



# The Graph-Simplex Correspondence and its Algorithmic Foundations

Candidate No. 1032098  
St. Cross College, Oxford

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## Abstract

We present and study the graph-simplex correspondence—a tool providing a series of relationships between connected, weighted graphs on  $n$  vertices and simplices in  $n - 1$ -dimensional Euclidean space. The core of the correspondence is a bijection between graphs and hyperacute simplices, first uncovered by Miroslav Fiedler in the 1990s.

We begin by consolidating and elucidating Fiedler’s work on the subject and then proceed to expand on it in several ways. The first relates purely to the mathematical properties of the correspondence. Among other things, we extend the correspondence to the normalized Laplacian matrix (whereas previously only the combinatorial Laplacian has been investigated), develop new equations and inequalities relating the aspects of the simplex to those of the graph, and give an isometry between a graph’s “inverse combinatorial simplex” and an  $n$ -dimensional polytope arising from the Laplacian’s pseudoinverse. Here, the goal is to convince the reader that the graph-simplex correspondence can provide new insights into the structure of both graphs and simplices and consequently is worthy of being included in their mathematical toolbox. Secondly, we examine the algorithmic underpinnings of the correspondence. We explore how quickly various aspects of the correspondence can be computed—computing the simplex of a graph or the graph of a simplex, for example. After giving lower bounds on such questions, we turn to approximating various aspects of the correspondence. In particular, we focus on low dimensional representations of the simplices and provide theoretical justifications for recent empirical work on Laplacian eigenmaps.

The ubiquity of graphs in practical applications and, more recently popularized, geometric perspectives on data sets makes a connection between graphs and high-dimensional geometry an exciting avenue for research. We hope to demonstrate that the graph-simplex correspondence can provide meaningful insights at the intersection of these areas.

**Keywords:** Graph theory, simplex geometry, laplacian matrix, effective resistance, convex polyhedra.

## Lay Summary

The most significant features of mathematical research, to the astonishment of many, do not involve generating contrived calculus questions with which to torture sleep-deprived undergraduates. Instead of course, one central focus of such research is on further developing its different branches—geometry, probability, number theory, etc. Another concern, however, is to seek connections between these different areas. Such connections are elusive, but often point to some deeper and beautiful (stay with me) mathematical structure.

This dissertation is concerned with research of the latter type. In the 1990s, Miroslav Fiedler began exploring what we are calling the “graph-simplex correspondence”. The reader is invited to draw several dots on a piece of paper and connect each one with several (or all) of the others by drawing lines between them. There; you have just succeeded in drawing a graph. Your graph can be described by listing the dots (formally called vertices), and whether or not there is a connection between them. Regardless of how far apart the dots are on the page are, we are simply interested in whether or not there is a connection between each pair of vertices. Thus, a graph lacks inherent geometry; it can be described with lists only. A simplex, on the other hand, is essentially a triangle but generalized to higher dimensions. Is it therefore inherently geometric, which makes a connection between graphs and simplices all the more surprising.

When studying an abstract topic, one can never be sure where whether the work will remain only of interest to theoreticians or will find some practical application. That being said, we expect this research to be highly applicable—it will most likely help develop interstellar travel, 6G networks, and clarify broad macroeconomic trends. Just kidding. We do hope, however, that this work will serve to inspire researchers to include the graph-simplex correspondence as a tool to use when investigating graphs and/or simplices, and will thereby contribute to future research.

## Acknowledgements

## Contents

Abstract . . . . .	i
Lay Summary . . . . .	ii
Acknowledgements . . . . .	iii
List of Figures . . . . .	vi
Nomenclature . . . . .	viii
<b>1 Introduction</b>	<b>1</b>
1.1 Prior Work . . . . .	2
1.2 Contribution . . . . .	3
1.3 Organization . . . . .	7
<b>2 Background and Fundamentals</b>	<b>8</b>
2.1 General Notation . . . . .	8
2.2 Linear Algebra . . . . .	9
2.2.1 Pseudoinverse . . . . .	11
2.3 Spectral Graph Theory . . . . .	11
2.3.1 Laplacian Matrices . . . . .	12
2.4 Electrical Flows . . . . .	15
2.5 Simplices . . . . .	16
2.5.1 Dual Simplex . . . . .	19
2.5.2 Angles in a Simplex . . . . .	21
<b>3 The Graph-Simplex Correspondence</b>	<b>23</b>
3.1 Convex Polyhedra of Matrices . . . . .	23
3.1.1 The Inverse Polytope . . . . .	24
3.2 A Bijection Between Graphs and Simplices . . . . .	26
3.2.1 The Simplices of a Graph . . . . .	26
3.2.2 The Graph of a Simplex . . . . .	28
3.3 Examples & Simplices of Special Graphs . . . . .	30
3.3.1 Examples . . . . .	32
3.4 Properties of $\mathcal{S}_G$ and $\mathcal{S}_G^+$ . . . . .	33
3.5 Properties of $\widehat{\mathcal{S}}_G$ and $\widehat{\mathcal{S}}_G^+$ . . . . .	42
<b>4 Further Properties of the Correspondence</b>	<b>49</b>

