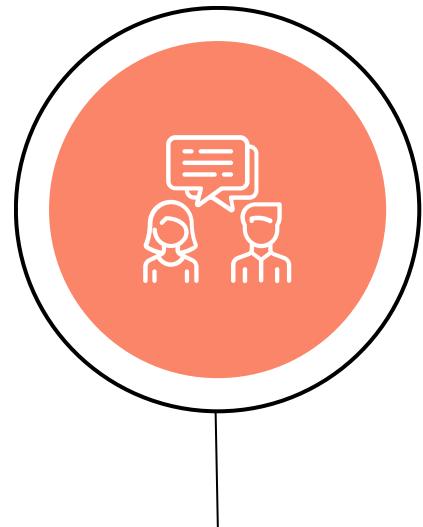
# Project Management Infographics



Concept 1

Saturn

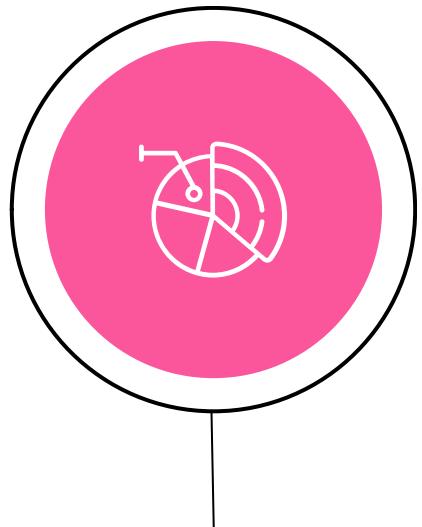
Saturn is a gas giant made of hydrogen and helium



Concept 2

Jupiter

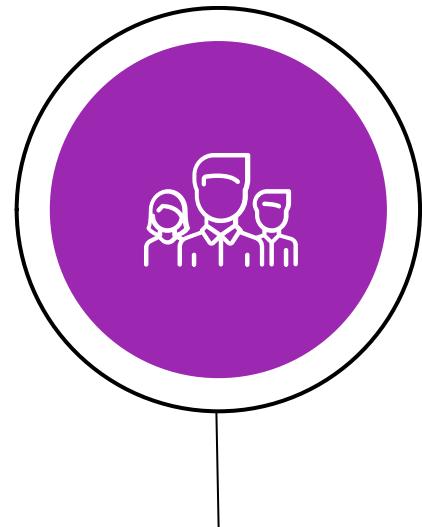
Jupiter is a gas giant and the biggest planet of them all



