Dense sub-graphs

Introduction to Network Science
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Topic 13

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Sources

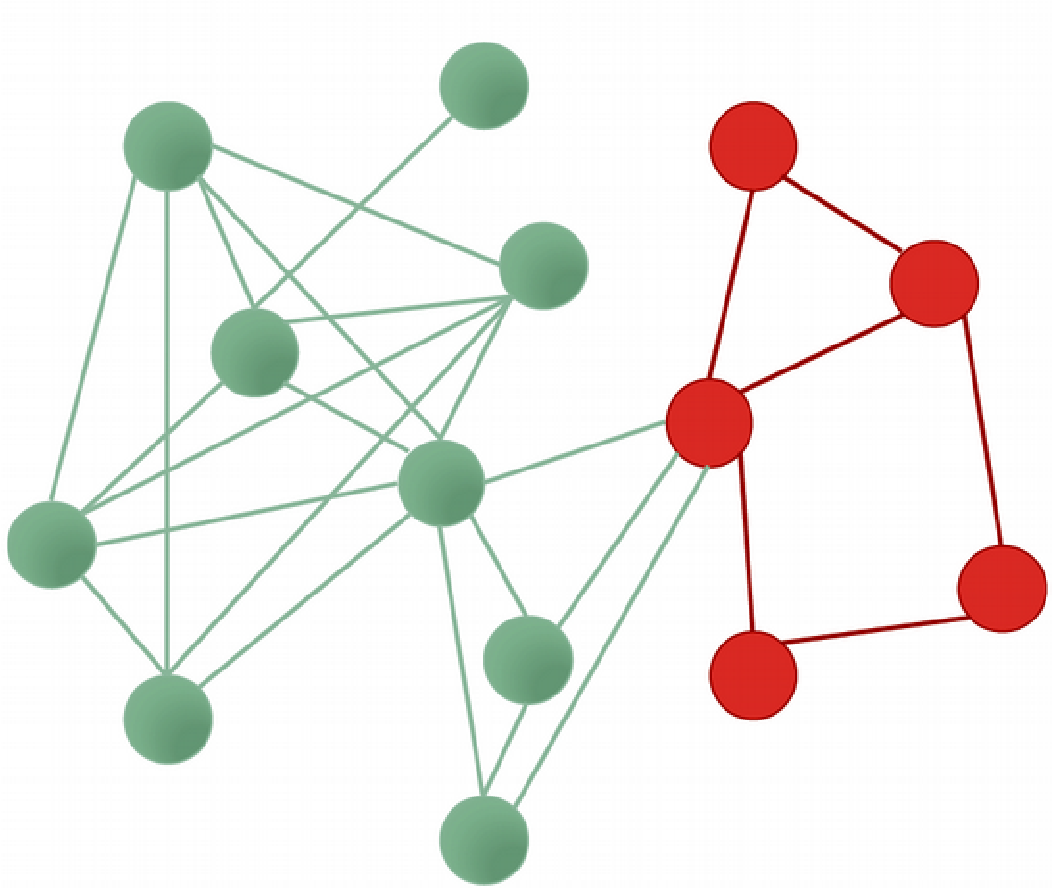
- Barabási 2016 Chapter 9
- Networks, Crowds, and Markets Ch 3
- C. Castillo (2017) Dense Sub-Graphs
- Tutorial by A. Beutel, L. Akoglu, C. Faloutsos [Link]
- Frieze, Gionis, Tsourakakis: "Algorithmic techniques for modeling and mining large graphs (AMAzING)" [Tutorial]
- A survey of algorithms for dense sub-graph discovery [link]

Communities

2 communities	[previous topic]
1 community	**[this topic]**
3+ communities	[next topic]

