

# Maximizing the Cohesion is NP-hard

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INSTITUT NATIONAL DE RECHERCHE EN INFORMATIQUE ET EN AUTOMATIQUE

## *Maximizing the Cohesion is NP-hard*

Adrien Friggeri — Eric Fleury

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*Rapport  
de recherche*



## Maximizing the Cohesion is NP-hard

Adrien Friggeri , Eric Fleury

Thème : Réseaux et télécommunications  
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**Abstract:** We show that the problem of finding a set with maximum cohesion in an undirected network is **NP**-hard.

**Key-words:** social networks, complex networks, cohesion, np-complete, complexity

## Maximiser la Cohésion est NP-dur

**Résumé :** Nous montrons que le problème de trouver un ensemble de cohésion maximum dans un graphe non orienté est **NP**-dur.

**Mots-clés :** réseaux sociaux, réseaux complexes, cohésion, np-complet, complexité

## Introduction

In [1], we have introduced a new metric called the *cohesion* which rates the community-ness of a group of people in a social network from a sociological point of view. Through a large scale experiment on Facebook, we have established that the cohesion is highly correlated to the subjective user perception of the communities. In this article, we show that finding a set of vertices with maximum cohesion is **NP**-hard.

## Notations

Let  $G = (V, E)$  be a graph with vertex set  $V$  and edge set  $E$  of size  $n = |V| \geq 4$ . For all vertices  $u \in V$ , we write  $d_G(u)$  the degree of  $u$ , or more simply  $d(u)$ <sup>1</sup>. A *triangle* in  $G$  is a triplet of pairwise connected vertices.

For all sets of vertices  $S \subseteq V$ , let  $G[S] = (S, E_S)$  be the subgraph induced by  $S$  on  $G$ . We write  $m(S) = |E_S|$  the number of edges in  $G[S]$ , and  $i(S) = |\{(u, v, w) \in S^3 : (uv, vw, uw) \in E^3\}|$  the number of triangles in  $G[S]$ . We define  $o(S) = |\{(u, v, w), (u, v) \in S^2, w \in V \setminus S : (uv, vw, uw) \in E^3\}|$ , the number of *outbound* triangles of  $S$ , that is: triangles in  $G$  which have exactly two vertices in  $S$ .

Moreover, for all  $(u, v)$  in  $E$ , let  $\Delta(uv) = |\{w \in V : (uw, vw) \in E^2\}|$  be the number of triangles the edge  $uv$  belongs to in  $G$ .

Finally, we recall the definition of the cohesion of a set  $S$  in  $G$ :

$$\mathcal{C}(S) = \frac{i(S)^2}{\binom{|S|}{3}(i(S) + o(S))}$$

An example is given on Figure 1. The cohesion of a given set  $S$  in  $G$  can naively be computed in  $\mathcal{O}(n^3)$  by listing all triangles in  $G$  and counting those inside and outbound to  $S$ .

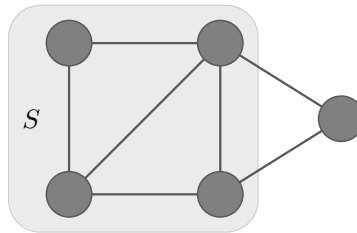


Figure 1: In this example,  $i(S) = 2$  and  $o(S) = 1$ , thus  $\mathcal{C}(S) = \frac{1}{6}$

In this article we examine the problem of finding a set of vertices  $S \subseteq V$  of maximum cohesion, i.e. for all subset  $S' \subseteq V$ ,  $\mathcal{C}(S') \leq \mathcal{C}(S)$ .

## Outline

We now proceed to prove that finding a set of vertices with maximum cohesion in  $G$  is **NP**-hard. We will first show in Section 1 that this problem is equivalent

<sup>1</sup>Here, as elsewhere, we drop the index referring to the underlying graph if the reference is clear.

to that of finding a connected set of vertices with maximum cohesion in  $G$ . The decision problem associated to the latter is **CONNECTED-COHESIVE**.