Concept 3

Venus

Venus has a beautiful name, but also high temperatures



Concept 4

Mercury

Mercury is the smallest planet in the Solar System

# Project Management Infographics

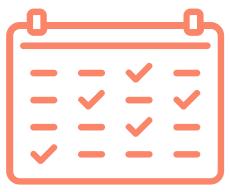
## STRENGTHS



### Venus

Venus has a beautiful name and high temperatures

## WEAKNESSES



### Mars

Despite being red, Mars is a cold place full of iron oxide dust

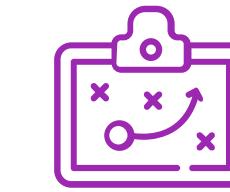
## OPPORTUNITIES



### Jupiter

Jupiter is the fourth and the biggest planet

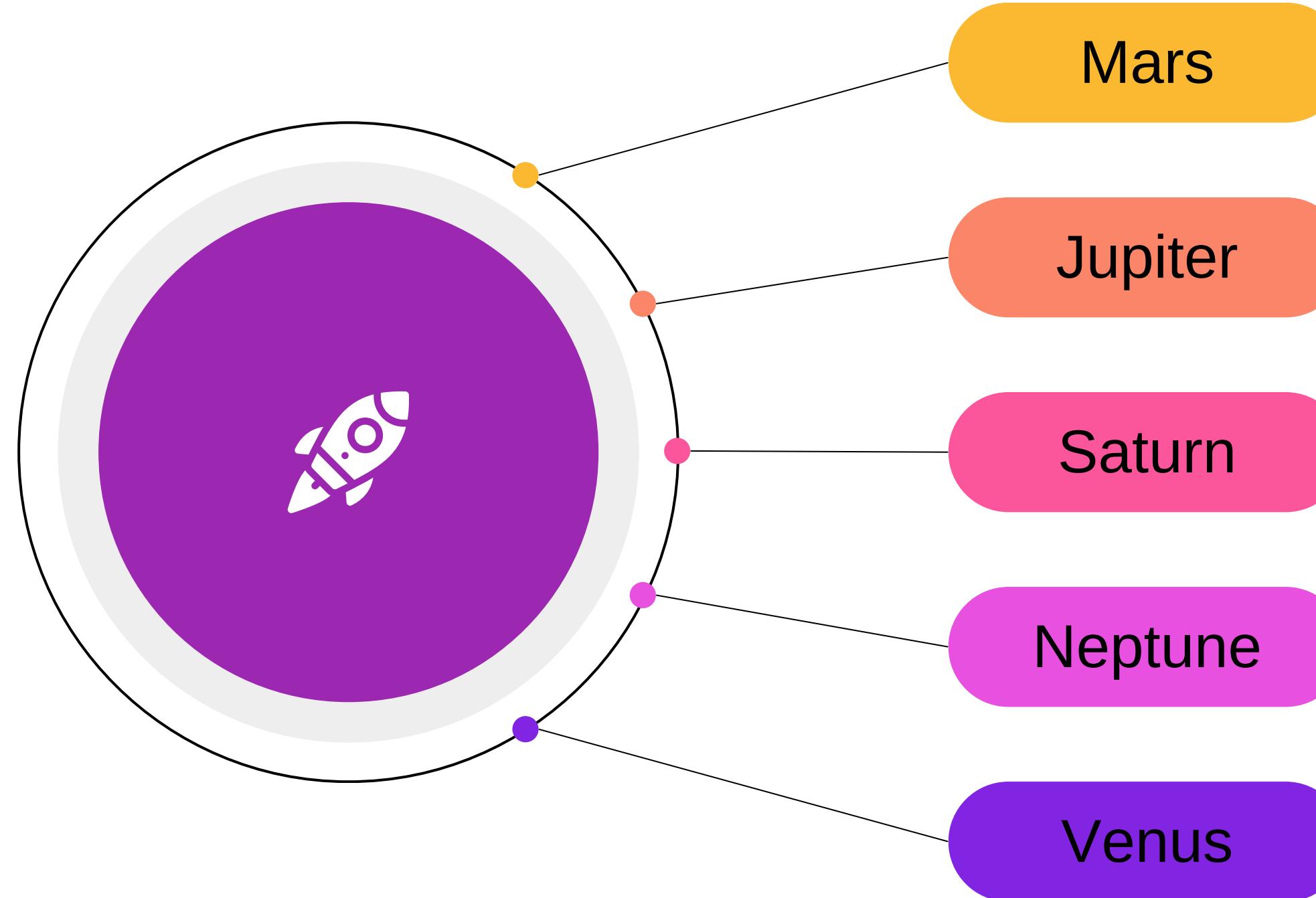
## THREATS



### Saturn

Saturn is composed of hydrogen and also helium

# Project Management Infographics



Despite being red, Mars is actually a cold place

Jupiter is a giant and the fourth planet from the Sun

Saturn is a gas giant made of hydrogen and helium

Neptune is the farthest planet from the Sun

Venus is the second planet from the Sun

# Project Management Infographics

## Step 01

Mercury is the closest planet to the Sun



## Step 02

Despite being red, Mars is a cold place



## Step 03

Jupiter is a gas giant and the biggest planet

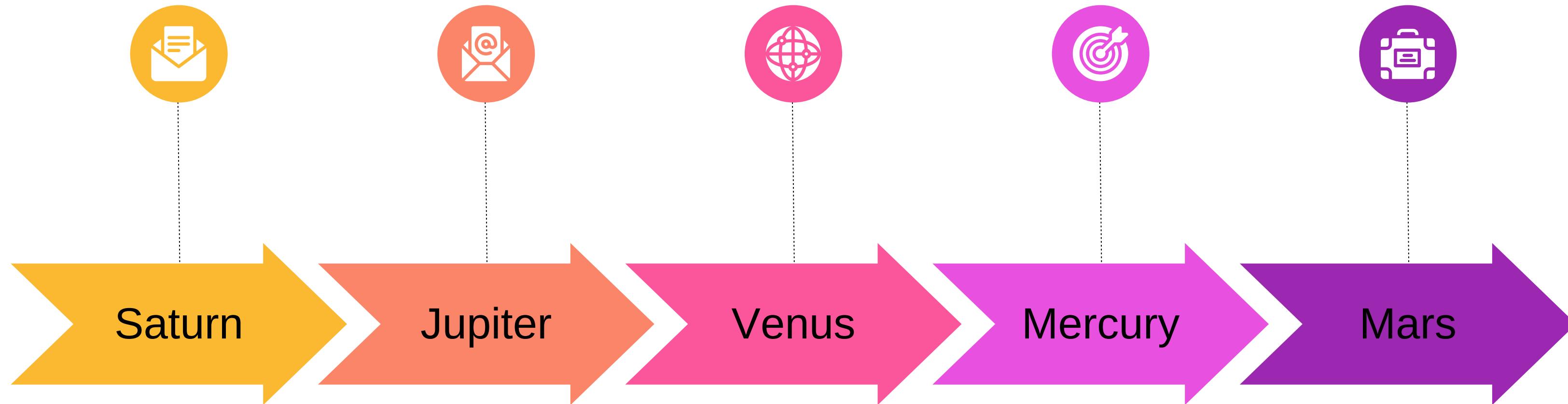


## Step 04

Neptune is the farthest planet from the Sun



# Project management infographics



Saturn is a gas giant made of hydrogen and helium

Jupiter is a gas giant and the biggest planet

Venus is the second planet from the Sun

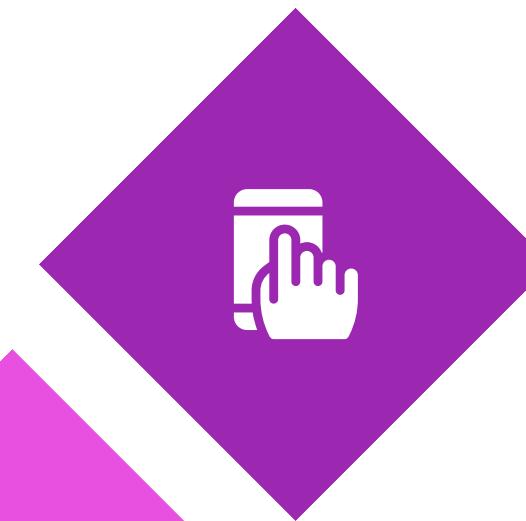
Mercury is the smallest planet in the Solar System

