

This part is organized as follows: the first two sections discuss graph Laplacian in the spectral domain, by bounding its eigenvalues and introducing its importance (Cheeger's inequality). The random walk section provides a use case of graph spectral in the analysis of convergence, and introduces the importance of Laplacian linear equations. The next two sections show how to solve it exactly by applying pseudo inverse, as the Laplacian is non-invertible. The rest sections show how to approximate a graph Laplacian and solve the Laplacian linear equation approximately and more efficiently.

## 1 Spectral Domain of the Graph Laplacian

We assume the graph has  $n$  vertices and  $m$  edges. The vertex set is  $V$  and the edge set is  $E$ .

### 1.1 Courant-Fischer Theorem

1. **Eigenvalue version:** Let  $A$  be a symmetric matrix with eigenvalues  $\lambda_1 \leq \dots \leq \lambda_n$ , then

$$\lambda_i = \min_{\substack{\text{subspace } W \subseteq \mathbb{R}^n \\ \dim(W)=i}} \max_{\substack{x \in W \\ x \neq 0}} \frac{x^\top A x}{x^\top x} = \max_{\substack{\text{subspace } W \subseteq \mathbb{R}^n \\ \dim(W)=n+1-i}} \min_{\substack{x \in W \\ x \neq 0}} \frac{x^\top A x}{x^\top x}.$$

2. **Eigenbasis version:** Let  $A$  be a symmetric matrix with eigenvalues  $\lambda_1 \leq \dots \leq \lambda_n$  and corresponding orthonormal eigenvectors  $x_1, \dots, x_n$ , then

$$\lambda_i = \min_{\substack{x \perp x_1, \dots, x_{i-1} \\ x \neq 0}} \frac{x^\top A x}{x^\top x} = \max_{\substack{x \perp x_{i+1}, \dots, x_n \\ x \neq 0}} \frac{x^\top A x}{x^\top x}.$$

Note that we also have  $\lambda_i = \frac{x_i^\top A x_i}{x_i^\top x_i}$ .

Applying Courant-Fischer theorem, we have  $\lambda_2 x^\top x \leq x^\top L x \leq \lambda_n x^\top x$  for all  $x \perp \mathbf{1}$ , as  $\mathbf{1}$  is the eigenvector of  $L$  corresponding to eigenvalue 0. For connected graphs,  $\lambda_2 > 0$ .

### 1.2 PSD Order (Loewner Order)

Defined only for symmetric matrices:  $A \leq B$  iff for all  $x \in \mathbb{R}^n$ , we have  $x^\top A x \leq x^\top B x$ . We also define  $G \leq H$  for two graphs  $G$  and  $H$  iff  $L_G \leq L_H$ . We always have  $G \geq H$  if  $H$  is a subgraph of  $G$ .

Properties:

1. If  $A \leq B$  and  $B \leq C$ , then  $A \leq C$ .
2. If  $A \leq B$ , then  $A + C \leq B + C$  for any symmetric  $C$ .
3. If  $A \leq B$  and  $C \leq D$ , then  $A + C \leq B + D$ .
4. If  $A > 0$  and  $\alpha \geq 1$ , then  $\frac{1}{\alpha} A \leq A \leq \alpha A$ .
5. If  $A \leq B$ , then  $\lambda_i(A) \leq \lambda_i(B)$  for all  $i$ . Proof by Courant-Fischer theorem. The converse is not true.
6. For any matrix  $C$ , if  $A \leq B$ , then  $C^\top A C \leq C^\top B C$ .
7. If  $0 \leq A \leq B$ , then  $B^{-1} \leq A^{-1}$ .

## 1.3 Bounding the $\lambda_2$ and $\lambda_n$

### 1.3.1 Test Vector Method

Since  $\lambda_2 \leq \frac{y^\top L y}{y^\top y}$  for any  $y \perp \mathbf{1}$ , we can upper bound the  $\lambda_2$  by any **test vector**  $y$ . Similarly, we can lower bound the  $\lambda_n$  by test vectors by  $\lambda_n \geq \frac{y^\top L y}{y^\top y}$ .