Then, we shall prove that **CONNECTED-COHESIVE** is **NP**-complete by reducing **CLIQUE** (problem GT19 in [2]). From there we deduce that the optimization problem of finding a set of vertices with maximum cohesion is **NP**-hard.

### Problems

1. **CONNECTED-COHESIVE**:

**Input** A graph  $G = (V, E)$ ,  $\lambda \in \mathbb{Q}$ ,  $\lambda \in [0, 1]$

**Question** Is there a subset connected  $S$  of  $V$  such that  $\mathcal{C}(S) \geq \lambda$ ?

2. **CLIQUE**:

**Input** A graph  $G = (V, E)$ ,  $k \in \mathbb{N}$ ,  $k \leq |V|$

**Question** Is there a subset  $S$  of  $V$  such that  $|S| = k$  and the subgraph induced by  $S$  is a clique?

## 1 A maximum cohesive group is connected

In order to prove that a set of vertices with maximum cohesion in a given network is connected, we need the following lemma:

**Lemma 1.1.** *Let  $S_1 \subseteq V$  and  $S_2 \subseteq V$  be two disconnected sets of vertices ( $(S_1 \times S_2) \cap E = \emptyset$ ). If  $\mathcal{C}(S_1) \leq \mathcal{C}(S_1 \cup S_2)$  then  $\mathcal{C}(S_2) > \mathcal{C}(S_1 \cup S_2)$ .*

*Proof.* Suppose  $\mathcal{C}(S_1) \leq \mathcal{C}(S_1 \cup S_2)$  and  $\mathcal{C}(S_2) \leq \mathcal{C}(S_1 \cup S_2)$ . Given that  $S_1$  and  $S_2$  are disconnected,  $i(S_1 \cup S_2) = i(S_1) + i(S_2)$  and  $o(S_1 \cup S_2) = o(S_1) + o(S_2)$ . We can then write:

$$\frac{i(S_1)^2}{\binom{|S_1|}{3}} \leq (i(S_1) + o(S_1))\mathcal{C}(S_1 \cup S_2) \quad (1)$$

$$\frac{i(S_2)^2}{\binom{|S_2|}{3}} \leq (i(S_2) + o(S_2))\mathcal{C}(S_1 \cup S_2) \quad (2)$$

By summing (1) and (2), we obtain:

$$\begin{aligned} \frac{i(S_1)^2}{\binom{|S_1|}{3}} + \frac{i(S_2)^2}{\binom{|S_2|}{3}} &\leq (i(S_1) + o(S_1) + i(S_2) + o(S_2))\mathcal{C}(S_1 \cup S_2) \\ &\leq (i(S_1 \cup S_2) + o(S_1 \cup S_2))\mathcal{C}(S_1 \cup S_2) \\ &\leq \frac{(i(S_1) + i(S_2))^2}{\binom{|S_1| + |S_2|}{3}} \end{aligned}$$

Furthermore, given that  $|S_1|, |S_2| > 1$ ,

$$\binom{|S_1|}{3} + \binom{|S_2|}{3} < \binom{|S_1| + |S_2|}{3}$$

We then have:

$$\frac{i(S_1)^2}{\binom{|S_1|}{3}} + \frac{i(S_2)^2}{\binom{|S_2|}{3}} < \frac{(i(S_1) + i(S_2))^2}{\binom{|S_1|}{3} + \binom{|S_2|}{3}}$$

Which simplifies to:

$$\left( \binom{|S_2|}{3} i(S_1) - \binom{|S_1|}{3} i(S_2) \right)^2 < 0$$

Hence the contradiction. Therefore, for all  $S_1, S_2 \subseteq V$ , disconnected:

$$\mathcal{C}(S_1) \leq \mathcal{C}(S_1 \cup S_2) \Rightarrow \mathcal{C}(S_2) > \mathcal{C}(S_1 \cup S_2) \quad \square$$