Despite being red, Mars is actually a cold place

# Project management infographics

## Saturn

Saturn is a gas giant composed mostly of hydrogen and helium



## Jupiter

Jupiter is a gas giant and the biggest planet in the Solar System



## Venus

Venus has a beautiful name, but it is terribly hot there

## Mars

Despite being red, Mars is a cold place full of iron oxide dust

## Mercury

Mercury is the smallest planet in the Solar System

# Project Management Infographics



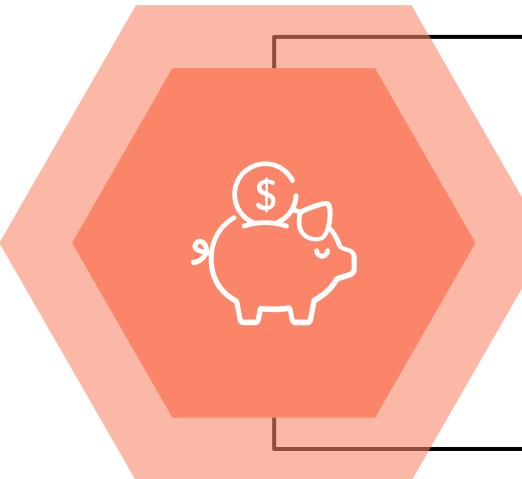
## Saturn

Saturn is a gas giant made of hydrogen and helium



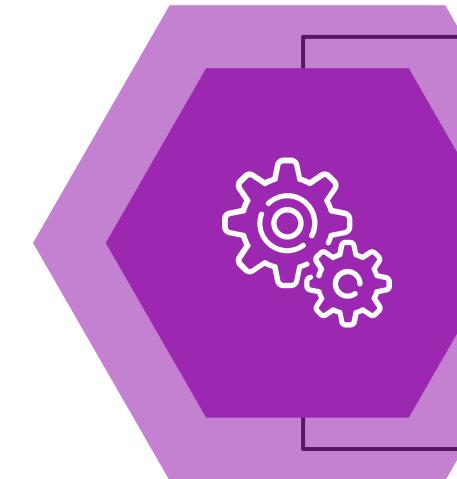
## Mercury

Mercury is the smallest planet in the Solar System



## Jupiter

Jupiter is a gas giant and the biggest planet