1. For a complete graph  $K_n$ ,  $L = nI - \mathbf{1}\mathbf{1}^\top$  and for any  $x \perp \mathbf{1}$  we have  $x^\top L x = n x^\top x$ . Therefore,  $\lambda_2(K_n) = \dots = \lambda_n(K_n) = n$  and any  $x \perp \mathbf{1}$  is an eigenvector.
2. For a path graph  $P_n$ , let  $x(i) = n + 1 - 2i$  be the test vector which satisfies  $x \perp \mathbf{1}$ , we get  $\lambda_2(P_n) \leq \frac{12}{n^2}$ . Let  $x(1) = -1$ ,  $x(n) = 1$  and  $x(i) = 0$  for other  $i$  to be the test vector, we get  $\lambda_n(P_n) \geq 1$ .
3. For a complete binary tree  $T_n$  (depth equals zero for a single root), let  $x(i) = 0$  for all non-leaf nodes,  $x(i) = -1$  for even-numbered leaf nodes and  $x(i) = 1$  for odd-numbered leaf nodes be the test vector, we get  $\lambda_n(T_n) \geq 1$ . Let  $x(1) = 0$ ,  $x(i) = 1$  for the left subtree of the root and  $x(i) = -1$  for the right subtree of the root be the test vector, we get  $\lambda_2(T_n) \leq \frac{2}{n-1}$ .

### 1.3.2 Consequences of PSD Order

Since  $x^\top (D - A)x = \sum_{(u,v)} w(u,v)(x(u) - x(v))^2 \geq 0$  and  $x^\top (D + A)x = \sum_{(u,v)} w(u,v)(x(u) + x(v))^2 \geq 0$ , we have  $D \geq A$  and  $D \geq -A$ . In addition, we have  $D \leq (\max D_{i,i})I$ . Therefore, we have  $L = D - A \leq 2D \leq (2 \max D_{i,i})I$ , which implies  $\lambda_n \leq 2 \max D_{i,i}$  for any graph. For unit-weight graphs, this means  $\lambda_n \leq 2 \max \text{degree}(v)$ . The bound is tight for a single-edge graph.

To get lower bounds of  $\lambda_2(H)$ , we first establish  $f(n)H \geq G$  for some  $G$  with known lower bounds on  $\lambda_2(G)$ . Usually  $G = K_n$  because  $\lambda_2(K_n) = n$ . Then it follows that  $\lambda_2(H) \geq \lambda_2(G)/f(n)$ .

1. **Path Graph  $P_n$ :** Let  $G_{i,j}$  denote a unit-weight graph consisting of one edge  $(i, j)$  and  $P_n$  be the path graph connecting 1 and  $n$ . Then  $(n-1)P_n \geq G_{1,n}$ . Proof follows from applying Cauchy-Schwartz for  $\delta_i := x(i+1) - x(i)$ . For weighted paths, we have  $G_{1,n} \leq \left(\sum_{i=1}^{n-1} \frac{1}{w_i}\right) \sum_{i=1}^{n-1} w_i G_{i,i+1}$ .

Applying path inequality, we have  $K_n = \sum_{i < j} G_{i,j} \leq \sum_{i < j} (j-i)P_{i,j} \leq \sum_{i < j} (j-i)P_n \leq n^3 P_n$ , which implies  $\lambda_2(P_n) \geq \lambda_2(K_n)/n^3 = 1/n^2$ .

2. **Any unit-weight graph  $G$ :** Define the diameter  $D$  of a graph  $G$  to be the maximum length of the shortest paths between any two nodes. Let  $G_{i,j}^s$  be the shortest path from  $i$  to  $j$ . Applying path inequality, we have  $K_n = \sum_{i < j} G_{i,j} \leq \sum_{i < j} D G_{i,j}^s \leq \sum_{i < j} D G \leq n^2 D G$ , which implies  $\lambda_2(G) \geq \frac{1}{nD}$ .