4.1	General Properties of Dual Simplex . . . . .	49
4.2	Block Matrix Equations . . . . .	51
4.2.1	Applications . . . . .	54
4.3	Inequalities . . . . .	59
4.4	Quadrics . . . . .	60
4.5	Resistive Polytope . . . . .	62
4.6	Continuous Time Random Walks . . . . .	65
<b>5</b>	<b>Algorithmics</b>	<b>68</b>
5.1	Preliminaries . . . . .	68
5.2	Computational Complexity . . . . .	70
5.3	There and Back Again: A Tale of Graphs and Simplices . . . . .	75
5.4	Approximations . . . . .	80
5.4.1	Dimensionality Reduction: $\mathcal{S}^+$ . . . . .	81
5.4.2	Dimensionality Reduction: $\mathbf{L}_G$ . . . . .	83
5.4.3	Distance Matrix of $\mathcal{S}_G^+$ . . . . .	85
<b>6</b>	<b>Conclusion</b>	<b>87</b>
6.1	Open Problems and Future Directions . . . . .	88
	<b>Bibliography</b>	<b>89</b>
	<b>Appendix</b>	<b>93</b>
<b>A</b>	<b>Omitted Proofs</b>	<b>94</b>
A.1	Chapter 2 . . . . .	94
A.2	Chapter 3 . . . . .	99
A.3	Chapter 4 . . . . .	100
<b>B</b>	<b>Intuition Behind Effective Resistance</b>	<b>106</b>
<b>C</b>	<b>Figures</b>	<b>108</b>

## List of Figures

1.1	An illustration of the various objects and relationships in the graph-simplex correspondence. The combinatorial simplices sit to the right of $G$ , while the normalized simplices sit to the left. We see that $\mathcal{S}_G$ and $\mathcal{S}_G^+$ are duals to one another. The normalized simplices, on the other hand, are not each others duals as exemplified by the discontinuity of the arrows. The arrows between $G$ and each of its simplices demonstrates how the relationship is formed. . . . .	4
1.2	Two examples of graphs ((a) and (b)) and their combinatorial and normalized simplices. The combinatorial simplices are figures (b) and (e); the red (lighter) simplex is the inverse combinatorial simplex. The normalized simplices are figures (c) and (f); the yellow (lighter) simplex is the inverse normalized simplex. Observe that the upper graph on three vertices gives rise to simplices in $\mathbb{R}^2$ , while that on four vertices to simplices in $\mathbb{R}^3$ . The reader may notice that the inverse simplex seems to be smaller in volume—we will address this relationship in Chapter 3. . . . .	5
1.3	A visualization of how the correspondence can be used to apply graph-theoretic knowledge to the geometry of the simplices and vice versa. For example, leveraging that the geometry of $\mathcal{S}_G^+$ is intimately related to the effective resistances of $G$ and relating the equations of $\mathcal{S}_G^+$ to those of $\mathcal{S}_G$ via duality allows us to, say, express equations of spanning trees in terms of effective resistances. . . . .	6
2.1	(a) Simplices in dimensions one, two, and three. We wish the reader luck in visualizing a simplex (or anything really) in more than three dimensions. (b) Example of affine dependence and independence. Here $x_1, x_2, x_3$ are not affinely independent, as evidenced by the fact that $x_2 - x_1$ and $x_2 - x_3$ are parallel. $y_1, y_2, y_3$ on the other hand, are affinely independent; one can easily visualize the triangle formed by their convex hull. We emphasize that the arrows representing the difference between two vectors, e.g., $x_2 - x_1$ , represent their <i>direction only</i> and not their absolute position. . . . .	17
2.2	(a) The <i>directions</i> of altitudes in a simplex. We emphasize that the arrows do not represent the actual altitudes themselves, which are vectors and hence originate at the origin. (b) A one ( $\mathcal{T}_{\{2,3\}}$ ) and two ( $\mathcal{S}_{\{1,2,4\}}$ ) dimensional face of a three dimensional simplex. . . . .	18
2.3	An example of a simplex $\mathcal{T} \subseteq \mathbb{R}^2$ (in black) and its dual, $\mathcal{T}^*$ (in gray). The blue lines serve to emphasize the fact that the dual vertex $\gamma_1^*$ is orthogonal to the face $\mathcal{T}_{2,3}$ just as $\gamma_3$ is to $\mathcal{T}_{1,2}^*$ . . . . .	19
2.4	The angles in a simplex and its dual. The angle $\phi_{ij}^*$ between $\gamma_i^*$ and $\gamma_j^*$ is the same as that between $-\gamma_i^*$ and $-\gamma_j^*$ . From here we see that $\theta_{ij} + \phi_{ij}^* = \pi$ . . . . .	22