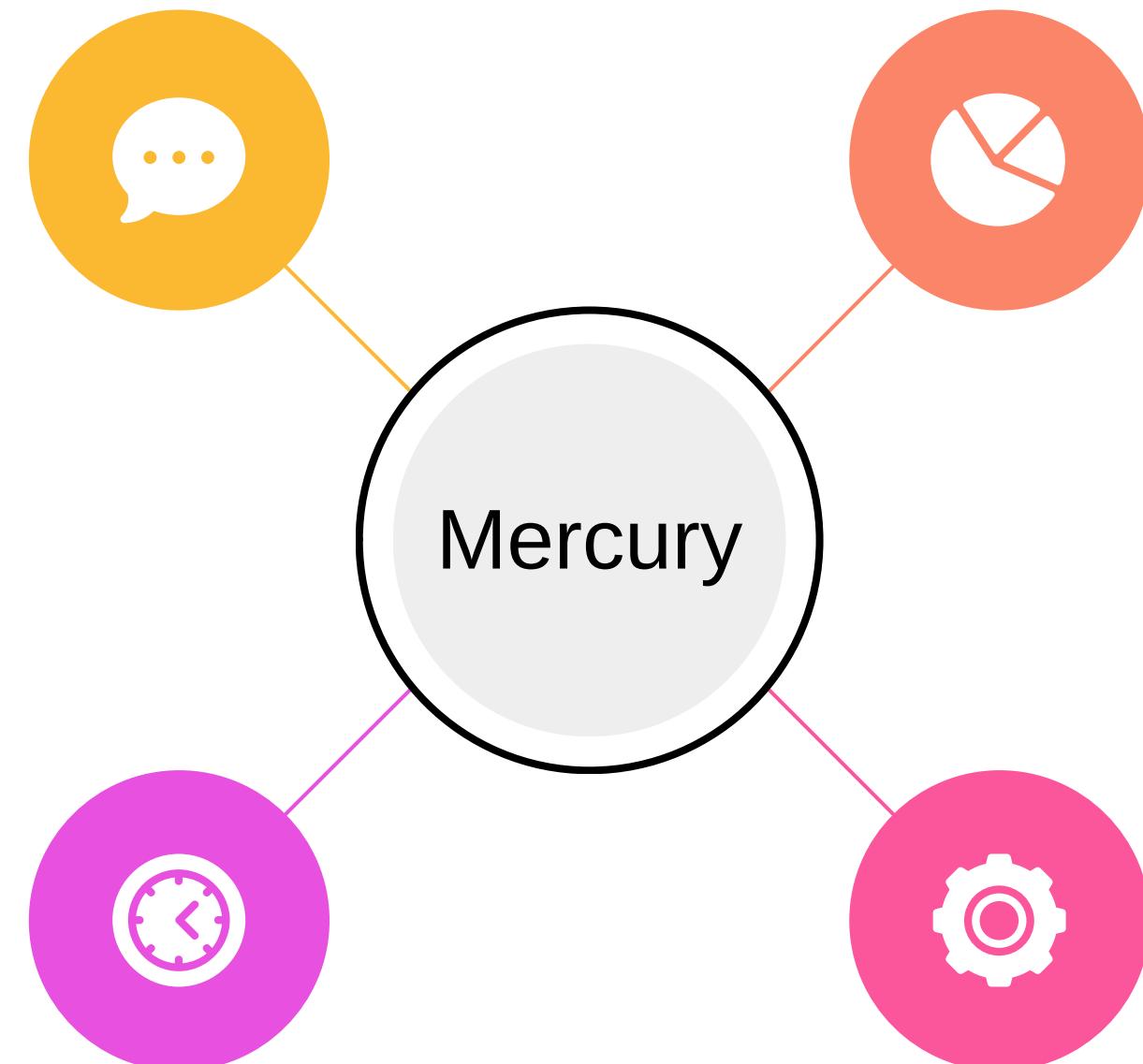
## Neptune

Neptune is the farthest planet from the Sun

# Project Management Infographics

## Mercury

Mercury is the closest planet to the Sun and the smallest one



## Neptune

Neptune is the farthest planet from the Sun and the fourth-largest

## Saturn

Despite being red, Mars is a cold place full of iron oxide dust

## Earth

Earth is the third planet from the Sun and the only one that harbors life

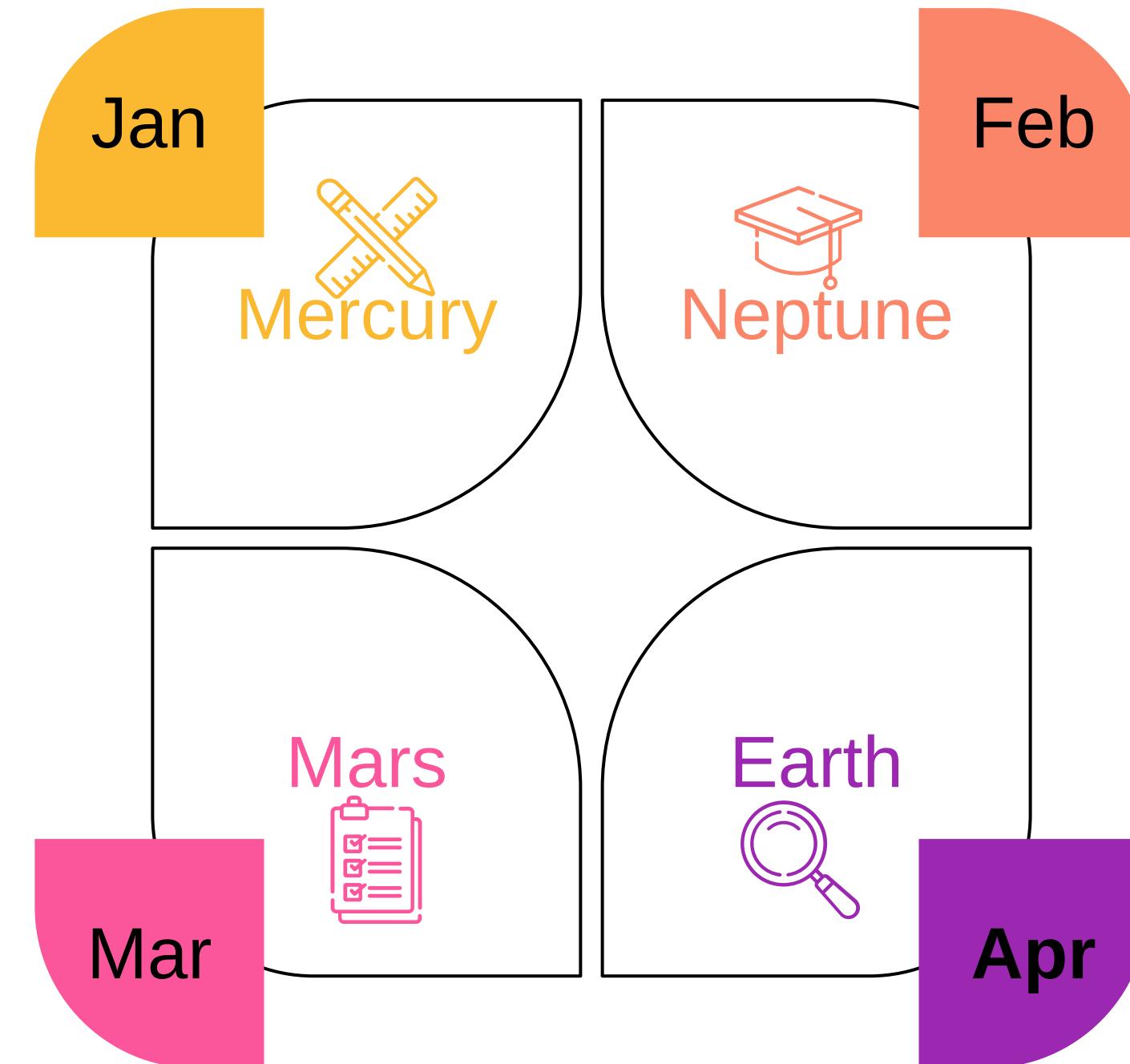
# Project Management Infographics

Mercury is the closest planet to the Sun and the smallest one

Despite being red, Mars is a cold place full of iron oxide dust

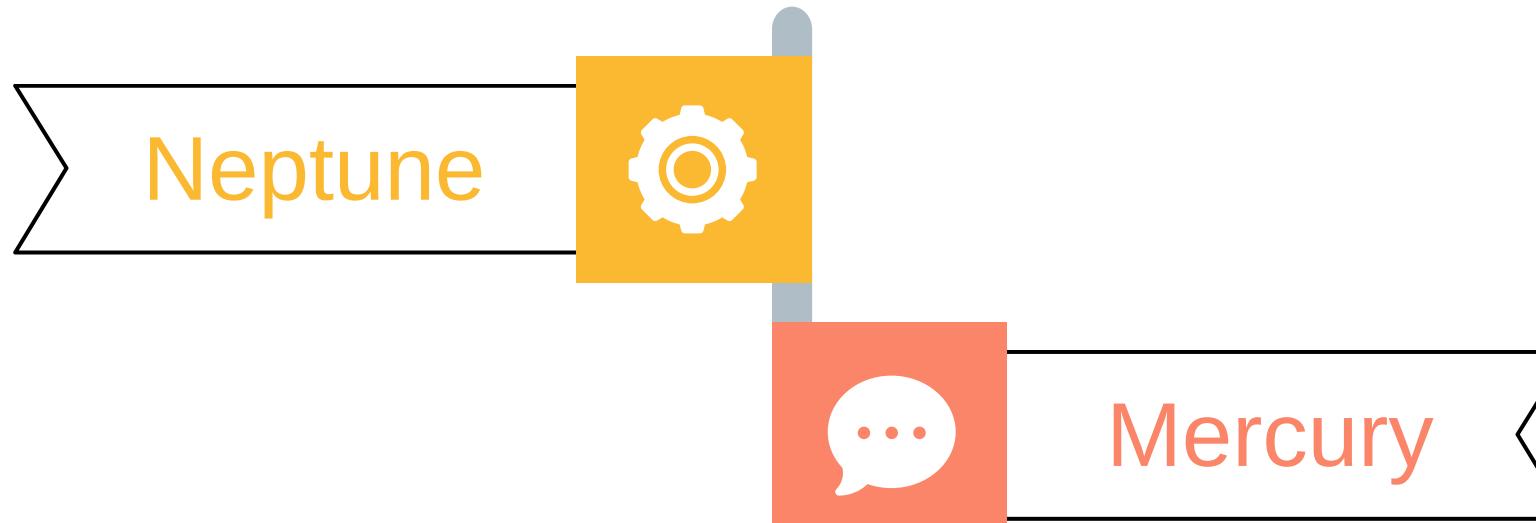
Neptune is the farthest planet from the Sun and the fourth-largest one

