

Notes on the SDP relaxation of k -means

The SDP relaxation of k -means

Iguchi et al.¹ formulated a semidefinite programming approach to k -means as follows²:

$$\begin{aligned} \arg \max_Z & -\text{Tr}(D_2 Z) \\ \text{s.t. } & \text{Tr}(Z) = k \\ & Ze = e \\ & Z \geq 0 \text{ element-wise} \\ & Z \text{ is positive semidefinite} \end{aligned}$$

Where

- $D_2 = [d_{ij}] = [\|x_i - x_j\|^2]$
- $x_1, \dots, x_n \in \mathbb{R}^q$
- The number of clusters, k , is known
- $e = \begin{bmatrix} 1 \\ \vdots \\ 1 \end{bmatrix} \in \mathbb{R}^q$

Note that without the SDP relaxation, we have a rigid structure for Z where $z_{ij} = \begin{cases} n_k^{-1} & x_i, x_j \text{ in same cluster } k \\ 0 & \text{else} \end{cases}$

Equating the trace formulation of k -means to kernel k -means

We can see that the data matrix $X = \begin{bmatrix} x_1^\top \\ \vdots \\ x_n^\top \end{bmatrix}$ is not explicitly in the objective, although squared Euclidean distances are. We can rewrite this as a kernel formulation by noting that $D_2 = \kappa(B)$ where B is a kernel matrix³:

¹<https://arxiv.org/abs/1505.04778>

²the notation is slightly different here

³In the following steps we use the fact that Z is symmetric, $Ze = e$, $e^\top Z = e^\top$, and $e^\top e = n$

$$\begin{aligned}
-\text{Tr}(D_2 Z) &= -\text{Tr}(\kappa(B)Z) \\
&= -\text{Tr}((be^\top - 2B + eb^\top)Z) \\
&= 2\text{Tr}(BZ) - \text{Tr}(be^\top Z) - \text{Tr}(eb^\top Z) \\
&= 2\text{Tr}(BZ) - \text{Tr}(be^\top) - \text{Tr}(Zeb^\top) \\
&= 2\text{Tr}(BZ) - \text{Tr}(be^\top) - \text{Tr}(eb^\top) \\
&= 2\text{Tr}(BZ) - 2\text{Tr}(be^\top) \\
&= 2\text{Tr}(BZ) - 2\text{Tr}(B)
\end{aligned}$$

... where $b = \text{diag}(B)$, the vector of diagonal entries of B . Note that if we think of B as a weight matrix for an undirected graph, $\text{Tr}(B) = 0$. Similarly, if we impose that the diagonal entries of B are equal to 1 (e.g., B is a correlation matrix), then $\text{diag}(B) = n$. Either way, $\text{Tr}(B)$ does not depend on Z , so we can ignore it in the objective, and we can see that $-\arg \max_Z \text{Tr}(D_2 Z) = \arg \max_Z \text{Tr}(BZ)$, which is just the typical kernel formulation of k -means:

$$\begin{aligned}
&\arg \max_Z \text{Tr}(BZ) \\
&\text{s.t. } \text{Tr}(Z) = k \\
&\quad z_{ij} = \begin{cases} n_k^{-1} & x_i, x_j \text{ in same cluster } k \\ 0 & \text{else} \end{cases}
\end{aligned}$$

Similarly, we can go from a kernel formulation of k -means to one based on squared Euclidean distances by noting that $D_2 = \tau(B)$. For simplicity of notation, we will rewrite $\arg \max_x f(x) = \arg \max_x 2f(x)$.

$$\begin{aligned}
2\text{Tr}(BZ) &= 2\text{Tr}(\tau(D_2)Z) \\
&= \text{Tr}(-PD_2PZ) \\
&= -\text{Tr}((I - n^{-1}ee^\top)D_2(I - n^{-1}ee^\top)Z) \\
&= -\text{Tr}((D_2 - n^{-1}D_2ee^\top - n^{-1}ee^\top D_2 + n^{-2}ee^\top ee^\top D_2)Z) \\
&= -\text{Tr}(D_2 Z) + n^{-1}\text{Tr}(D_2 ee^\top Z) + n^{-1}\text{Tr}(ee^\top D_2 Z) - n^{-1}\text{Tr}(ee^\top D_2 Z) \\
&= -\text{Tr}(D_2 Z) + 2n^{-1}\text{Tr}(D_2 ee^\top) - n^{-1}\text{Tr}(D_2 ee^\top) \\
&= -\text{Tr}(D_2 Z) + n^{-1}\text{Tr}(D_2 ee^\top)
\end{aligned}$$