3.1	Two graphs and their product graph. . . . .	31
3.2	An illustration of the combinatorial simplex $\mathcal{S}_G \subseteq \mathbb{R}^3$ and its face $\mathcal{S}_{\{i\}^c}$ contained in the hyperplane $\mathcal{H}_i$ . . . . .	37
3.3	An illustration of the fact that, in general, $\widehat{\mathcal{S}}_{\{i\}^c}$ is not contained in $\widehat{\mathcal{H}}_i = \{\mathbf{x} : \langle \mathbf{x}, \widehat{\boldsymbol{\sigma}}_i^+ \rangle + \beta_i = 0\}$ . . . . .	46
4.1	A simplex $\mathcal{T} \subseteq \mathbb{R}^2$ and its corresponding Steiner circumscribed ellipsoid in orange (light) and circumscribed sphere in purple (dark). The arrows illustrate the semi-axes of the ellipsoid. . . . .	61
4.2	The resistive embedding (in orange; light) of a graph with three nodes sits in a plane (gray) which is parallel to the all ones vector. . . . .	64
4.3	Random walk dynamics plotted as points in the simplex. Figures (a) and (b) are plotted using the normalized simplex; figure (c) uses the normalized simplex. The underlying graph of Figure (a) has edges (1, 2), (2, 3), (3, 4), (2, 4), that underling (b) edges (1, 2) and (2, 3) and that of (c) is the complete graph $K_4$ . . . . .	66
5.1	Illustration of the relationships between the classes NP, NP-hard, and NP-complete. “Poly-time” refers to problems with polynomial time solutions. Such algorithms can trivially be verified in polynomial time, hence are a subset of problems in NP. We emphasize that the diagram is for intuitive purposes only, and may not reflect the true relationships between these classes. For example, in the unlikely case that $P=NP$ (i.e., all problems in NP are solvable in polynomial time), then the regions “Poly time”, NP and NP-complete coincide. . . . .	70
5.2	(a) A connected graph. (b) Two of its independent sets; one in red (dark) and one yellow (light). The red set constitutes a maximum sized independent set. (c) Two of its cliques; one in blue (dark), one turquoise (light). The blue set constitutes a maximum sized clique. . . . .	72
5.3	Summary of results for precise mappings. A slash refers to a difference in runtimes when the graph is available versus when it isn’t. The quantity before the slash indicates the runtime <i>without</i> the graph, after the slash the runtime <i>with</i> the graph. A question mark indicates that the runtime isn’t known. . . . .	77
C.1	The six unique unweighted graphs on four vertices, up to isomorphism, and a comparison of all of their simplices. Below each graph in the first row are its two combinatorial simplices ( $\mathcal{S}_G$ and $\mathcal{S}_G^+$ ), then its two normalized simplices ( $\widehat{\mathcal{S}}_G$ and $\widehat{\mathcal{S}}_G^+$ ), then its combinatorial and normalized simplex ( $\mathcal{S}_G$ and $\widehat{\mathcal{S}}_G$ ), followed in the final row by the two inverse simplices ( $\mathcal{S}_G^+$ and $\widehat{\mathcal{S}}_G^+$ ). The combinatorial simplex and its inverse are coloured blue and red respectively, and the normalized simplex and its inverse are in green and yellow respectively. The relative size of the the simplices in each subfigure are to scale but the same scale is not maintained across figures. . . .	108