3. **Complete Binary Tree  $T_n$ :** Define  $G_e$  be the single-edge graph with edge  $e$ , and  $T_{i,j}$  be the unique path between  $i$  and  $j$ . Applying the weighted path inequality, we have  $K_n = \sum_{i < j} G_{i,j} \leq \sum_{i < j} \left(\sum_{e \in T_{i,j}} \frac{1}{w(e)}\right) \left(\sum_{e \in T_{i,j}} w(e) G_e\right) \leq$

$\left(\max_{i < j} \sum_{e \in T_{i,j}} \frac{1}{w(e)}\right) \left(\sum_{i < j} \sum_{e \in T_{i,j}} w(e) G_e\right)$ . For  $e$  connecting level  $i$  and  $i+1$  for  $i \in [d-1]$ , we set  $w(e) = 2^i$ . Then  $\max_{i < j} \sum_{e \in T_{i,j}} \frac{1}{w(e)} \leq 4$ . Since the number of occurrence of  $e$  in  $T_{i,j}$  for any  $i < j$  is upper bounded by  $n^2 2^{-i}$ , we have  $\sum_{i < j} \sum_{e \in T_{i,j}} w(e) G_e \leq \sum_e w(e) n^2 2^{-i} G_e = \sum_e n^2 G_e = n^2 T_n$ . Therefore,  $K_n \leq 4n^2 T_n$ , which implies  $\lambda_2(T_n) \geq \frac{1}{4n}$ .

## 2 Conductance

Definitions:

1. **Conductance of a vertex subset:** Given  $\emptyset \subset S \subset V$ , the conductance  $\phi(S) := \phi(S) = \frac{|E(S, V \setminus S)|}{\min\{\text{vol}(S), \text{vol}(V \setminus S)\}}$ , where  $\text{vol}(S) := \sum_{v \in S} \text{degree}(v)$ . Define  $\mathbf{1}_S$  to be the  $n$ -dimensional vector with only 1 for the vertices of  $S$  and 0 for the vertices of  $V \setminus S$ . Assuming  $\text{vol}(S) \leq \text{vol}(V)/2$ , thus  $|E(V, V \setminus S)| = \sum_{(u,v) \in E} (\mathbf{1}_S(u) - \mathbf{1}_S(v))^2 = \mathbf{1}_S^\top L \mathbf{1}_S$  and  $\text{vol}(S) = \mathbf{1}_S^\top D \mathbf{1}_S$ . Then  $\phi(S) = \frac{\mathbf{1}_S^\top L \mathbf{1}_S}{\mathbf{1}_S^\top D \mathbf{1}_S}$ .

2. **Conductance of a graph:** The conductance  $\phi(G) := \min_{\emptyset \subset S \subset V} \phi(S) = \min_{\substack{\emptyset \subset S \subset V \\ \text{vol}(S) \leq \text{vol}(V)/2}} \phi(S)$ .

3.  **$\phi$ -expander:** For any  $\phi \in (0, 1]$ , we call a graph  $G$  to be a  $\phi$ -expander if  $\phi(G) \geq \phi$ .

4.  **$\phi$ -expander decomposition of quality  $q$ :** A partition  $\{X_i\}$  of the vertex set  $V$  is called a  $\phi$ -expander decomposition of quality  $q$  if (1) each induced graph  $G[X_i]$  is a  $\phi$ -expander, and (2.i) #edges not contained in any  $G[X_i]$  is at most  $q \cdot \phi \cdot m$ . The second condition is equivalent to (2.ii) The partition removes at most  $q \cdot \phi \cdot m$  edges.

5. **Normalized Laplacian:** We define the *normalized Laplacian* to be  $N := D^{-1/2} L D^{-1/2}$ .  $N$  is still PSD, with first eigenvalue equals 0 associated with eigenvector  $D^{1/2} \mathbf{1}$ . By Courant-Fischer theorem,  $\lambda_2(N) = \min_{x \perp D^{1/2} \mathbf{1}} \frac{x^\top N x}{x^\top x} = \min_{z \perp d} \frac{z^\top L z}{z^\top D z}$ .

### 2.1 Cheeger's Inequality

Notice that the  $\lambda_2(N)$  has similar forms to  $\phi(G)$ . Cheeger's inequality aims to bound  $\phi(G)$  by  $\lambda_2(N)$ .