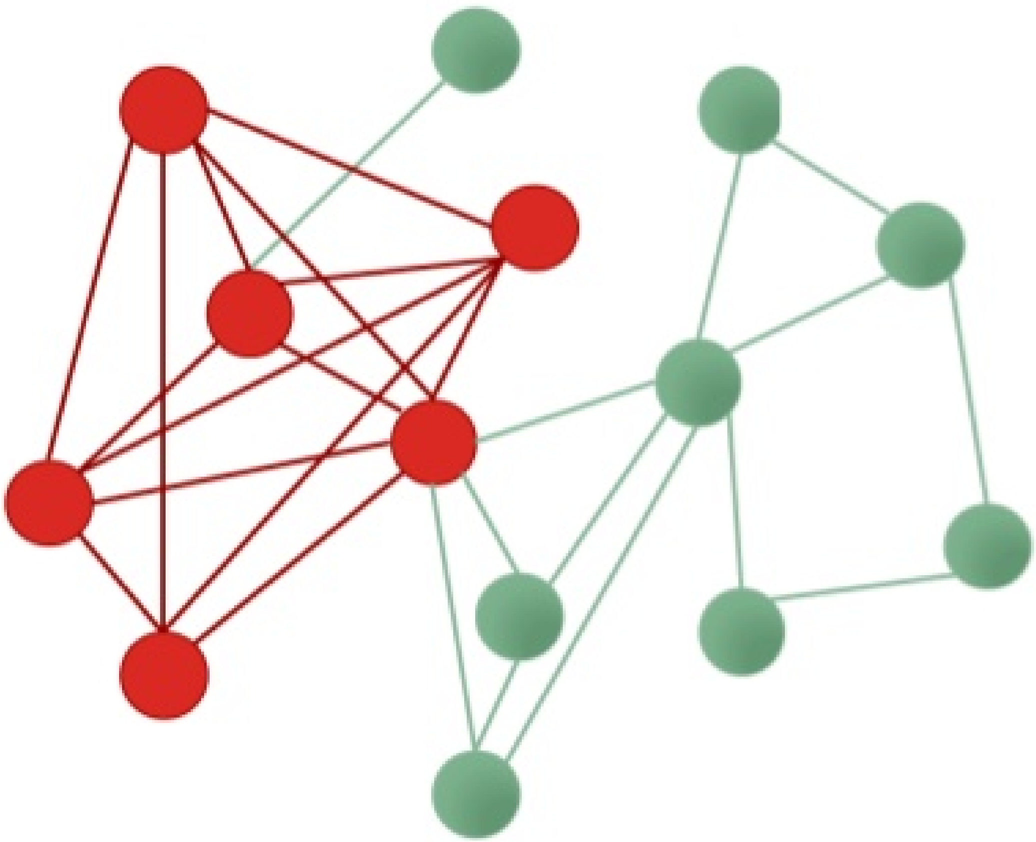
What is a sub-graph?

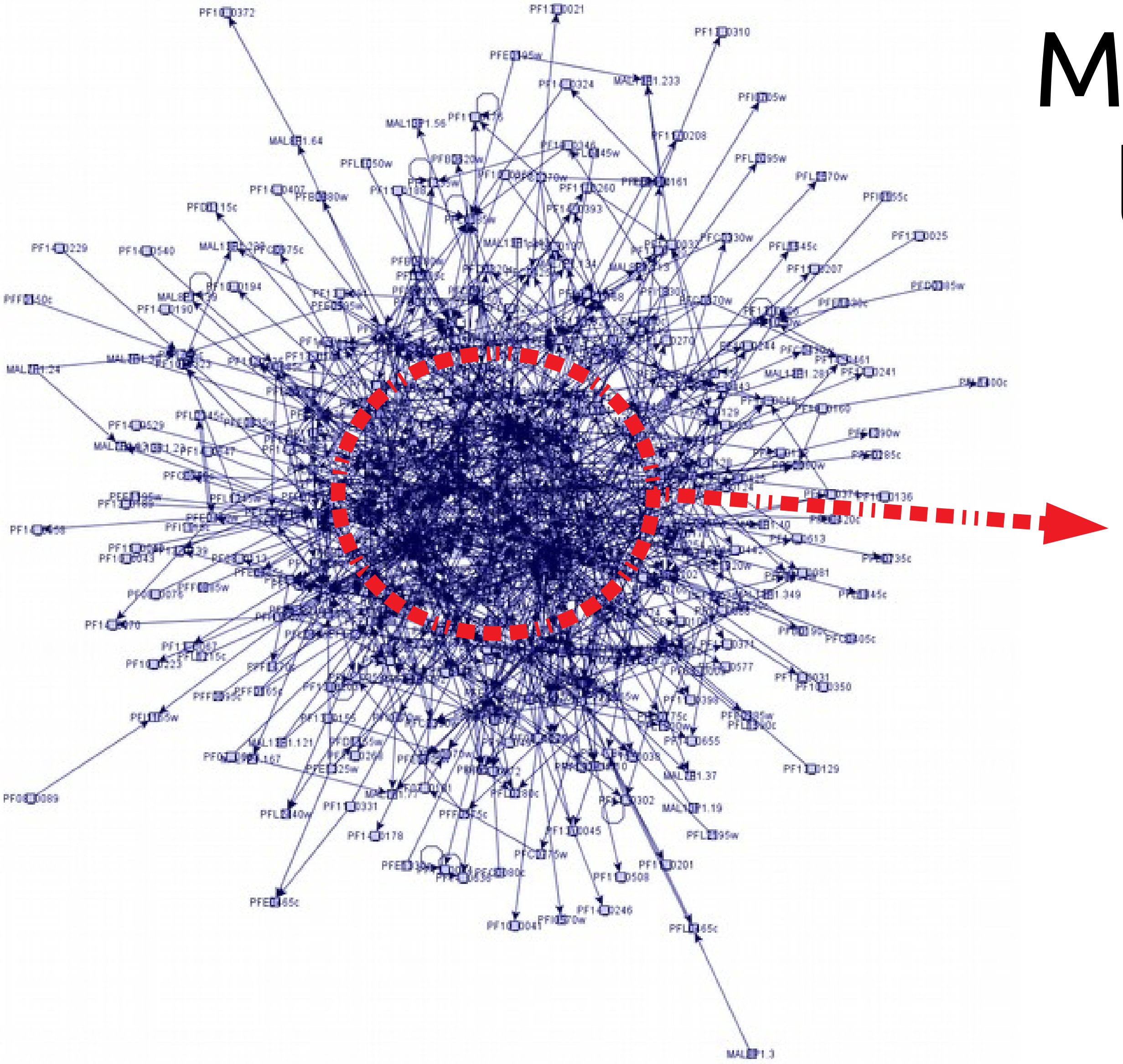
Subset of nodes, and edges among those nodes