## Nomenclature<sup>2</sup>

### Simplex Geometry

$\mathcal{T}$	General simplex	Section 2.5
$\mathcal{T}^*$	Dual simplex to $\mathcal{T}$	Section 2.5.1
$\Sigma(\mathcal{T})$	Vertex matrix of simplex $\mathcal{T}$	
$\mathcal{S}_G (\hat{\mathcal{S}}_G)$	(Normalized) Simplex of $G$	Section 3.2.1
$\mathcal{S}_G^+ (\hat{\mathcal{S}}_G^+)$	Inverse simplex of $\mathcal{S}_G (\hat{\mathcal{S}}_G)$	Section 3.2.2
$\mathcal{T} \upharpoonright_U, \mathcal{T}_U, \mathcal{T}[U]$	Face of simplex $\mathcal{T}$ restricted to $U$	Equation (2.19)
$\Sigma_G (\hat{\Sigma}_G)$	Vertex matrix of the simplex $\mathcal{S}_G (\hat{\mathcal{S}}_G)$	Section 3.2
$\Sigma_G^+ (\hat{\Sigma}_G^+)$	Vertex matrix of the simplex $\mathcal{S}_G^+ (\hat{\mathcal{S}}_G^+)$	
$\{\sigma_i\} (\{\hat{\sigma}_i\})$	Vertex vectors of (normalized) simplex	
$\mathbf{a}(\mathcal{T}_U)$	Altitude vector from $\mathcal{T}_U$ to $\mathcal{T}_{U^c}$	Section 2.5
$\mathbf{c}(\mathcal{T}_U)$	Centroid of simplex $\mathcal{T}_U$	Equation (2.21)
$\mathcal{E}(\mathcal{T})$	Steiner circumscribed ellipsoid of $\mathcal{T}$	Definition 4.1
$\bar{d}$	Avg. squared distance in a simplex	Equation (4.2)
$\xi$	Avg. squared distance of vertices minus $\bar{d}$	Equation (4.2)
$\mathbf{x}_{U^c}$	Barycentric coordinate for face $\mathcal{T}_U$	
$\mathcal{S}_0$	Canonical/Centred Simplex of $\mathcal{S}$	Definition 2.5
$\cong$	Translational Congruency between simplices	Section 2.5
$[\mathcal{T}]$	Congruence class of simplices	Equation (2.20)
$\phi_{ij} (\phi_{ij}^+)$	Angle between $\sigma_i (\sigma_i^+)$ and $\sigma_j (\sigma_j^+)$	
$\theta_{ij} (\theta_{ij}^+)$	Angle between $\mathcal{S}_{\{i\}^c} (\mathcal{S}_{\{i\}^c}^+)$ and $\mathcal{S}_{\{j\}^c} (\mathcal{S}_{\{j\}^c}^+)$	Section 2.5.2
$\mathcal{H}_i (\mathcal{H}_i^+)$	Hyperplane containing $\mathcal{S}_{\{i\}^c} (\mathcal{S}_{\{i\}^c}^+)$	Equation (3.7)

### Graph Theory

$G = (V, E, w)$	Undirected, connected, and weighted graph	Section 2.3
$V(G), E(G)$	Vertex set and edge set of graph $G$	
$\mathbf{A}_G$	Adjacency matrix of graph $G$	
$\mathbf{W}_G$	Weight matrix of graph $G$	
$G[U], G_U$	Graph restricted to vertices in $U$	Section 2.3
$w_G(i, j)$	Weight of edge $(i, j)$ in $G$	
$\partial_G(i)$	Set of neighbours of $i$ in $G$	Equation (2.6)
$\partial_G U$	Cut set of $U$ in $G$	
$w_G(i)$	Weight of vertex $i \in V(G)$	
$\text{vol}_G(U)$	Volume of set $U$ , i.e., $\sum_{i \in U} w(i)$	Equation (2.7)

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<sup>2</sup>The subscript  $G$  and paranthetical  $(G)$  is often dropped from relevant symbols.