**Cheeger's Inequality:**  $\frac{\lambda_2(N)}{2} \leq \phi(G) \leq \sqrt{2 \lambda_2(N)}$ .

The lower bound is proved by restricting the minimum in  $\lambda_2(N)$  to be  $z_S = \mathbf{1}_S - \alpha \mathbf{1}$  for some  $\alpha$  such that  $z_S \perp d$ . The upper bound is proved by constructing  $S$  for any  $z \perp d$  such that

$$\frac{\mathbf{1}_S^\top L \mathbf{1}_S}{\mathbf{1}_S^\top D \mathbf{1}_S} \leq \sqrt{2 \frac{z^\top L z}{z^\top D z}}.$$

### 3 Random Walks on a Graph

A **random walk on a graph**  $G$  is a Markov Chain with transition probability  $\mathbb{P}(v_{t+1} = v \mid v_t = u) = w(u, v)/d(u)$  iff  $(u, v) \in E$  and 0 otherwise. The transition matrix is thus  $W = A D^{-1} = I - D^{1/2} N D^{-1/2}$  and  $p_t = W^t p_0$ . Define  $\pi = \frac{d}{1^\top d}$ , thus  $\pi = W \pi$  for any  $G$ , so every  $G$  has a stationary distribution.

### 3.1 Lazy Random Walks

A **lazy random walk on a graph**  $G$  is a random walk, but has half probability to not move for every step. Assuming that

$G$  is connected, the lazy random walk guarantees ergodicity of the Markov Chain, and thus convergence to the stationary distribution. The transition matrix is  $\tilde{W} = \frac{1}{2}(I + W) = I - \frac{1}{2}D^{1/2}ND^{-1/2}$ .

**Relation between lazy random walk and normalized Laplacian:** For the  $i$ -th eigenvalue  $v_i$  of  $N$  associated with eigenvector  $\psi_i$ , the  $\tilde{W}$  has an eigenvalue  $1 - \frac{1}{2}v_i$  associated with eigenvector  $D^{1/2}\psi_i$ . Since  $0 \leq L \leq 2D$ , we have  $0 \leq N \leq 2I$  and thus  $0 \leq \lambda_i(N) \leq 2$ . Therefore, we conclude that all eigenvalues of  $\tilde{W} \in [0, 1]$ .

**Dynamics of lazy random walk:** Expanding the starting distribution  $p_0$  by the eigenvectors of  $\tilde{W}$ , we have for some  $\{\alpha_i\}$  that  $p_0 = \sum_{i=1}^n \alpha_i D^{1/2} \psi_i$ . Therefore, we have  $p_t = \tilde{W}^t p_0 = \sum_{i=1}^n \alpha_i (1 - \frac{1}{2}v_i)^t D^{1/2} \psi_i \rightarrow \alpha_1 D^{1/2} \psi_1$  as  $v_1 = 0$  and  $v_i > 0$  for  $i \neq 1$ . Since  $\psi_1 \propto D^{1/2} \mathbf{1}$ , we have  $\psi_1 = \frac{d^{1/2}}{(\mathbf{1}^\top d)^{1/2}}$ , thus  $\alpha_1 = \psi_1^\top D^{-1/2} p_0 = \frac{\mathbf{1}^\top p_0}{(\mathbf{1}^\top d)^{1/2}} = \frac{1}{(\mathbf{1}^\top d)^{1/2}}$  and  $\alpha_1 D^{1/2} \psi_1 = \pi$ , which implies  $p_t \rightarrow \pi$ , the stationary distribution.

**Rate of Convergence:** For any unit-weight connected graph  $G$  and any starting distribution  $p_0$ , we have  $\|p_t - \pi\|_\infty \leq e^{-v_2 t/2} \sqrt{n}$ . Therefore, a larger  $v_2$  and smaller vertex set means faster convergence, and the convergence rate is exponential.