**Theorem 1.2.** *Let  $S$  be the set of vertices of  $G$  with the highest cohesion,  $S$  is connected.*

*Proof.* Suppose  $S$  is not connected, then there exist two disconnected subsets  $S_1, S_2 \subseteq S$  such that  $S = S_1 \cup S_2$ . Given that  $S$  has maximum cohesion, we have  $\mathcal{C}(S) \geq \mathcal{C}(S_1)$ . Thus per Lemma 1.1:  $\mathcal{C}(S) < \mathcal{C}(S_2)$  and  $S$  does not have the highest cohesion, hence the contradiction.  $\square$

**Corollary 1.3.** *Per Theorem 1.2, the problem of searching for a set of vertices with maximum cohesion is strictly equivalent to that of searching a set of connected vertices with maximum cohesion.*

## 2 CONNECTED-COHESIVE is NP-complete

First note that given a set  $S$  of vertices of  $G$ , it is possible to verify that  $S$  is a solution of CONNECTED-COHESIVE by computing its cohesion, its size, its connectivity and the minimum degree of its vertices, all in polynomial time. Therefore CONNECTED-COHESIVE is in **NP**.

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**Algorithm 1** Transforms an instance of CLIQUE in an instance of CONNECTED-COHESIVE

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**Require:**  $G = (V, E), k \in \mathbb{N}$

- 1:  $W := \emptyset$
  - 2:  $E' := E$
  - 3: **for**  $uv \in V^2 \setminus E$  **do**
  - 4:   let  $K$  be a clique of size  $2\binom{n}{3}^4$
  - 5:    $W \leftarrow W \cup K$
  - 6:    $E' \leftarrow E' \cup \{uv\} \cup (\{u, v\} \times K)$
  - 7: **end for**
  - 8: **return**  $G' = (V \cup W, E'), \lambda = \frac{\binom{k}{3}}{\binom{k}{3} + \binom{k}{2}(n-k)}$
- 

Let us now reduce CLIQUE to CONNECTED-COHESIVE. Let  $(G = (V, E), k \in \mathbb{N})$  be an instance of CLIQUE<sup>2</sup>. We can assume that  $G$  is connected (if not, we

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<sup>2</sup>We consider here that  $|G| > 2$  and  $k > 2$ , although this is not exactly CLIQUE, this problem is clearly **NP**-complete, given that the complexity of CLIQUE does not arise from those small values.



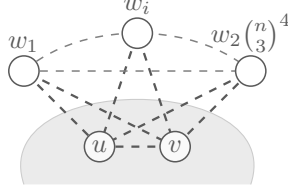


Figure 2: Illustration of Algorithm 1. At this step, we join  $u$  and  $v$ , add a clique of size  $2\binom{n}{3}^4$  to the network, and join  $u$  and  $v$  to all vertices in the added clique.

use the following reasoning separately on each connected component of  $G$ ). We construct an instance  $(G' = (V', E'), \lambda)$  of CONNECTED-COHESIVE by adding an edge between all non connected vertices  $u$  and  $v$  in  $G$  and then linking those two vertices to all vertices in a clique of size  $2\binom{n}{3}^4$  which we add to the network, as described in Algorithm 1 and illustrated by Figure 2.

**Theorem 2.1.** *There exist a clique of size  $k$  in  $G$  iff there exist a connected group of vertices of  $G'$  with cohesion  $\lambda \geq \frac{\binom{k}{3}}{\binom{k}{3} + \binom{k}{2}(n-k)}$ .*

*Proof.* Let  $K \subseteq V$ , be a clique of size  $|K| = k$  in  $G$ . Given that no node or edges are deleted when constructing  $G'$ ,  $G$  is a subgraph of  $G'$  and thus  $K$  is a clique in  $G'$  and  $i_{G'}(K) = \binom{k}{3}$ .