$\Gamma_G$	Total weight of all spanning trees in $G$	Equation (2.16)
$r_G^{\text{eff}}(i, j)$	Effective resistance between $i$ and $j$	Definition 2.2
$\mathbf{R}_G$	Effective resistance matrix	Section 2.4
$R_G$	Total effective resistance of $G$	
$\mathcal{R}_G$	Effective Polytope of $G$	Equation (4.17)

## Linear Algebra & Spectral Graph Theory

$\mathbf{L}_G$	Combinatorial Laplacian Matrix of $G$	Equation (2.8)
$\hat{\mathbf{L}}_G$	Normalized Laplacian Matrix of $G$	Equation (2.11)
$\mathcal{L}_G$	Quadratic form associated with $\mathbf{L}_G$	Equation (2.10)
$\hat{\mathcal{L}}_G$	Quadratic form associated with $\hat{\mathbf{L}}_G$	Equation (2.13)
$\{\lambda_i(G)\} (\{\lambda_i(G)\})$	Eigenvalues of $\mathbf{L}_G$ ( $\hat{\mathbf{L}}_G$ )	Section 2.3.1
$\mathbf{\Lambda}_G$ ( $\hat{\mathbf{\Lambda}}_G$ )	Diagonal Eigenvalue matrix of $\mathbf{L}_G$ ( $\hat{\mathbf{L}}_G$ )	
$\{\varphi_i(G)\} (\{\hat{\varphi}_i(G)\})$	Eigenvectors of $\mathbf{L}_G$ ( $\hat{\mathbf{L}}_G$ )	
$\Phi_G$ ( $\hat{\Phi}_G$ )	Eigenvector matrix of $\mathbf{L}_G$ ( $\hat{\mathbf{L}}_G$ )	
$\mathbf{Q}^+$	Pseudoinverse of matrix $\mathbf{Q}$	Section 2.2.1
$\Delta$	Vector of diagonals of $\mathbf{L}_G^+$	
$\dim \mathbf{Q}$	Dimension of space spanned by $\mathbf{Q}$	
$\text{range } \mathbf{Q}$	Range of $\mathbf{Q}$	
$\ker \mathbf{Q}$	Kernel of $\mathbf{Q}$	
$\ \cdot\ _p$	$p$ -norm in $\mathbb{R}^d$	
$\perp$	Perpendicular to; orthogonal complement	

## Miscellaneous

$\mathbb{R}$	Real numbers	Section 2.1
$\mathbb{Q}$	Rational numbers	
$\mathbb{N}$	Natural numbers	
$\delta_{ij}$	Kronecker delta function	
$\chi_U$	Indicator for event $U$	
$\chi_U$	Indicator vector for set $U$	
$\mathbf{D}(\mathcal{X})$	Squared distance matrix of set of points $\mathcal{X}$	
$\text{conv}(\mathcal{X})$	Convex hull of set of points $\mathcal{X}$	Equation (2.1)

## Introduction

*Confusion is the natural state of the mathematician.*

— Lior Silberman

*What if I slept a little more and forgot about all this nonsense.*

— Franz Kafka

This thesis is concerned with uniting two fundamental mathematical objects: the graph and the simplex. A graph is fundamentally a *combinatorial* object—it can be described purely by means of finite sets and must not refer to any underlying geometric space. Simplices, on the other hand, are inherently geometric. Essentially a high dimensional triangle, any complete description of a simplex must include certain geometric information; the distance between its vertices, for example. Thus, a simplex cannot be divorced from an underlying metric space.

The pessimistic reader may interject that graphs can *of course* be viewed geometrically. For instance, he or she continues, it is well-known that the shortest path between two vertices constitutes a metric on the graph. We in turn interrupt the interrupter and remark that while graphs *can* be given geometric interpretations, it is *not necessary* that they are. Indeed, a graph can be described by two finite lists: a list of its vertices and a second of the connections between these vertices (perhaps with weights given to the edges). No underlying geometric space need be defined.

Due to the combinatorial nature of the graph and the geometric nature of the simplex, a connection between the two objects might seem unlikely a priori. It is precisely this fact which makes such a connection worth studying. The original link between graphs and simplices was uncovered by Miroslav Fiedler in his 1993 paper entitled “A geometric approach to the Laplacian matrix of a graph” [Fie93]. Here he introduced the machinery needed to define what will be a central object in our study of the relationship between graphs and simplices: a bijection between connected, weighted graphs and hyperacute simplices. However, we will be concerned with more than this single bijective mapping. Indeed, what we will term the *graph-simplex correspondence* includes four (not necessarily bijective) mappings between graphs and simplices. They arise as natural extensions of Fiedler’s original work.