### 3.2 Hitting Time

**The expected hitting time** from  $a$  to  $s$  is defined by  $\mathbb{E}H_{a,s}$ , where  $H_{a,s} = \text{argmin}_t \{v_t = s \mid v_0 = a\}$ . We want  $\mathbb{E}H_{a,s}$  for all vertices  $a$  and denote the vector as  $h$ , e.g.,  $h(s) = 0$ .

By one-step analysis, we have  $h(a) = 1 + \sum_{(a,b) \in E} \frac{w(a,b)}{d(a)} h(b) = 1 + \mathbf{1}_a^\top W^\top h$ , and thus  $1 = \mathbf{1}_a^\top (I - W^\top) h$ . Combining the equation for all vertices except  $s$ , we have  $\mathbf{1} - \alpha \mathbf{1}_s = (I - W^\top) h$ , where  $\alpha$  represents the extra freedom from the  $n-1$  equations. Multiplying both side by  $D$ , we get  $d - \alpha d(s) \mathbf{1}_s = (D - A)h = Lh$ , which only have solution when  $d - \alpha d(s) \mathbf{1}_s \perp \mathbf{1}$ . Therefore,  $\alpha = \|d\|_1 / d(s)$ .

To summarize, by solving  $Lh = d - \|d\|_1 \mathbf{1}$ , we can get the expected hitting time from all vertices to  $s$ . Note that the solution has one extra freedom because  $\dim(\ker(L)) = 1$ , and the correct expected hitting time is  $h - h(s) \mathbf{1}$  to enforce the constraint that  $h(s) = 1$ . The equation can be solved in  $\tilde{O}(m)$ .

### 4 Pseudo-Inverse and Effective Resistance

Given a Laplacian  $L$ , its (Moore-Penrose) pseudo inverse is defined to be either of the two equivalents:

1. A matrix  $L^+$  that is (1) symmetric, (2)  $L^+ v = 0$  for  $v \in \ker(L)$ , and (3)  $L^+ L v = LL^+ v = v$  for  $v \in \ker(L)$ .
2. Let  $\lambda_i, v_i$  be the  $i$ -th eigenvalue and eigenvector. Then  $L^+ = \sum_{\lambda_i \neq 0} \lambda_i^{-1} v_i v_i^\top$ .

Property:

- Assume  $M = XYX^\top$ , where  $X$  is real and invertible, and  $Y$  is real and symmetric. Let  $\Pi_M$  be the orthogonal projection to the image of  $M$ . Then  $M^+ = \Pi_M (X^\top)^{-1} Y^+ X^{-1} \Pi_M$ .

- For symmetric  $L$ ,  $\Pi_L := \sum_{\lambda_i \neq 0} v_i v_i^\top = L^{+/2} L L^{+/2} = L^+ L = L L^+$  is the orthogonal projection to the image of  $L$ , i.e.,  $\Pi_L v = 0$  for any  $v \in \ker(L)$  and  $\Pi_L v = v$  for any  $v \in \text{im}(L)$ . For connected  $G$ ,  $\Pi_L = I - \frac{1}{n} \mathbf{1} \mathbf{1}^\top$ .

The effective resistance between vertex  $a$  and  $b$  is defined to be the cost (energy lost) to routing one unit (of positive electric charge) from  $a$  to  $b$ :  $R_{\text{eff}}(a, b) = \min_{Bf = \mathbf{1}_b - \mathbf{1}_a} f^\top R f = \tilde{f}^\top R \tilde{f}$ , where  $\tilde{f}$  is the electric flow. Let  $\tilde{x}$  be the electric voltages, we also have  $L\tilde{x} = \mathbf{1}_b - \mathbf{1}_a$ , and thus  $R_{\text{eff}}(a, b) = \tilde{x}^\top L \tilde{x} = (\mathbf{1}_b - \mathbf{1}_a)^\top L^+ (\mathbf{1}_b - \mathbf{1}_a) = \|L^{+/2} (\mathbf{1}_b - \mathbf{1}_a)\|_2^2$ .

Effective Resistance is a distance defined on the vertex pairs, i.e.  $R_{\text{eff}}(a, c) \leq R_{\text{eff}}(a, b) + R_{\text{eff}}(b, c)$ .