Earth is the third planet from the Sun and the only one that harbors life

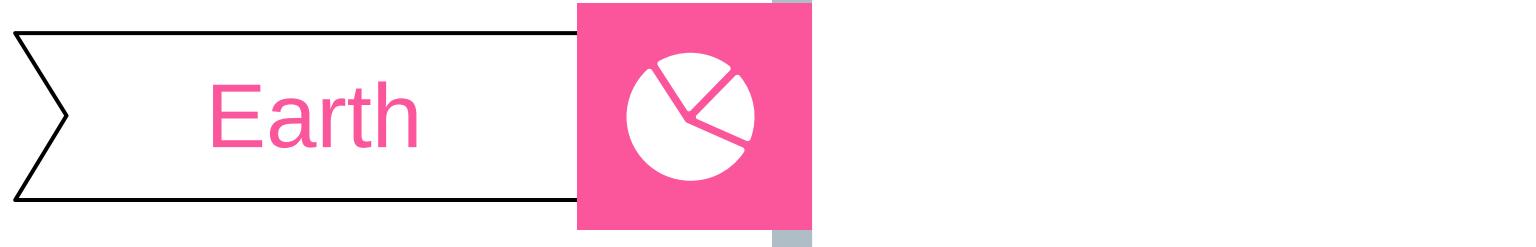


# Project Management Infographics

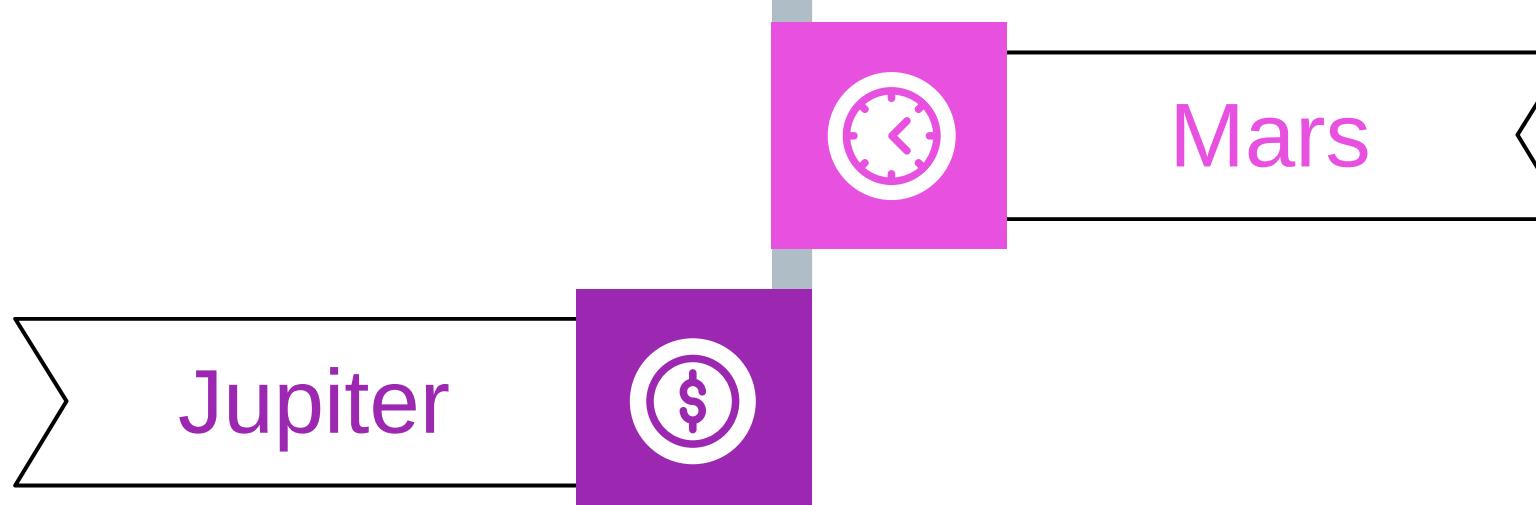
Neptune is the farthest planet from the Sun and a gas giant