Moreover, by construction,  $G'[V]$  is a clique and for all  $u$  un  $K$ , the neighbors of  $u$  are also in  $V$ . Therefore, each edge in  $K$  forms one triangle with each vertex in  $V \setminus K$ , which leads to  $o_{G'}(K) = \binom{k}{2}(n-k)$ . Finally, this gives a cohesion:

$$\mathcal{C}_{G'}(K) = \frac{\binom{k}{3}}{\binom{k}{3} + \binom{k}{2}(n-k)}$$

Conversely, let  $S \subseteq V'$  be a connected set of vertices such that  $\mathcal{C}_{G'}(S) \geq \frac{\binom{k}{3}}{\binom{k}{3} + \binom{k}{2}(n-k)}$ . We will show that  $S$  is a clique of size larger than  $k$  and that  $S \subseteq V$ . First note that  $|S| \geq 3$ , because by definition, if  $|S| < 3$ ,  $\mathcal{C}_{G'}(S) = 0$  which would lead to a contradiction.

First, suppose that  $S$  is not a clique in  $G$ , then let us distinguish two cases:

1. If  $S \subseteq V$  and  $S$  is not a clique, then  $S$  contains two vertices  $u, v \in V^2$  such that  $uv \notin E$ .
2. If  $S \not\subseteq V$ , then  $\exists u \in S \setminus V$ , and  $S$  being connected, there exist  $v \in V'$  such that  $uv \notin E$ .

Therefore, if  $S$  is not a clique in  $G$ , it contains an edge  $uv \notin E$  and by construction, this edge belongs to at least  $2\binom{n}{3}^4$  triangles, which leads to:

$$\begin{aligned} i_{G'}(S) + o_{G'}(S) &\geq K \\ \mathcal{C}_{G'}(S) &\leq \frac{i_{G'}(S)^2}{2\binom{|S|}{3}\binom{n}{3}^4} \\ &\leq \frac{1}{2\binom{n}{3}^2} \\ &< \frac{\binom{k}{3}}{\binom{k}{3} + \binom{k}{2}(n-k)} \end{aligned}$$

Hence the contradiction, therefore  $S$  must be a clique in  $G$ . From there it comes that:

$$\mathcal{C}_{G'}(S) = \frac{\binom{k'}{3}}{\binom{k'}{3} + \binom{k'}{2}(n-k')}$$

where  $k' = |S|$ . Therefore:

$$\begin{aligned} \mathcal{C}_{G'}(S) \geq \frac{\binom{k}{3}}{\binom{k}{3} + \binom{k}{2}(n-k)} &\Leftrightarrow \frac{\binom{k'}{2}(n-k')}{\binom{k'}{3}} \leq \frac{\binom{k}{2}(n-k)}{\binom{k}{3}} \\ &\Leftrightarrow \frac{n-k'}{k'-3} \leq \frac{n-k}{k-3} \\ &\Leftrightarrow k' \geq k \end{aligned}$$

Therefore, we can now conclude that if there exist a connected set  $S$  in  $G'$  with cohesion  $\mathcal{C}_{G'}(S) \geq \frac{\binom{k}{3}}{\binom{k}{3} + \binom{k}{2}(n-k)}$ , then  $S$  is a clique of size at least  $k$  in  $G$ , and thus there exist a clique  $K \subseteq S$  of size  $k$  in  $G$ .  $\square$

**Theorem 2.2.** CONNECTED-COHESIVE is NP-complete.

*Proof.* Per Theorem 2.1, there exist a clique of size  $k$  in  $G$  iff there exist a connected subset of vertices of  $G'$  of cohesion  $\lambda \geq \frac{\binom{k}{3}}{\binom{k}{3} + \binom{k}{2}(n-k)}$  and the transformation from  $G, k$  to  $G', \lambda$  runs in polynomial time. Thus CLIQUE is reducible to CONNECTED-COHESIVE and CONNECTED-COHESIVE is NP-hard.

Given that CONNECTED-COHESIVE is in NP, the problem is thus NP-complete.  $\square$

### 3 Conclusion

The associated decision problem being NP-complete, the problem of finding a set of vertices with maximum cohesion is NP-hard<sup>3</sup>.

<sup>3</sup>Note that the problem of finding a set of vertices of maximum cohesion containing a set of predefined vertices is also NP-hard, by an immediate reduction

## References

- [1] Adrien Friggeri, Guillaume Chelius, and Eric Fleury. Triangles to Capture Social Cohesion. In *Third IEEE International Conference on Social Computing*, Cambridge, United States, September 2011.
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