### 5 Solving Laplacian Linear Equations Exactly

#### 5.1 Optimization View

Solving  $Lx = d$  is equivalent to solving  $\text{argmin}_x -d^\top x + \frac{1}{2} x^\top L x$ . By iteratively optimize over  $x_i$ , we get a series of similar optimizations. The final optimization is straightforward, then we can back substitute to get  $x$ .

#### 5.2 Additive View

Given an invertible square lower/upper triangular matrix  $M$ , we can solve  $Mx = d$  by back substitution in  $O(\text{nnz}(M))$ , where  $\text{nnz}(M)$  means the number of non-zeros in  $M$ . Therefore, if we know the **Cholesky decomposition**  $L = MM^\top$  (requires  $O(n^3)$ ), then we can solve  $Lx = d = M(M^\top x)$  by (1) solving  $My = d$  then (2) solving  $M^\top x = y$  in  $O(\text{nnz}(M))$ .

However, the Laplacian is non-invertible, leading to one diagonal of  $M$  equals 0. Therefore, we need to play a trick. Define  $\hat{M}$  equals  $M$  but has value 1 for the zero diagonal, and  $\hat{D}$  be a diagonal matrix that has value 0 at the zero diagonal of  $M$  and 1 otherwise. Then  $L = \hat{M} \hat{D} \hat{M}^\top$ , and each  $\hat{M}$  is now invertible. Since  $\hat{D}^+ = \hat{D}$ , we can find a special solution of  $Lx = d$  by (1) solving  $\hat{M}z = d$ , (2) computing  $y = \hat{D}z$ , and (3) solving  $\hat{M}^\top x = y$ . The solution space is obtained by adding a subspace spanned by  $\mathbf{1}$ .

### 6 Approximating a Dense Graph in the Spectral Domain

#### 6.1 Concentration of Random Matrices

1. **Chernoff Bound for Bounded independent variables:** Suppose  $\{X_i \in \mathbb{R}\}$  are independent random variables and  $0 \leq X_i \leq R$ . Let  $X = \sum_i X_i$  and  $\mu = \mathbb{E}X$ . Then for any  $0 < \epsilon \leq 1$ , we have  $\mathbb{P}(X \geq (1 + \epsilon)\mu) \leq \exp(-\frac{\epsilon^2 \mu}{4R})$  and  $\mathbb{P}(X \leq (1 - \epsilon)\mu) \leq \exp(-\frac{\epsilon^2 \mu}{4R})$ .
2. **Bernstein Bound for independent, zero-mean and bounded variables:** Suppose  $\{X_i \in \mathbb{R}\}$  are independent, zero-mean random variables and  $|X_i| \leq R$ . Let  $X = \sum_i X_i$ , and  $\sigma^2 = \text{Var}(X)$ . Then for any  $t > 0$ , we have  $\mathbb{P}(|X| \geq t) \leq 2 \exp(-\frac{t^2}{2Rt + 4\sigma^2})$ .

The proof is similar to Chernoff bound. (1)  $\mathbb{P}(X \geq t) = \mathbb{P}(\exp(\theta X) \geq \exp(\theta t)) \leq \exp(-\theta t) \mathbb{E}(\exp(\theta X))$ , (2) upper

bound  $\mathbb{E}(\exp(\theta X)) \leq \exp(\theta^2 \sigma^2)$  given  $\theta \in (0, \frac{1}{R}]$ , which allows  $\exp(\theta X_i) \leq 1 + \theta X_i + (\theta X_i)^2$ , and (3) take the minimum among  $\theta \in (0, \frac{1}{R}]$ .

3. **Bernstein Bound for independent, zero-mean and bounded symmetric matrices:** Suppose  $\{X_i \in \mathbb{R}^{n \times n}\}$  are independent, zero-mean, symmetric random matrices and  $\|X_i\| \leq R$ , where  $\|\cdot\|$  is the spectral norm (the largest singular value). Let  $X = \sum_i X_i$ , and  $\sigma^2 = \|\sum_{i=1}^n \mathbb{E}X_i^2\|$ . Then  $\mathbb{P}(\|X\| \geq t) \leq 2n \exp(-\frac{t^2}{2Rt + 4\sigma^2})$ .