Earth is the third planet from the Sun and the one that harbors life



Jupiter is a gas giant and the biggest planet in the Solar System



Mercury is the closest planet to the Sun and the smallest one

Despite being red, Mars is a cold place full of iron oxide dust

# Project Management Infographics

01

Mercury is the closest planet to the Sun



02

Despite being red, Mars is a cold place



03

Jupiter is a gas giant and the biggest planet



04

Neptune is the farthest planet from the Sun



# Project Management Infographics

## Neptune

Neptune is the farthest planet from the Sun and a gas giant



## Mercury

Mercury is the closest planet to the Sun and the smallest

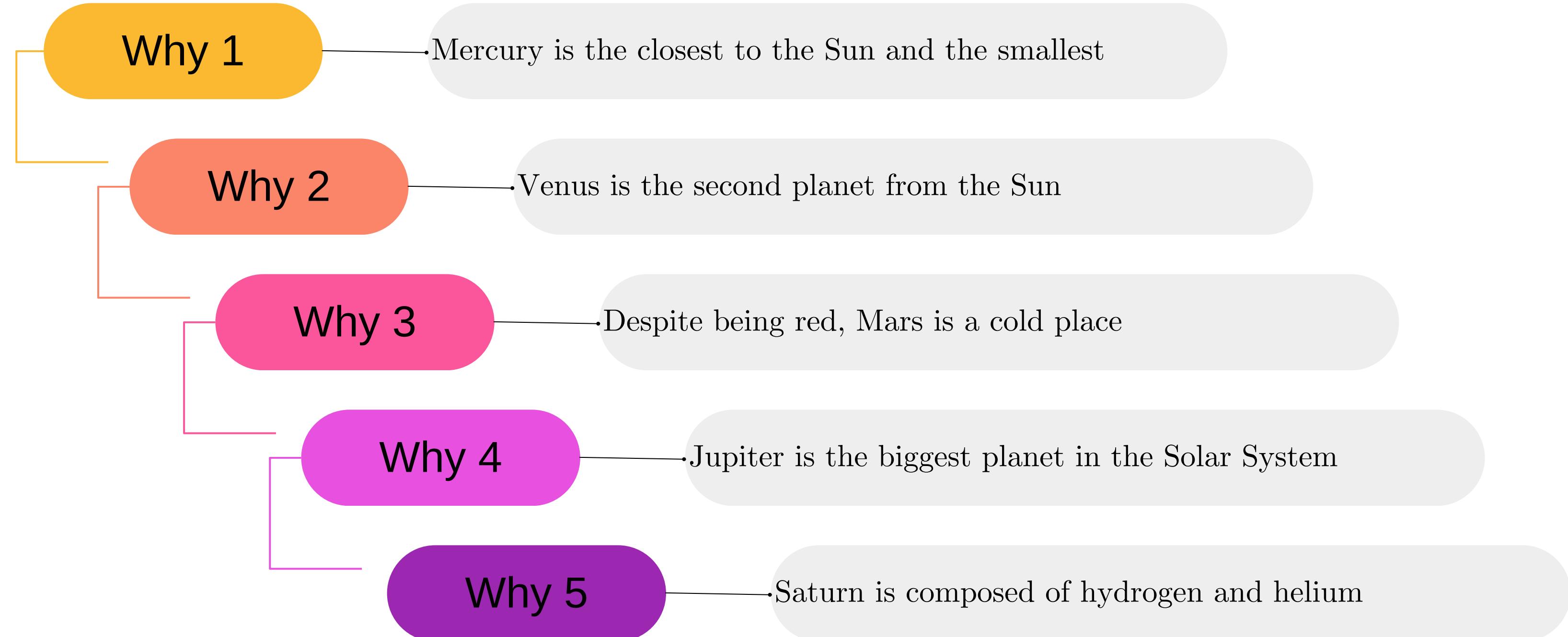
## Earth

Earth is the third planet from the Sun

## Mars

Despite being red, Mars is actually a cold place

# Project Management Infographics



# Project Management Infographics

Neptune is the farthest planet from the Sun and a gas giant



Earth is the third planet from the Sun and the only one that harbors life

Despite being red, Mars is a very cold place full of iron oxide dust

Jupiter is a gas giant and the biggest planet in the Solar System

# Project Management Infographics

Neptune

Neptune is the farthest planet from the Sun and a gas giant

Mercury

Mercury is the closest planet to the Sun

Earth

Earth is the third planet from the Sun

Mars

Despite being red, Mars is actually a cold place



Jupiter

Jupiter is a gas giant and the biggest planet of them all

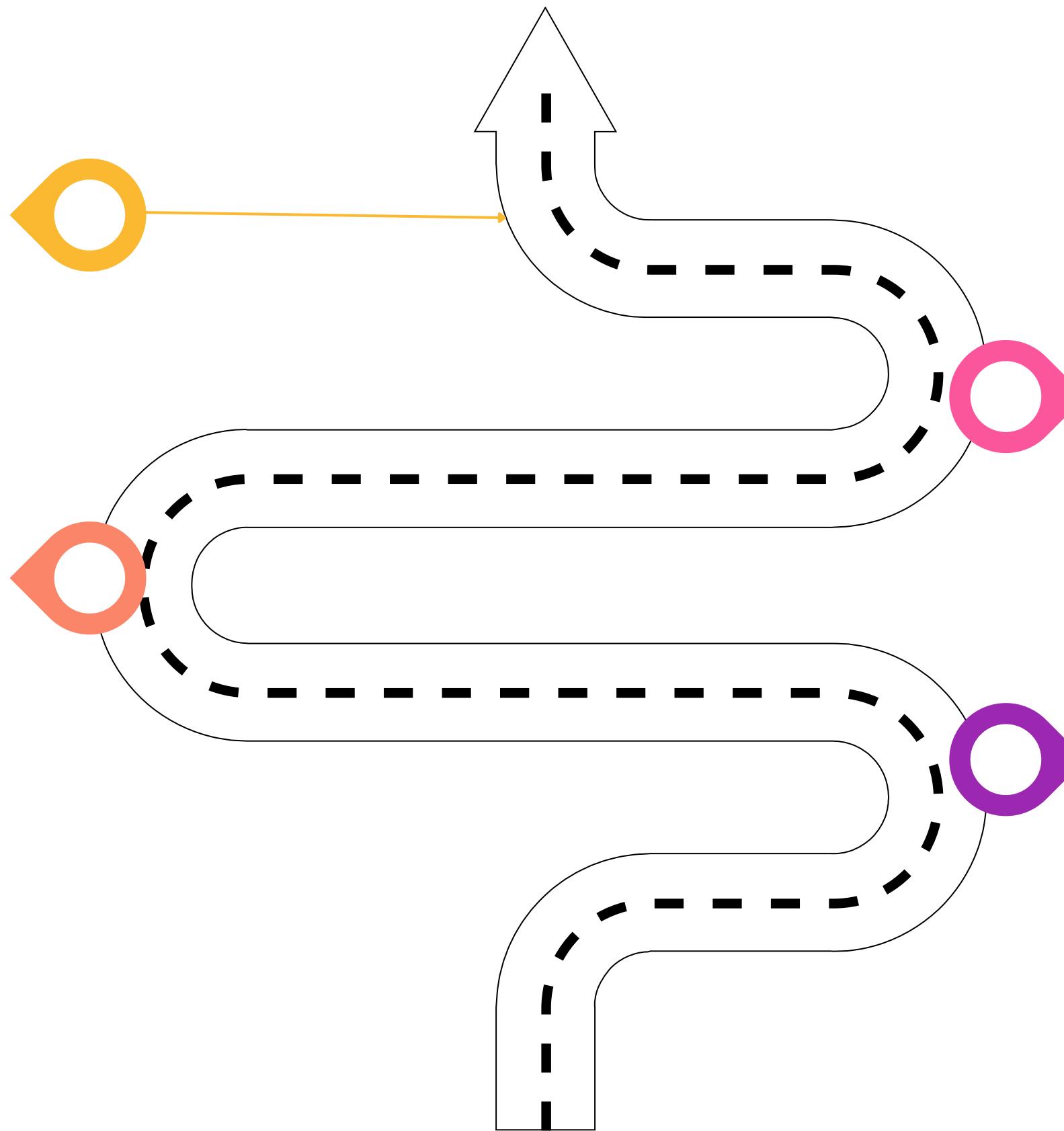
# Project Management Infographics

## Neptune

Neptune is the farthest planet from the Sun

## Saturn

Saturn is composed of hydrogen and helium



## Mars

Despite being red, Mars is a very cold place

## Mercury

Mercury is the closest planet to the Sun

# Project management infographics

## Saturn

Saturn is a gas giant made of hydrogen and helium

## Jupiter

Jupiter is a gas giant and the biggest planet

## Venus

Venus is the second planet from the Sun



## Mercury

Mercury is the smallest planet in the Solar System

## Neptune

Neptune is the farthest planet from the Sun

## Mars

Despite being red, Mars is actually a cold place

# Project Management Infographics

Venus has a beautiful name and is the second planet from the Sun. It's terribly hot—even hotter than Mercury—and its atmosphere is extremely poisonous. It's the second-brightest natural object in the night sky after the Moon