Densest sub-graph

Sub-graph having the maximum density





Many graphs look like "hairballs"

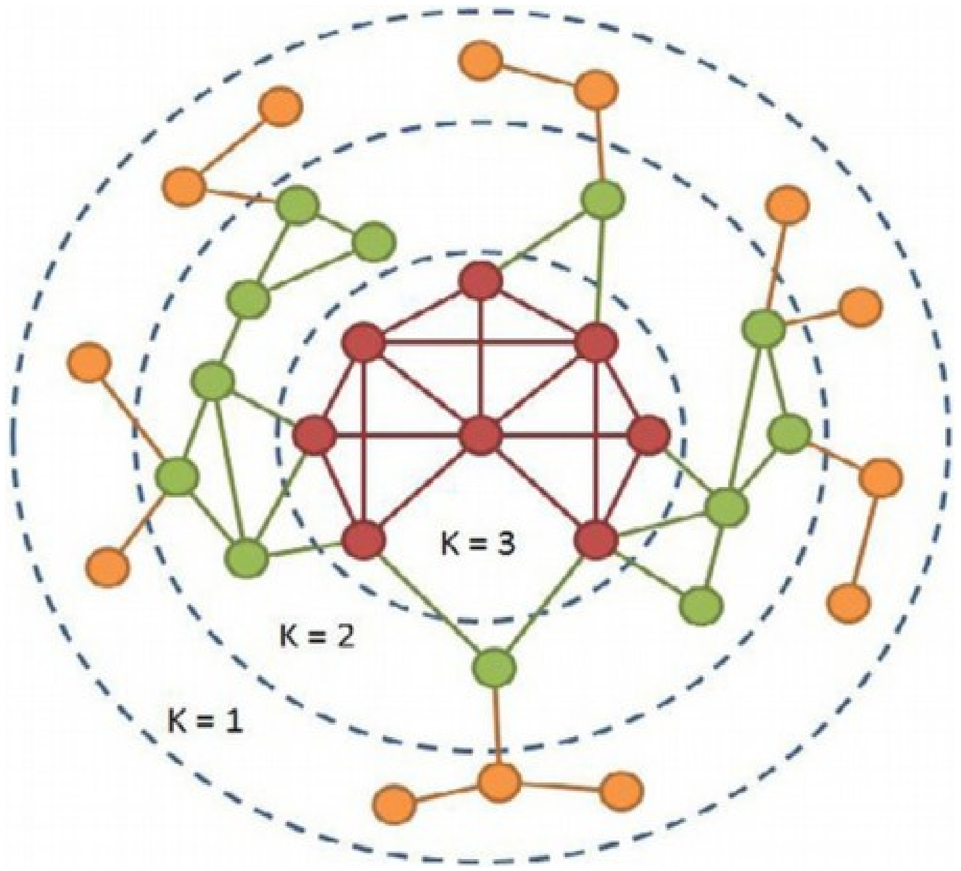
Sometimes, at the center these graphs may have an interesting dense sub-graph