### 6.2 Matrix Functions

Given a real-valued function  $f : \mathbb{R} \rightarrow \mathbb{R}$  and a symmetric matrix  $A$  with eigen-decomposition  $A = V \Lambda V^\top$ , we define  $f(A) = V f(\Lambda) V^\top$ . This is compatible to the Taylor expansion  $f(x) = \sum_i \alpha_i x^i$ , as  $f(A) = \sum_i \alpha_i A^i = V (\sum_i \alpha_i f(\Lambda)) V^\top = V f(\Lambda) V^\top$ .

**Monotonicity:** Given  $f : \mathcal{D} \rightarrow \mathcal{C}$  and partial orders  $\leq_{\mathcal{C}}$  and  $\leq_{\mathcal{D}}$ , we call  $f$  is monotonically increasing w.r.t. these orders iff for all  $d_1 \leq_{\mathcal{D}} d_2 \in \mathcal{D}$  we have  $f(d_1) \leq_{\mathcal{C}} f(d_2)$ . For matrix functions, we use the PSD order as the ordering.

Property:

- If the scalar function  $f$  is monotonically increasing, then the matrix function  $X \rightarrow \text{Tr}(f(X))$  is monotonically increasing.
- $\log(\cdot)$  is monotonically increasing.
- The matrix function  $(\cdot)^2$  and  $\exp(\cdot)$  is **not** monotone.
- $\exp(A) \leq I + A + A^2$  for  $\|A\| \leq 1$ .
- $\log(I + A) \leq A$  for  $A \succ -I$ .
- (Lieb's theorem):  $f(A) := \text{Tr}(\exp(H + \log(A)))$  for some symmetric  $H$  is concave in the domain of PSD matrices. This is in particular useful with Markov inequality because  $\mathbb{P}(\|X\| \geq t) = \mathbb{P}(\lambda_n \geq t) \leq \mathbb{P}(\text{Tr}(\exp(\theta X)) \geq \exp(\theta t)) \leq \exp(-\theta t) \mathbb{E}(\text{Tr}(\exp(\theta X)))$ .

### 6.3 Spectral Sparsifiers

Given PD matrices  $A, B$  and  $\epsilon > 0$ , we say  $A \approx_\epsilon B$  iff  $\frac{1}{1+\epsilon} A \leq B \leq (1 + \epsilon) A$ . If  $L_G \approx_\epsilon L_{\tilde{G}}$  and  $|\tilde{E}| \ll |E|$ , we call  $\tilde{G}$  a spectral sparsifier of  $G$ .

Properties:

- Define  $c_G(T) := \sum_{e \in E \cap (T \times V \setminus T)} w(e)$  to be the value of the cut  $(T, V \setminus T)$ . If  $L_G \approx_\epsilon L_{\tilde{G}}$ , then for all  $T \subset V$ , we have  $\frac{1}{1+\epsilon} c_G(T) \leq c_{\tilde{G}}(T) \leq (1 + \epsilon) c_G(T)$ . The proof is by noticing  $c_G(T) = \mathbf{1}_T^\top L_G \mathbf{1}_T$ .
  - $L \approx_\epsilon \tilde{L} \Leftrightarrow \Pi_L \approx_\epsilon L^{+/2} \tilde{L} L^{+/2}$ , as  $A \leq B$  implies  $C^\top A C \leq C^\top B C$  for any  $C \in \mathbb{R}^{n \times n}$ .
  - For  $\epsilon \leq 1$ , if  $\|\Pi_L - L^{+/2} \tilde{L} L^{+/2}\| \leq \epsilon/2$ , then  $\Pi_L \approx_\epsilon L^{+/2} \tilde{L} L^{+/2}$ .
- Theorem:** Consider a connected graph  $G = (V, E, w)$ , with  $n = |V|$ . For any  $0 < \epsilon < 1$  and  $0 < \delta < 1$ , there exist sampling probabilities  $p_e$  for each edge  $e \in E$  s.t. if we include each edge  $e$  in  $\tilde{E}$  independently with probability  $p_e$  and set its weight  $\tilde{w}(e) = \frac{1}{p_e} w(e)$ , then with probability at least  $1 - \delta$  the graph