Planet Jupiter is a gas giant and also the biggest one in the Solar System

## Task 1

Mercury is the closest to the Sun and the smallest one in the Solar System

## Task 2

Despite being red, Mars is a very cold place full of iron oxide dust

## Task 3

Earth is the third planet from the Sun and the only one that harbors life

# Project Management Infographics

## Option 1

### Mars

Despite being red,  
Mars is actually a  
cold place



## Option 2

### Jupiter

Jupiter is a gas  
giant and the  
biggest planet



## Option 3

### Saturn

Saturn is a gas  
giant and has  
several rings



## Option 4

### Neptune

Neptune is the  
farthest planet  
from the Sun



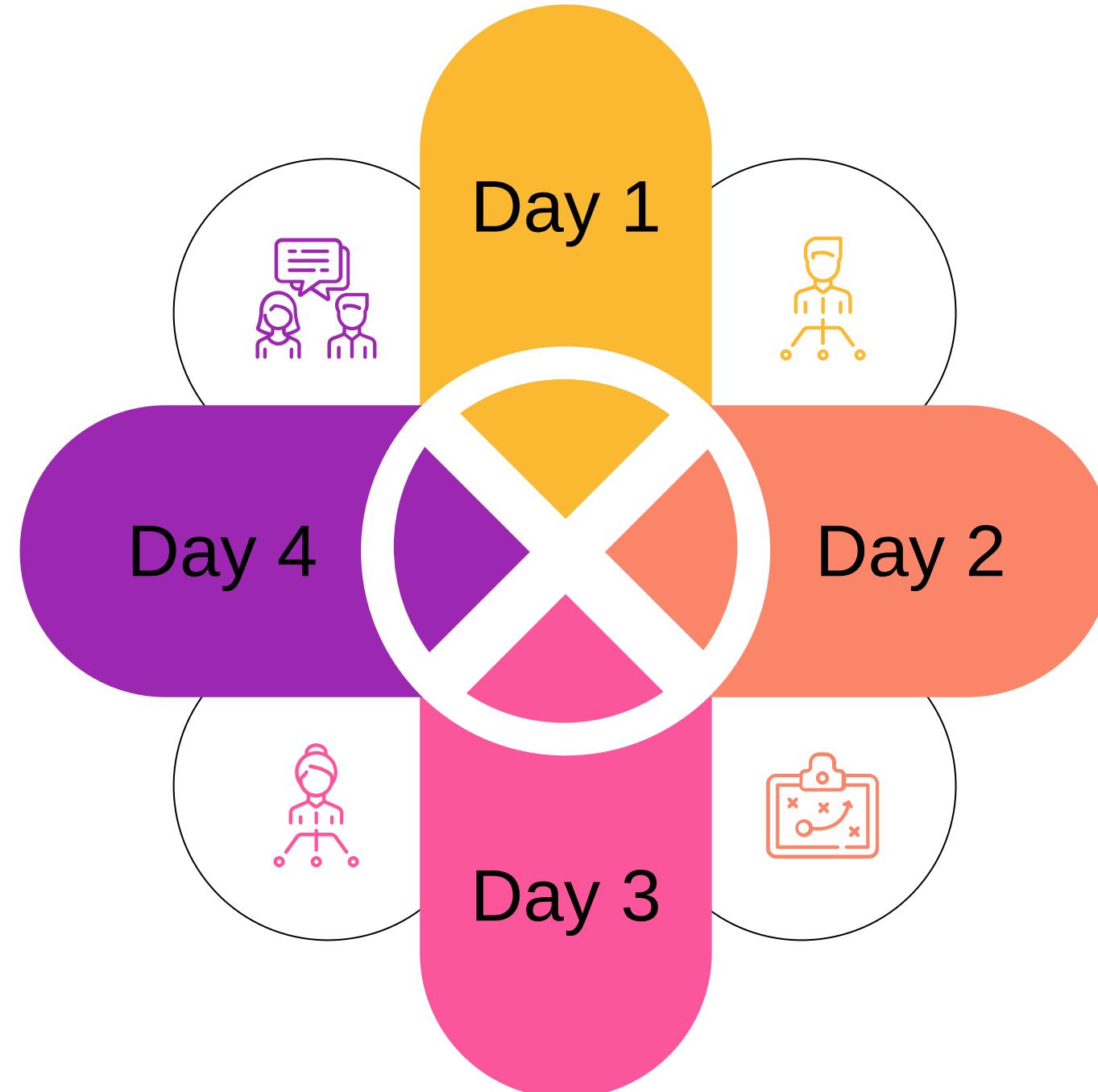
# Project Management Infographics

## Neptune

Neptune is the farthest planet from the Sun and a gas giant

## Earth

Earth is the third planet from the Sun



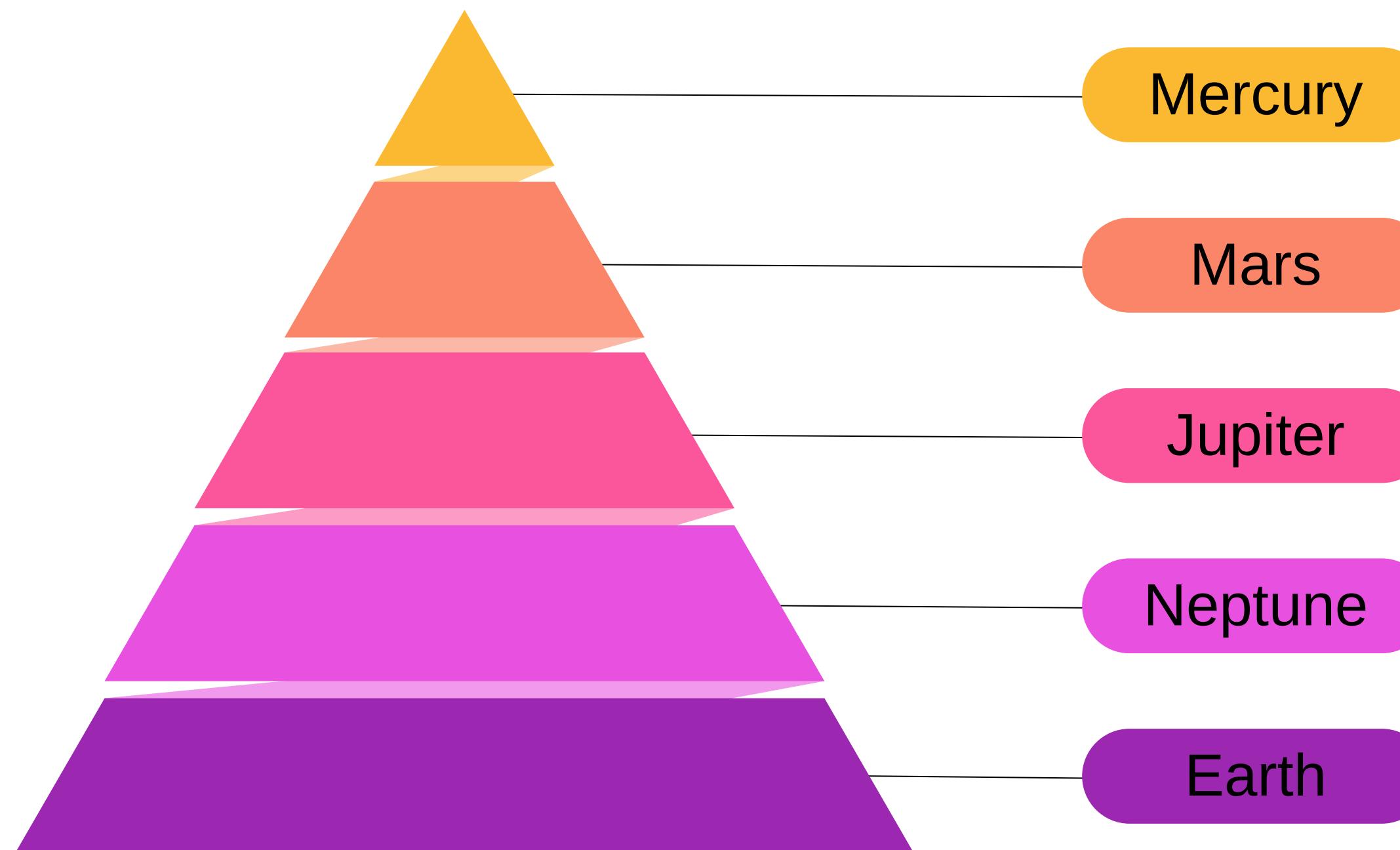
## Mercury

Mercury is the closest planet to the Sun

## Mars

Despite being red, Mars is actually a cold place

# Project Management Infographics



Mercury is the smallest planet in the Solar System

Despite being red, Mars is actually a cold place

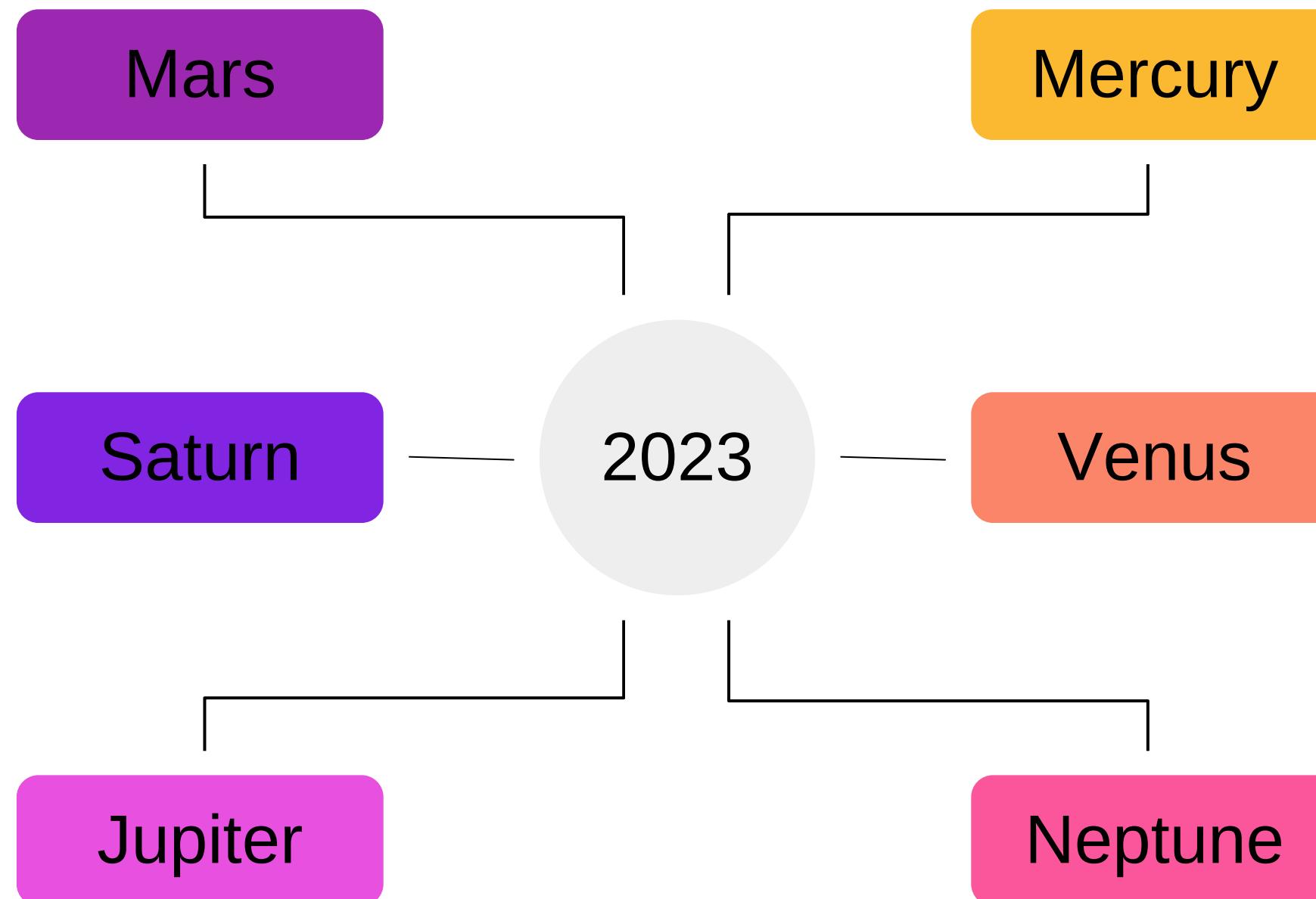
Jupiter is a gas giant and the biggest planet of them all