k-core decomposition

k-core decomposition

- Remove all nodes having degree 1
  - Those are in the 1-core
- Remove all nodes having degree 2 *in the remaining graph*
  - Those nodes are in the 2-core
- Remove all nodes having degree 3 *in the remaining graph*
  - Those nodes are in the 3-core
- Etc.

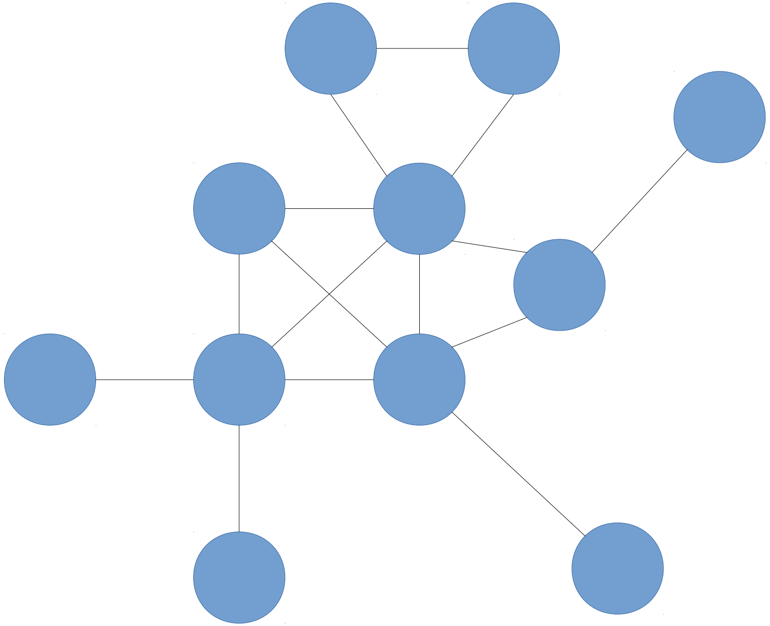
Example



https://openi.nlm.nih.gov/detailedresult.php?img=3368241_fnagi-04-00013-g0001&req=4

Try it!

How many nodes are there in each core of this graph?



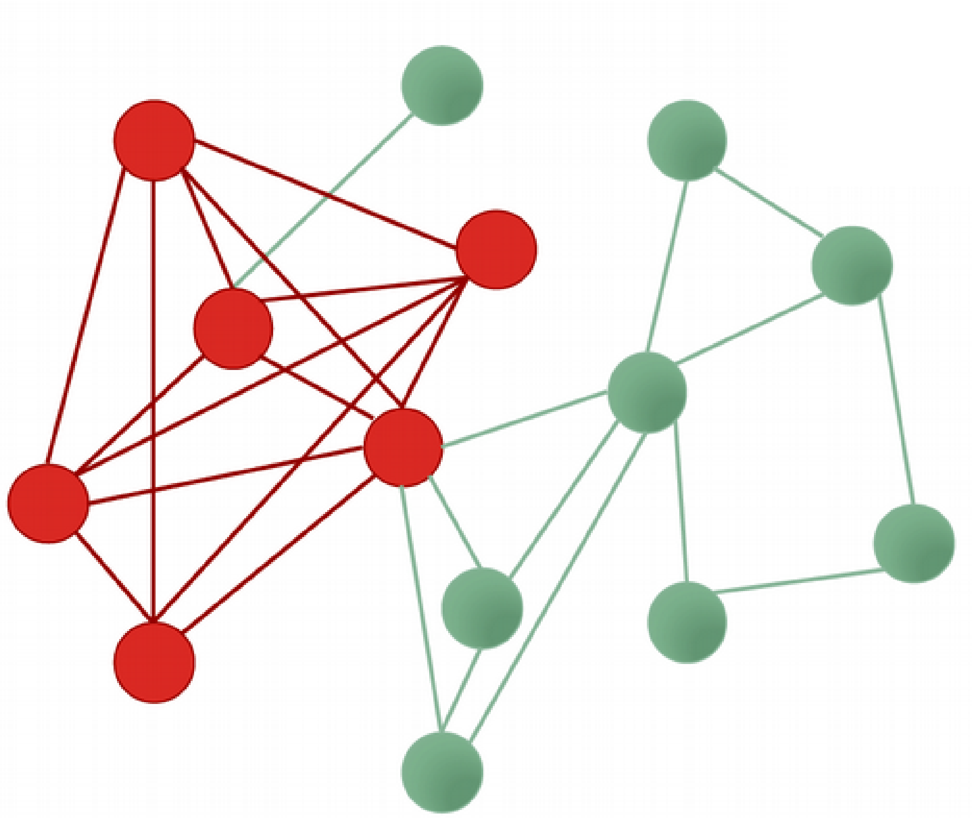
http://www.cpt.univ-mrs.fr/~barrat/NHM.pdf