Since the second and third terms do not depend on Z , we can discard them, and we get $\arg \max_Z \text{Tr}(BZ) = \arg \max_Z -\text{Tr}(D_2 Z)$.⁴

Equating the SDP relaxation of k -means to the SDP relaxation of ratio cut

The ratio cut objective is:

$$\arg \min_Z \text{Tr}(LZ)$$

⁴We can rewrite $\text{Tr}(D_2 ee^\top) = \sum_{i,j} d_{ij}^2 = 2 \sum_{i < j} d_{ij}^2$

where L is the combinatorial graph Laplacian and Z has the same structure as before. If we relax the optimization problem by not enforcing Z to have this structure, we can see that:

$$\arg \min_Z \text{Tr}(LZ) = \arg \max_Z \text{Tr}(L^\dagger Z)$$

where L^\dagger is the generalized inverse of L . Since L^\dagger is positive semidefinite, it can be thought of as a kernel matrix, and we can apply the $\tau(\cdot)$ transformation to it to obtain D_2 . In this case, D_2 is the expected commute time of the graph that generated L .

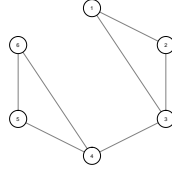
The argmin and argmax equivalence is not true in general if we force Z to have the structure that we want. It also is not true if we apply the SDP constraints (namely $Z \geq 0$ element-wise). One question of interest is under what conditions can we equate the two objectives under the SDP constraints.

Examples

Example 1

Here we look at a case where $\arg \min_Z \text{Tr}(LZ) = \arg \max_Z \text{Tr}(L^\dagger Z)$ under the SDP restrictions ($Ze = e$, $\text{Tr}(Z) = k$, Z is positive semidefinite, $Z \geq 0$ element-wise). In fact, in this example, not only do the two problems have the same solution, the solution coincides with the solution to the unrelaxed ratio cut problem.

Here we have a very simple graph with just six vertices. The “intuitive cut” for $k = 2$ is the 3 – 4 cut, which happens to also be the solution to the (fully constrained) ratio cut problem.



The RatioCut-SDP solution (Ling and Strohmer)⁵ yields:

```
rc.sdp(L, k = 2)$Z %>%
  MASS::fractions()
```

	[,1]	[,2]	[,3]	[,4]	[,5]	[,6]
[1,]	1/3	1/3	1/3	0	0	0
[2,]	1/3	1/3	1/3	0	0	0
[3,]	1/3	1/3	1/3	0	0	0
[4,]	0	0	0	1/3	1/3	1/3
[5,]	0	0	0	1/3	1/3	1/3
[6,]	0	0	0	1/3	1/3	1/3

The k -means SDP solution using L^\dagger as a kernel matrix (adapted from Peng and Wei)⁶ yields:

```
kmeans.sdp(L.dagger, k = 2)$Z %>%
  MASS::fractions()
```

	[,1]	[,2]	[,3]	[,4]	[,5]	[,6]
[1,]	1/3	1/3	1/3	0	0	0
[2,]	1/3	1/3	1/3	0	0	0
[3,]	1/3	1/3	1/3	0	0	0