Neptune is the farthest planet from the Sun and a gas giant

Earth is the third planet from the Sun and the one with life

# Project Management Infographics

Despite being red,  
Mars is actually a  
cold place



Mercury is the  
smallest planet in the  
Solar System

Saturn is composed  
mostly of hydrogen  
and helium

Venus is the second  
planet from the Sun

Planet Jupiter is a  
gas giant and the  
biggest one

Neptune is the  
farthest planet from  
the Sun

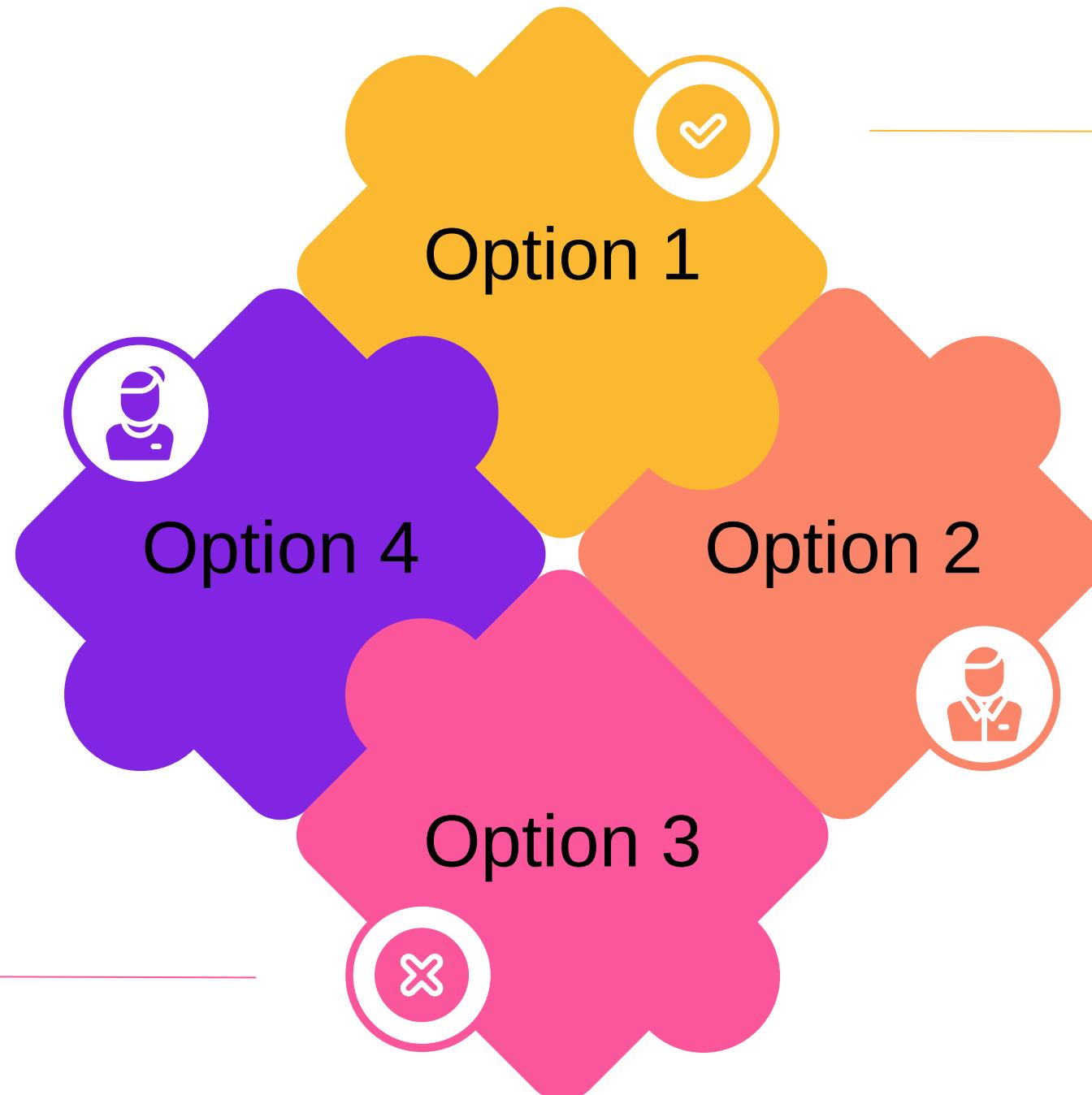
# Project Management Infographics

## Saturn

Saturn is composed of hydrogen and helium

## Jupiter

Jupiter is a gas giant and the biggest planet



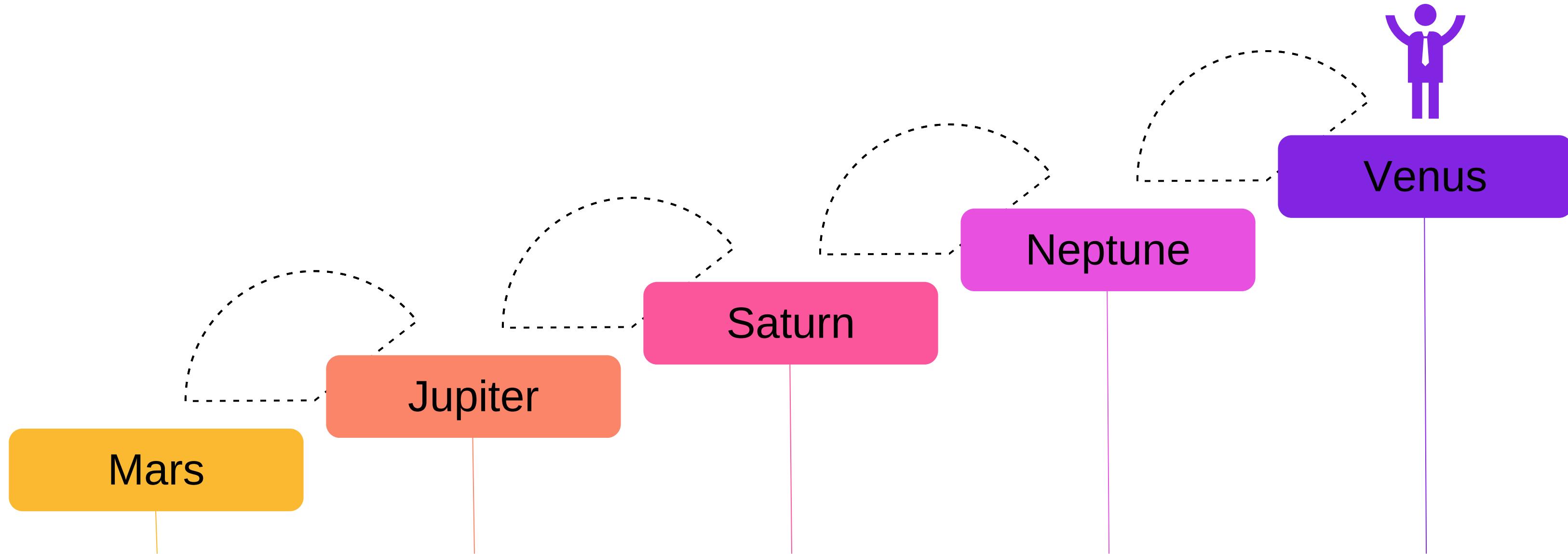
## Mercury

Mercury is the smallest planet in the Solar System

## Neptune

Neptune is the farthest planet from the Sun

# Project Management Infographics



Despite being red,  
Mars is actually a  
cold place

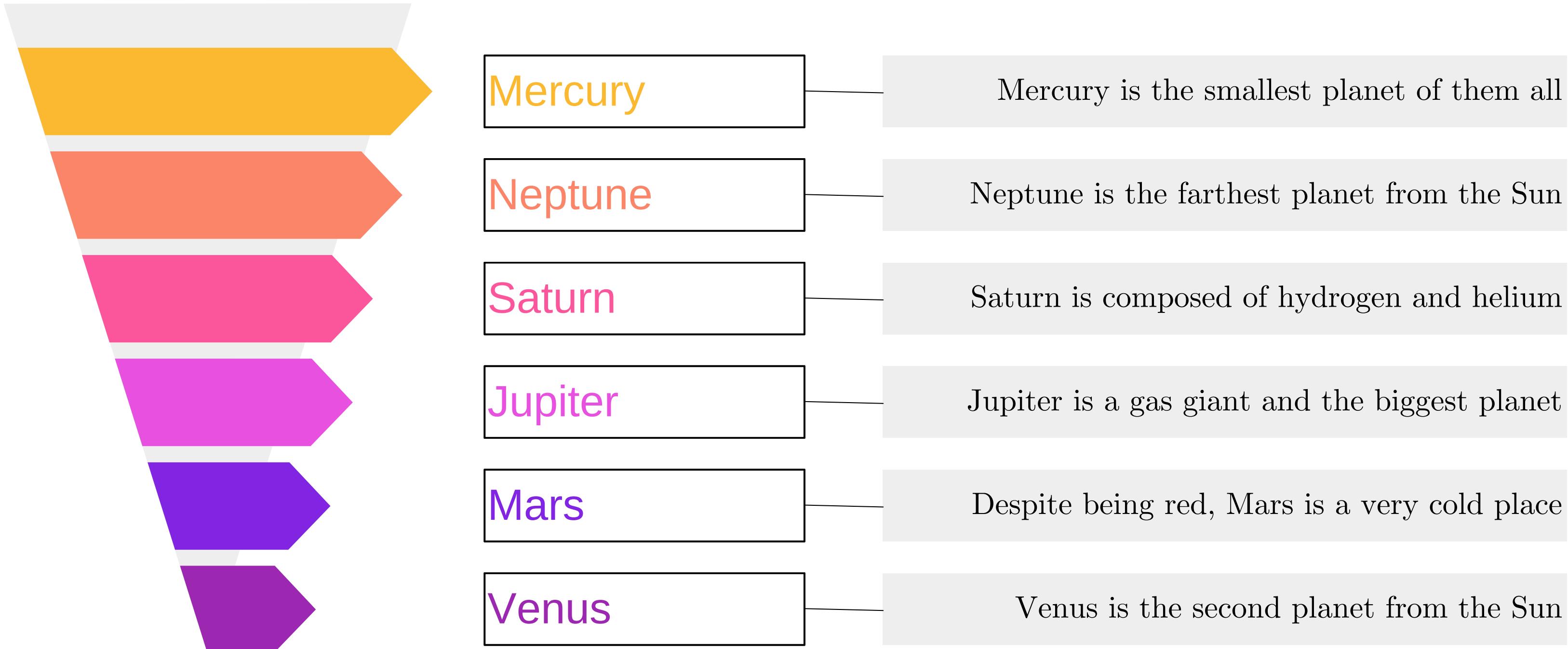
Jupiter is a gas  
giant and also the  
biggest planet

Saturn is a giant  
made of hydrogen  
and helium

Neptune is the  
farthest planet  
from the Sun

Venus is the second  
planet from the Sun

# Project Management Infographics



# Project Management Infographics

01 Saturn



Planet Saturn is a gas giant composed mostly of hydrogen and helium

02 Mercury

Mercury is the smallest planet in the Solar System and the closest to the Sun

03 Mars

Despite being red, Mars is a very cold place full of iron oxide dust

04 Venus

Venus has a beautiful name and is the second planet from the Sun

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- **Change the color** by clicking on the paint bucket.
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# References

A Survey and Taxonomy of Graph Sampling - <https://doi.org/10.48550/arXiv.1308.5865>

Local Graph Sparsification for Scalable Clustering - <https://doi.org/10.1145/1989323.1989399>