Density-based methods

Density measures

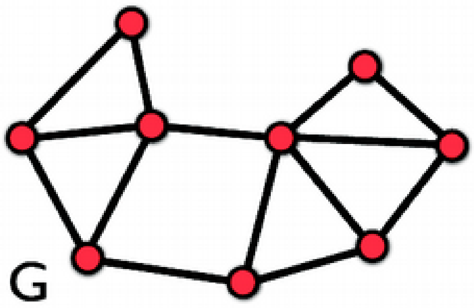
- Density = Average degree = $2|E|/|V|$
  - Sometimes just $|E|/|V|$
- Edge ratio = $$\frac{2|E|}{|V|(|V|-1)}$$
- What is $|V|(|V|-1)/2$?

Densest sub-graph



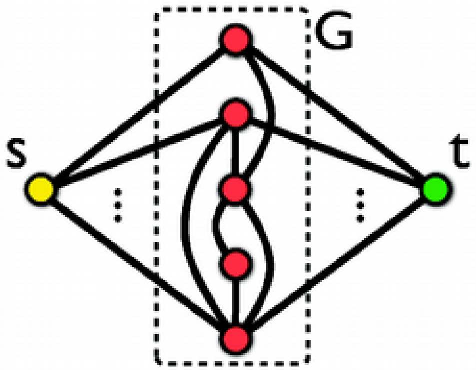
Goldberg's algorithm (1)

- consider first degree density d



- is there a subgraph S with $d(S) \geq c$?
- transform to a min-cut instance

- on the transformed instance:
- is there a cut smaller than a certain value?



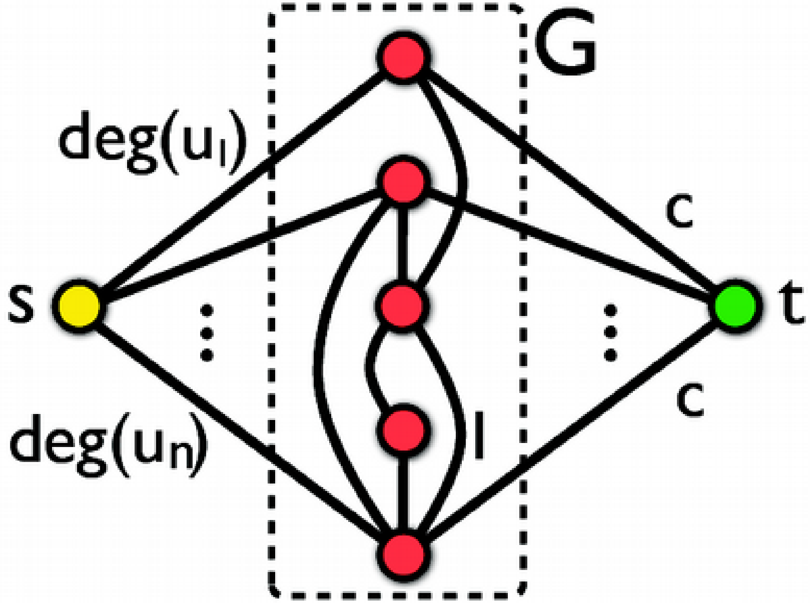
Goldberg's algorithm (2)

is there S with $d(S) \geq c$?