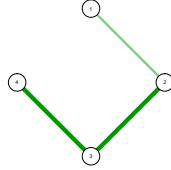
⁵<https://arxiv.org/abs/1806.11429>

⁶http://www.optimization-online.org/DB_FILE/2005/04/1114.pdf

[4,]	0	0	0	1/3	1/3	1/3
[5,]	0	0	0	1/3	1/3	1/3
[6,]	0	0	0	1/3	1/3	1/3

Example 2

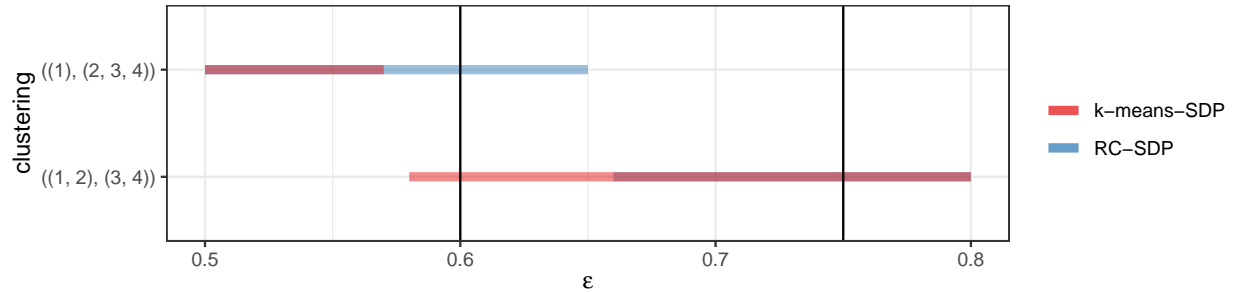
Let's try the epsilon graph example from the text. This graph has four vertices connected in series by three edges. The 2 – 3 and 3 – 4 edges have weight 1 but the 1 – 2 edge has weight $\epsilon \in (0, 1)$.



Recall that the graph Laplacian is of the form

$$\begin{bmatrix} \epsilon & -\epsilon & 0 & 0 \\ -\epsilon & 1+\epsilon & -1 & 0 \\ 0 & -1 & 2 & -1 \\ 0 & 0 & -1 & 1 \end{bmatrix}.$$

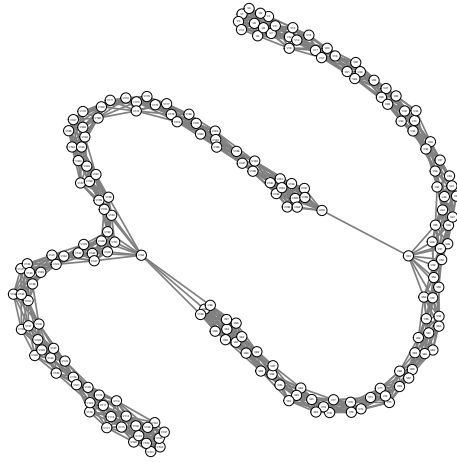
We previously showed that when $\epsilon \in (0, 0.75)$, the optimal ratio cut is the 1 – 2 cut, and when $\epsilon \in (0.75, 1)$, the optimal ratio cut is the 2 – 3 cut. However, for kernel k -means, the optimal clustering is $\{\{1\}, \{2, 3, 4\}\}$ when $\epsilon \in (0, 0.6)$ and $\{\{1, 2\}, \{3, 4\}\}$ when $\epsilon \in (0.6, 1)$. One thing that might be of interest is whether RatioCut-SDP and k -means-SDP yields the same results.



Interestingly, both RatioCut-SDP and k -means-SDP fail to find the correct ϵ where the optimal cut switches from 1 – 2 to 2 – 3.

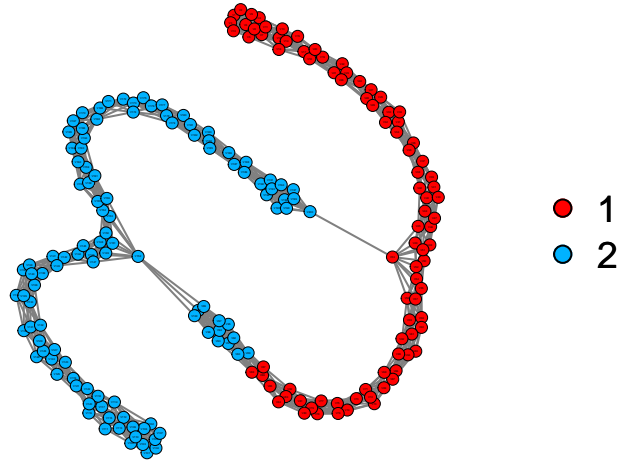
Example 3

Here we look at the “spiral graph”:

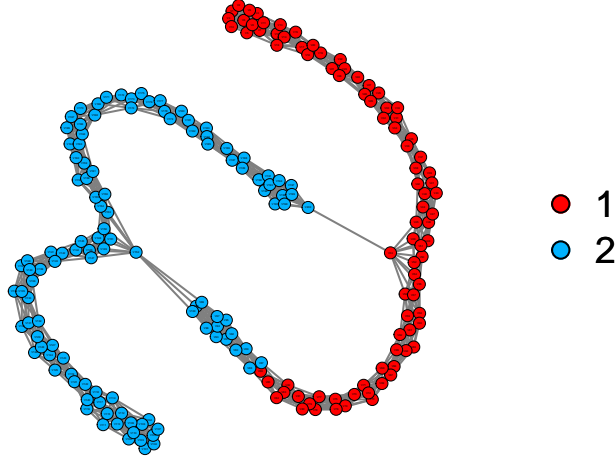


We know that the optimal ratio cut clustering is $\{\{1, \dots, 100\}, \{101, \dots, 200\}\}$. This also happens to coincide with the optimal k -means clustering. We also know that the spectral clustering relaxation of ratio cut fails to provide the optimal ratio cut (even when the k -means rounding step is initialized with the correct clustering).

Applying RatioCut-SDP to this graph:



Here we see that RatioCut-SDP makes the same mistake the spectral clustering relaxation of ratio cut makes. We can also try k -means SDP:



Strangely, k -means-SDP makes a similar mistake RatioCut-SDP makes, while performing k -means on the embedding of L^\dagger is able to find the optimal ratio cut (although Lloyd's algorithm runs into local minima issues as we add more embedding dimensions, so it's not always practically feasible).

It's also worth noting that these optimization problems takes a while to solve.

RatioCut-SDP optimality criterion

Ling and Strohmer outlines the following as being required for RatioCut-SDP to find the optimal ratio cut:

$$\|D_\delta\|_{op} < \frac{\lambda_{k+1}(L_{iso})}{4}$$

where

- W_{iso} is the weight matrix given that the optimal ratio cut is known and the edges of W are cut accordingly
- $W_\delta = W - W_{iso}$, the edges that are to be cut for the optimal ratio cut
- D_{iso} , D_δ , L_{iso} , and L_δ are the degree and combinatorial graph Laplacian matrices constructed from W_{iso} and W_δ
- $\|\cdot\|_{op}$ is the operator norm
- $\lambda_i(A)$ is the i^{th} eigenvalue of matrix A

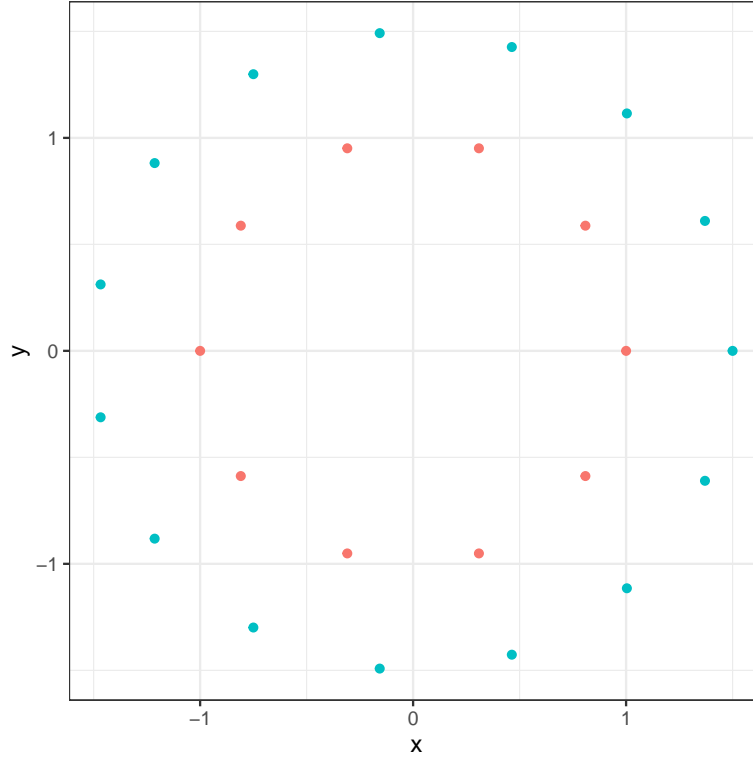
Examples 1-3 all violate this criterion.

