



Graphs in Machine Learning

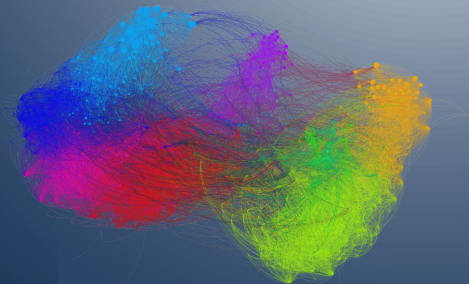
Laplacian and Random Walks

Stationary Distribution

Michal Valko

Inria & ENS Paris-Saclay, MVA

Partially based on material by: Ulrike von Luxburg,
Gary Miller, Doyle & Schnell, Daniel Spielman



Normalized Laplacians

\mathbf{L}_{sym} and \mathbf{L}_{rw} are PSD with non-negative real eigenvalues

$$0 = \lambda_1 \leq \lambda_2 \leq \lambda_3 \leq \dots \leq \lambda_N$$

.

(λ, \mathbf{u}) is an eigenpair for \mathbf{L}_{rw} iff (λ, \mathbf{u}) solve the generalized eigenproblem $\mathbf{L}\mathbf{u} = \lambda\mathbf{D}\mathbf{u}$.

Normalized Laplacians

\mathbf{L}_{sym} and \mathbf{L}_{rw} are PSD with non-negative real eigenvalues

$$0 = \lambda_1 \leq \lambda_2 \leq \lambda_3 \leq \dots \leq \lambda_N$$

.

(λ, \mathbf{u}) is an eigenpair for \mathbf{L}_{rw} iff (λ, \mathbf{u}) solve the generalized eigenproblem $\mathbf{L}\mathbf{u} = \lambda\mathbf{D}\mathbf{u}$.

$(0, \mathbf{1}_N)$ is an eigenpair for \mathbf{L}_{rw} .

Normalized Laplacians

\mathbf{L}_{sym} and \mathbf{L}_{rw} are PSD with non-negative real eigenvalues

$$0 = \lambda_1 \leq \lambda_2 \leq \lambda_3 \leq \dots \leq \lambda_N$$

(λ, \mathbf{u}) is an eigenpair for \mathbf{L}_{rw} iff (λ, \mathbf{u}) solve the generalized eigenproblem $\mathbf{L}\mathbf{u} = \lambda\mathbf{D}\mathbf{u}$.

$(0, \mathbf{1}_N)$ is an eigenpair for \mathbf{L}_{rw} .

$(0, \mathbf{D}^{1/2}\mathbf{1}_N)$ is an eigenpair for \mathbf{L}_{sym} .

Normalized Laplacians

\mathbf{L}_{sym} and \mathbf{L}_{rw} are PSD with non-negative real eigenvalues

$$0 = \lambda_1 \leq \lambda_2 \leq \lambda_3 \leq \dots \leq \lambda_N$$

(λ, \mathbf{u}) is an eigenpair for \mathbf{L}_{rw} iff (λ, \mathbf{u}) solve the generalized eigenproblem $\mathbf{L}\mathbf{u} = \lambda\mathbf{D}\mathbf{u}$.

$(0, \mathbf{1}_N)$ is an eigenpair for \mathbf{L}_{rw} .

$(0, \mathbf{D}^{1/2}\mathbf{1}_N)$ is an eigenpair for \mathbf{L}_{sym} .

Multiplicity of eigenvalue 0 of \mathbf{L}_{rw} or \mathbf{L}_{sym} equals to the number of connected components.

Normalized Laplacians

\mathbf{L}_{sym} and \mathbf{L}_{rw} are PSD with non-negative real eigenvalues

$$0 = \lambda_1 \leq \lambda_2 \leq \lambda_3 \leq \dots \leq \lambda_N$$

(λ, \mathbf{u}) is an eigenpair for \mathbf{L}_{rw} iff (λ, \mathbf{u}) solve the generalized eigenproblem $\mathbf{L}\mathbf{u} = \lambda\mathbf{D}\mathbf{u}$.

$(0, \mathbf{1}_N)$ is an eigenpair for \mathbf{L}_{rw} .

$(0, \mathbf{D}^{1/2}\mathbf{1}_N)$ is an eigenpair for \mathbf{L}_{sym} .