$$
\begin{aligned}
\frac{2\,|E(S,S)|}{|S|} &\geq c \\
2\,|E(S,S)| &\geq c|S| \\
\sum_{u \in S} \deg(u) - |E(S,\bar{S})| &\geq c|S| \\
\sum_{u \in S} \deg(u) + \sum_{u \in \bar{S}} \deg(u) - \sum_{u \in \bar{S}} \deg(u) - |E(S,\bar{S})| &\geq c|S| \\
\sum_{u \in \bar{S}} \deg(u) + |E(S,\bar{S})| + c|S| &\leq 2\,|E|
\end{aligned}
$$

Goldberg's algorithm (3)

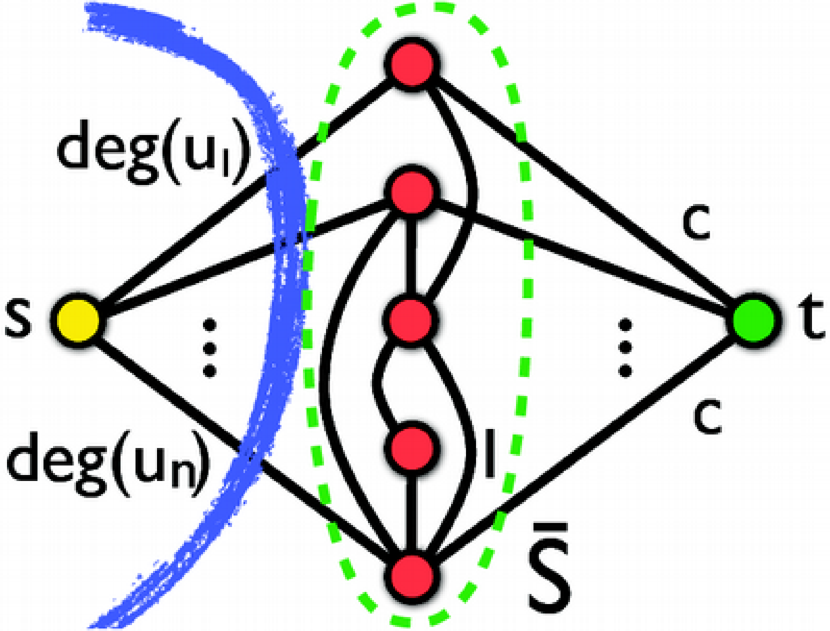
- transformation to min-cut instance



- is there S s.t. $\sum_{u \in \bar{S}} \deg(u) + |e(S, \bar{S})| + c|S| \leq 2|E|$?

Goldberg's algorithm (4)

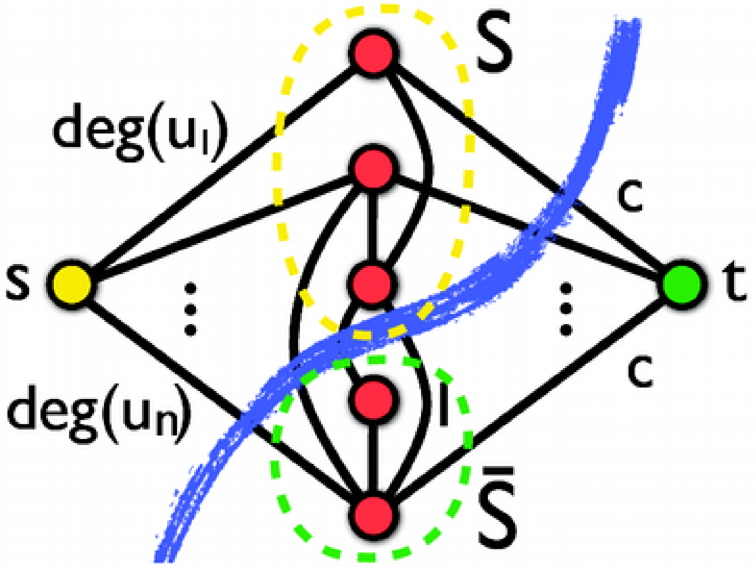
- transform to a min-cut instance



- is there S s.t. $\sum_{u \in \bar{S}} \deg(u) + |e(S, \bar{S})| + c|S| \leq 2|E|$?
- a cut of value $2|E|$ always exists, for $S = \emptyset$