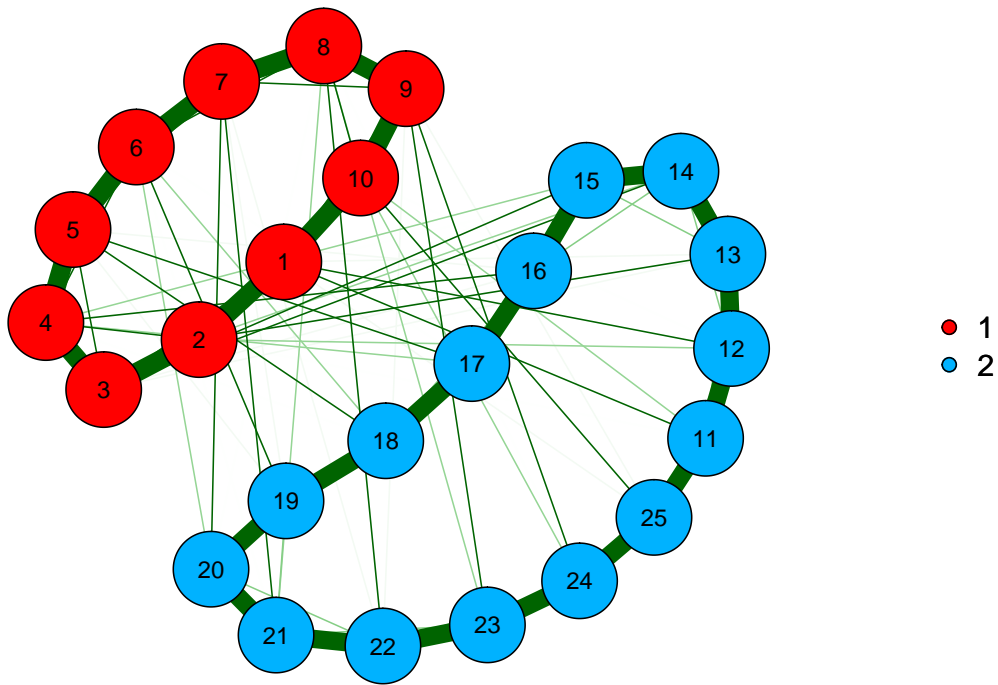
Intuitively, the criterion says that the within-cluster connectivity must be large compared to the magnitude of the between-cluster edges. Note that L_{iso} has k zero eigenvalues, one for each subgraph, and $\lambda_{k+1}(L_{iso})$ is the smallest “fiedler value” among the subgraphs. The fiedler value characterizes how tightly connected a graph (or in this case, subgraph) is. The first k eigenvectors of L_{iso} produce exactly the solution to the (fully constrained) ratio cut.

Examples from the Paper

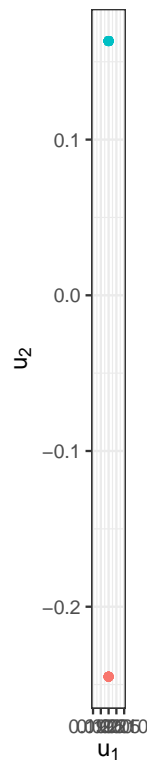
Concentric Circles

Here, we will set $r_2 = \frac{3}{2}$, $r_1 = 1$, $n = 10$, $m = 15$. Theorem 4.1 says if $\gamma \leq \left(2 + \frac{\log 4m}{\log \frac{m}{2\pi}}\right)^{-1} \left(\frac{\frac{n^2 \Delta^2}{16} - 1}{2}\right)$, where $\Delta = \frac{r_2 - r_1}{r_1}$, then a graph constructed using the heat kernel with $\sigma^2 = \frac{16r_1^2 \gamma}{n^2 \log \frac{m}{2\pi}}$ will always be solved by RatioCut-SDP. Here, we will set γ directly at the boundary of the condition.