Multiplicity of eigenvalue 0 of \mathbf{L}_{rw} or \mathbf{L}_{sym} equals to the number of connected components.

Laplacian and Random Walks on Undirected Graphs

- stochastic process: vertex-to-vertex jumping

Laplacian and Random Walks on Undirected Graphs

- stochastic process: vertex-to-vertex jumping
- transition probability $v_i \rightarrow v_j$ is $p_{ij} = w_{ij}/d_i$

Laplacian and Random Walks on Undirected Graphs

- stochastic process: vertex-to-vertex jumping
- transition probability $v_i \rightarrow v_j$ is $p_{ij} = w_{ij}/d_i$
 - $d_i \stackrel{\text{def}}{=} \sum_j w_{ij}$

Laplacian and Random Walks on Undirected Graphs

- stochastic process: vertex-to-vertex jumping
- transition probability $v_i \rightarrow v_j$ is $p_{ij} = w_{ij}/d_i$
 - $d_i \stackrel{\text{def}}{=} \sum_j w_{ij}$
- transition matrix $\mathbf{P} = (p_{ij})_{ij} = \mathbf{D}^{-1}\mathbf{W}$ (notice $\mathbf{L}_{rw} = \mathbf{I} - \mathbf{P}$)

Laplacian and Random Walks on Undirected Graphs

- stochastic process: vertex-to-vertex jumping
- transition probability $v_i \rightarrow v_j$ is $p_{ij} = w_{ij}/d_i$
 - $d_i \stackrel{\text{def}}{=} \sum_j w_{ij}$
- transition matrix $\mathbf{P} = (p_{ij})_{ij} = \mathbf{D}^{-1}\mathbf{W}$ (notice $\mathbf{L}_{rw} = \mathbf{I} - \mathbf{P}$)
- if G is connected and non-bipartite \rightarrow unique **stationary distribution** $\pi = (\pi_1, \pi_2, \pi_3, \dots, \pi_N)$ where $\pi_i = d_i/\text{vol}(V)$

Laplacian and Random Walks on Undirected Graphs

- stochastic process: vertex-to-vertex jumping
- transition probability $v_i \rightarrow v_j$ is $p_{ij} = w_{ij}/d_i$
 - $d_i \stackrel{\text{def}}{=} \sum_j w_{ij}$
- transition matrix $\mathbf{P} = (p_{ij})_{ij} = \mathbf{D}^{-1}\mathbf{W}$ (notice $\mathbf{L}_{rw} = \mathbf{I} - \mathbf{P}$)
- if G is connected and non-bipartite \rightarrow unique **stationary distribution** $\pi = (\pi_1, \pi_2, \pi_3, \dots, \pi_N)$ where $\pi_i = d_i/\text{vol}(V)$
 - $\text{vol}(G) = \text{vol}(V) = \text{vol}(\mathbf{W}) \stackrel{\text{def}}{=} \sum_i d_i = \sum_{i,j} w_{ij}$

Laplacian and Random Walks on Undirected Graphs

- stochastic process: vertex-to-vertex jumping
- transition probability $v_i \rightarrow v_j$ is $p_{ij} = w_{ij}/d_i$
 - $d_i \stackrel{\text{def}}{=} \sum_j w_{ij}$
- transition matrix $\mathbf{P} = (p_{ij})_{ij} = \mathbf{D}^{-1}\mathbf{W}$ (notice $\mathbf{L}_{rw} = \mathbf{I} - \mathbf{P}$)
- if G is connected and non-bipartite \rightarrow unique **stationary distribution** $\pi = (\pi_1, \pi_2, \pi_3, \dots, \pi_N)$ where $\pi_i = d_i/\text{vol}(V)$
 - $\text{vol}(G) = \text{vol}(V) = \text{vol}(\mathbf{W}) \stackrel{\text{def}}{=} \sum_i d_i = \sum_{i,j} w_{ij}$
- $\pi = \frac{\mathbf{1}^\top \mathbf{W}}{\text{vol}(\mathbf{W})}$ verifies $\pi \mathbf{P} = \pi$ as:

Laplacian and Random Walks on Undirected Graphs

- stochastic process: vertex-to-vertex jumping
- transition probability $v_i \rightarrow v_j$ is $p_{ij} = w_{ij}/d_i$
 - $d_i \stackrel{\text{def}}{=} \sum_j w_{ij}$
- transition matrix $\mathbf{P} = (p_{ij})_{ij} = \mathbf{D}^{-1}\mathbf{W}$ (notice $\mathbf{L}_{rw} = \mathbf{I} - \mathbf{P}$)
- if G is connected and non-bipartite \rightarrow unique **stationary distribution** $\pi = (\pi_1, \pi_2, \pi_3, \dots, \pi_N)$ where $\pi_i = d_i/\text{vol}(V)$
 - $\text{vol}(G) = \text{vol}(V) = \text{vol}(\mathbf{W}) \stackrel{\text{def}}{=} \sum_i d_i = \sum_{i,j} w_{ij}$
- $\pi = \frac{\mathbf{1}^\top \mathbf{W}}{\text{vol}(\mathbf{W})}$ verifies $\pi \mathbf{P} = \pi$ as:

Laplacian and Random Walks on Undirected Graphs

- stochastic process: vertex-to-vertex jumping
- transition probability $v_i \rightarrow v_j$ is $p_{ij} = w_{ij}/d_i$
 - $d_i \stackrel{\text{def}}{=} \sum_j w_{ij}$
- transition matrix $\mathbf{P} = (p_{ij})_{ij} = \mathbf{D}^{-1}\mathbf{W}$ (notice $\mathbf{L}_{rw} = \mathbf{I} - \mathbf{P}$)
- if G is connected and non-bipartite \rightarrow unique **stationary distribution** $\pi = (\pi_1, \pi_2, \pi_3, \dots, \pi_N)$ where $\pi_i = d_i/\text{vol}(V)$
 - $\text{vol}(G) = \text{vol}(V) = \text{vol}(\mathbf{W}) \stackrel{\text{def}}{=} \sum_i d_i = \sum_{i,j} w_{ij}$
- $\pi = \frac{\mathbf{1}^\top \mathbf{W}}{\text{vol}(\mathbf{W})}$ verifies $\pi \mathbf{P} = \pi$ as:

$$\pi \mathbf{P} = \frac{\mathbf{1}^\top \mathbf{W} \mathbf{P}}{\text{vol}(\mathbf{W})} = \frac{\mathbf{1}^\top \mathbf{D} \mathbf{P}}{\text{vol}(\mathbf{W})} = \frac{\mathbf{1}^\top \mathbf{D} \mathbf{D}^{-1} \mathbf{W}}{\text{vol}(\mathbf{W})} = \frac{\mathbf{1}^\top \mathbf{W}}{\text{vol}(\mathbf{W})} = \pi$$

Laplacian and Random Walks on Undirected Graphs

- stochastic process: vertex-to-vertex jumping
- transition probability $v_i \rightarrow v_j$ is $p_{ij} = w_{ij}/d_i$
 - $d_i \stackrel{\text{def}}{=} \sum_j w_{ij}$
- transition matrix $\mathbf{P} = (p_{ij})_{ij} = \mathbf{D}^{-1}\mathbf{W}$ (notice $\mathbf{L}_{rw} = \mathbf{I} - \mathbf{P}$)
- if G is connected and non-bipartite \rightarrow unique **stationary distribution** $\pi = (\pi_1, \pi_2, \pi_3, \dots, \pi_N)$ where $\pi_i = d_i/\text{vol}(V)$
 - $\text{vol}(G) = \text{vol}(V) = \text{vol}(\mathbf{W}) \stackrel{\text{def}}{=} \sum_i d_i = \sum_{i,j} w_{ij}$
- $\pi = \frac{\mathbf{1}^\top \mathbf{W}}{\text{vol}(\mathbf{W})}$ verifies $\pi \mathbf{P} = \pi$ as:

$$\pi \mathbf{P} = \frac{\mathbf{1}^\top \mathbf{W} \mathbf{P}}{\text{vol}(\mathbf{W})} = \frac{\mathbf{1}^\top \mathbf{D} \mathbf{P}}{\text{vol}(\mathbf{W})} = \frac{\mathbf{1}^\top \mathbf{D} \mathbf{D}^{-1} \mathbf{W}}{\text{vol}(\mathbf{W})} = \frac{\mathbf{1}^\top \mathbf{W}}{\text{vol}(\mathbf{W})} = \pi$$

Michal Valko

`michal.valko@inria.fr`

Inria & ENS Paris-Saclay, MVA

`https://misovalko.github.io/mva-ml-graphs.html`