$\tilde{G} = (V, \tilde{E}, \tilde{w})$  satisfies  $L_G \approx_\epsilon L_{\tilde{G}}$  and  $|\tilde{E}| \leq O(n\epsilon^{-2} \log(n/\delta))$ . **8.3 Duality of Max Flow and Min Cut**

The proof uses Bernstein bounds to prove the concentration of the constructed random graph.

## 7 Solving Laplacian Linear Equations Approximately

Idea: solving Laplacian linear equations requires  $O(n^3)$  to get the Cholesky decomposition, which is expensive when the graph is large. By approximating the Laplacian, we can get an approximation of the solution quickly, especially in sparse graphs.

Given PSD matrix  $M$  and  $d \in \text{im}(M)$ , let  $Mx^* = d$ . We say that  $\tilde{x}$  is an  $\epsilon$ -approximate solution to  $Mx = d$  iff  $\|\tilde{x} - x^*\|_M^2 \leq \epsilon \|x^*\|_M^2$ , where  $\|x\|_M^2 = x^\top Mx$ . Note that any solution to  $Mx = d$  has the same  $\|\cdot\|_M^2$ , as they differ by a vector in the kernel of  $M$ .

**Theorem:** Given a Laplacian  $L$  of a weighted undirected graph  $G = (V, E, w)$  with  $|E| = m$  and  $|V| = n$  and a demand vector  $d \in \mathbb{R}^V$ , we can find  $\tilde{x}$  that is an  $\epsilon$ -approximate solution to  $Lx = d$ , using an algorithm that takes time  $O(m \log^c n \log(1/\epsilon))$  for some fixed constant  $c$  and succeeds with probability  $1 - 1/n^{10}$ . Note that without knowing the Cholesky decomposition in advance, the exact solution requires  $O(n^3)$  and  $m \leq n^2/2$ .

## Combinatorial Graph Algorithms

## 8 Maximum Flows and Minimum Cuts

### 8.1 Flows

Definition:

1.  **$s$ - $t$  flow:** A  $s$ - $t$  flow is a flow such that  $Bf = F(-\mathbf{1}_s + \mathbf{1}_t)$  for some  $F \geq 0$ , i.e., routes some unit from  $s$  to  $t$ .
2. **Maximum flow problem:** Given a source vertex and a sink vertex, maximize  $F$  such that  $Bf = F(-\mathbf{1}_s + \mathbf{1}_t)$  and  $0 \leq f \leq c$ .
3. **Path flow:** A  $s$ - $t$  path flow is a  $s$ - $t$  flow that only uses a simple path from  $s$  to  $t$ .
4. **Cycle flow:** A cycle flow is a flow that only uses a simple cycle, it does not create net-in or net-out.

**Path-cycle decomposition lemma:** Any  $s$ - $t$  flow can be decomposed to a sum of  $s$ - $t$  path flows and cycle flows such that the summation has at most  $\text{nnz}(f)$  terms.

There is always an optimal flow that can be decomposed to only path flows, as the cycle flow does not route anything from  $s$ - $t$  and removing all cycle flows in an optimal flow creates another optimal flow.

### 8.2 Cuts

Definition:

1.  **$s$ - $t$  cuts:** A  $s$ - $t$  cut is a cut  $(S, V \setminus S)$  such that  $s \in S$  and  $t \in V \setminus S$ .
2. **Minimum cut problem:** Given two vertices  $s$  and  $t$ , minimize the cut value  $c_G(S) = \sum_{e \in E \cap (S \times V \setminus S)} w(e)$  such that  $s \in S$  and  $t \in V \setminus S$ .

If there is no feasible  $s$ - $t$  flow, then define  $S$  to be the set of vertices reachable from  $s$ ,  $(S, V \setminus S)$  is a  $s$ - $t$  cut.