Looking at the original data and the heat kernel graph, it seems like this should be a very “easy” problem to solve. Sure enough, spectral clustering is able to solve this very easily. In fact, the 1-dimensional Laplacian eigenmap has the points in each cluster almost lying on top of one another:

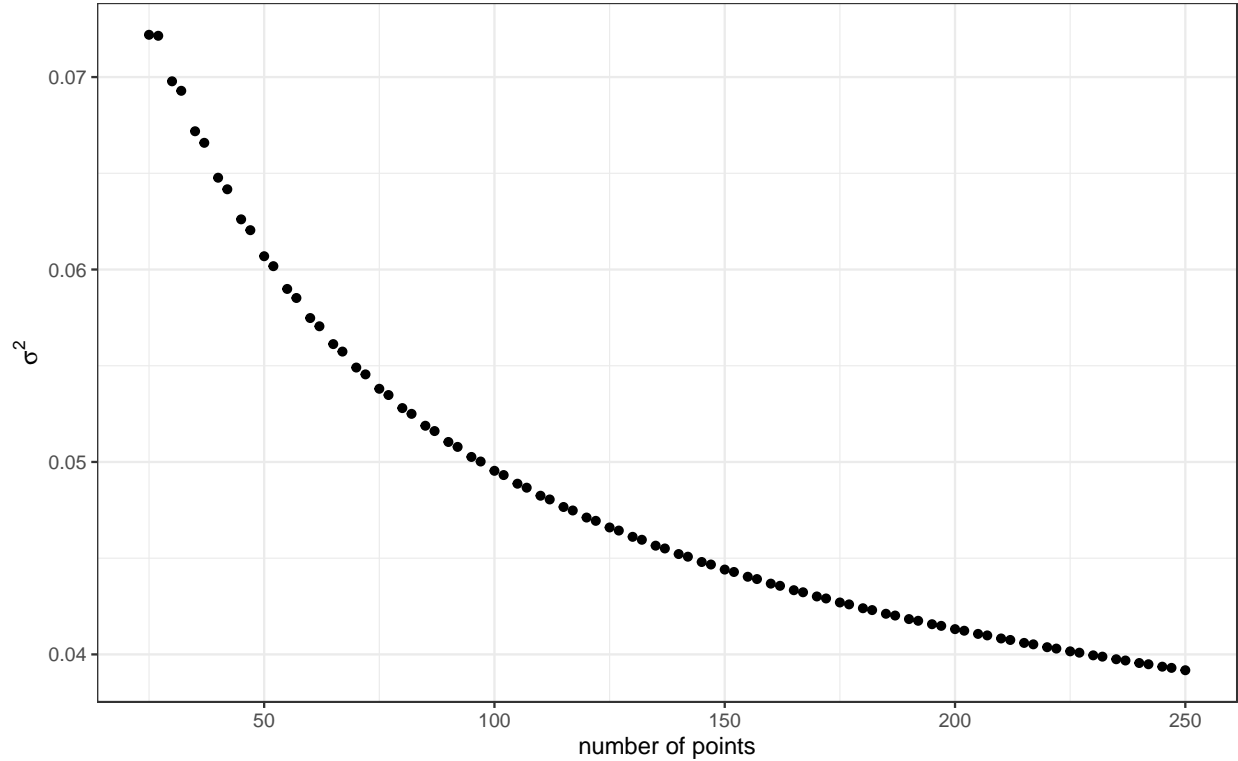



```

clustering  1  2
           1 10  0
           2  0 15

```

We can also see that σ^2 is a decreasing function of the sample sizes, so we actually get better separation as we increase n (and therefore m), and spectral clustering is even more able to separate the two clusters.



This illustrates the main criticism of the Ling and Strohmer result: the condition under which RatioCut-SDP is guaranteed to work is so stringent that it only captures the “easy” problems. Perhaps this points to other methods being guaranteed under this condition.

Next steps

1. RatioCut-SDP provides $Z \in \mathbb{R}^{n \times n}$, which, under the full ratio cut constraints, should be $Z = HH^\top$. We saw that in example 1, both RatioCut-SDP and k -means-SDP were able to find this exact Z , but in examples 2 and 3, we needed a “rounding” step where we embedded Z and used Lloyd’s algorithm to find a clustering. Ling and Strohmer are not clear on how this should be handled, and neither are Peng and Wei.
2. Ling and Strohmer provide some criteria under which RatioCut-SDP is guaranteed to find the optimal ratio cut clustering. So far, we haven’t checked if these criteria hold before running these experiments.
3. More examples . . .
4. Figure out when RatioCut-SDP and k -means SDP (using L^\dagger as a kernel matrix) coincide.