Goldberg's algorithm (5)

- transform to a min-cut instance



- is there S s.t. $\sum_{u \in \bar{S}} \deg(u) + |e(S, \bar{S})| + c|S| \leq 2|E|$?
- $S \neq \emptyset$ gives cut of value $\sum_{u \in \bar{S}} \deg(u) + |e(S, \bar{S})| + c|S|$

If this exists for non-empty S, then S is a sub-graph of density c

Goldberg's algorithm (6)

- to find the densest subgraph perform binary search on c
  - logarithmic number of min-cut calls
  - each min-cut call requires O(|V||E|) time
- problem can also be solved with one min-cut call using the parametric max-flow algorithm

A faster algorithm

- Charikar, M. (2000). Greedy approximation algorithms for nding dense components in a graph. In APPROX.
- Approximate algorithm (by a factor of 2)

Greedy algorithm

input: undirected graph $G = (V, E)$
output: S, a dense subgraph of G

1 set $G_n \leftarrow G$
2 for $k \leftarrow n$ downto 1
2.1 let v be the smallest degree vertex in G_k
2.2 $G_{k-1} \leftarrow G_k \setminus \{v\}$
3 output the densest subgraph among $G_n, G_{n-1}, \ldots, G_1$

Compute density as |V|/|E|

Try it!

Compute density as |V|/|E|

input: undirected graph $G = (V, E)$
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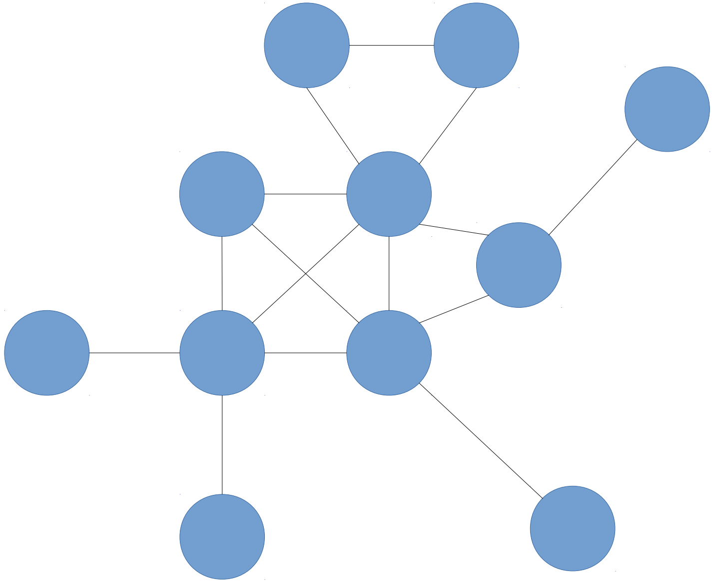

Approximation guarantee

- S^* = optimal sub-graph (highest density)
- density(S_*) = λ = $|e(S_*)| / |S_*|$
- For all v in S*, deg(v) >= λ, because

$$\frac{|e(S^*)|}{|S^*|} \geq \frac{|e(S^* \backslash v)|}{|S^* \backslash v|} = \frac{|e(S^*)| - deg_{S^*}(v)}{|S^*| - 1}$$

Because of optimality of S*

https://people.cs.umass.edu/~barna/paper/dense-subgraph-full.pdf

Approximation guarantee (cont)

$$\frac{|e(S^*)|}{|S*|} \geq \frac{|e(S*\backslash v)|}{|S*\backslash v|} = \frac{|e(S^*)| - deg_{S^*}(v)}{|S*| - 1}$$

Hence,

$$deg_{S^*}(v) \geq \frac{|e(S^*)|}{|S*|} = d(S^*) = \lambda$$

Approximation guarantee (cont.)

- Now, let's consider when greedy removes the **first** vertex of the optimal solution $v \in S^*$
- At that point, all the vertices of the remaining subgraph (S) have degree >= λ, because v has degree >= λ
- Hence, this subgraph has more than $\frac{\lambda|S|}{2}$ edges, and density more than $\frac{\frac{\lambda|S|}{2}}{|S|} = \frac{\lambda}{2}$

Hence this is a 2-approximate algorithm