Unfortunately (we believe) for the mathematical community, Fiedler’s investigations in this

area have gone relatively unnoticed. Convinced as we are of the beauty and utility of such work, this dissertation aims to present Fiedler’s results in a concise, clarifying, and self-contained fashion, expand on the mathematical foundations of the correspondence, and explore new applications thereof. Our primary motivation is to convince the reader that the graph-simplex correspondence is a useful tool for studying both graphs and simplices, and can shed light on various aspects of both of these objects which are overlooked by other methods. Given the ubiquity of graphs in the mathematical sciences, both in theory and in application, the possibility of a new tool with which to analyze them holds possibly vast promise.

### §1.1. Prior Work

As we stated above, Miroslav Fiedler was the “primary mover” in uncovering the graph-simplex correspondence [Fie93, Fie05, Fie11]. This work was remained largely unnoticed until very recently, when Devriendt and Van Mieghem used the simplex geometry of the graph as intuition behind investigating a graph’s “best conducting node” [VMDC17] and then provided a summary of Fiedler’s results [DVM18]. All of this work is concerned with a connected and possibly weighted graph  $G$  and what we will henceforth refer to as its *combinatorial simplices*, denoted  $\mathcal{S}_G$  and  $\mathcal{S}_G^+$ . (This is in contrast its *normalized simplices*, which we will define and explore later.)

Fiedler uncovered the graph-simplex correspondence by means of a more general relationship between matrices and simplices. In particular, he associated with each symmetric matrix  $\mathbf{Q}$  whose range space is orthogonal to the all ones vector (i.e.,  $\mathbf{Q}\mathbf{1} = \mathbf{0}$ ) a unique (up to congruence) hyperacute simplex. Since the Laplacian matrix  $\mathbf{L}_G$  of a connected, weighted graph  $G$  obeys this constraint, this associates with each such graph a hyperacute simplex  $\mathcal{S}_G^+$ . For reasons which will become clear later, we call  $\mathcal{S}_G^+$  the *inverse* (combinatorial) simplex of  $G$ . Fiedler associated  $\mathbf{L}_G$  and  $\mathcal{S}_G^+$  by means of a block matrix equation which involved several somewhat complex components, including the Gram matrix of the outer normals of the simplex and the radius of its circumscribed ellipsoid. While this matrix representation is useful for various reasons—elaborated upon in Section 4.2—the correspondence can be simplified by means of working solely with the graph’s Laplacian matrix. This is the approach recently taken by Devriendt and Van Mieghem [DVM18]. They simplify and summarize Fiedler’s main results and focus mainly on one side of the correspondence—namely, given  $G$ , they examine the properties of its associated simplices  $\mathcal{S}_G$  and  $\mathcal{S}_G^+$ . Devriendt and Van Mieghem also make explicit the connection between a graph’s (combinatorial) simplex,  $\mathcal{S}_G$ , and its inverse simplex,  $\mathcal{S}_G^+$ . While Fiedler was aware of the existence of  $\mathcal{S}_G$ —he later examines the properties of its circumscribed ellipsoid [Fie05]—the majority of his work on the graph-simplex correspondence focuses on the inverse simplex,  $\mathcal{S}_G^+$ .

Due to Fiedler’s more general interest in the relationship between matrices and simplices, the majority of his results pertaining to the graph-simplex correspondence are implicit consequences thereof. His block matrix approach lends itself more readily to the study of volumes, angles and

circumscribed quadrics, which thus constitute the core of Fiedler’s results. Devriendt and Van Mieghem make many of these implicit results explicit, giving equations which directly relate properties of the graph to those of the simplex. Since many of these results will be stated in later Chapters, we do not list them here.

Very recently, the graph-simplex correspondence has also been applied in computer science to the problem of low dimensional graph embeddings. Such embeddings seek to embed the vertices of a given graph in Euclidean space (ideally a space whose dimension is much lower than the number of nodes of the graph) in such a way that particular graph properties are preserved [CZC18]. Torres, Chan, and Eliassi-Rad examine the use of low-dimensional embeddings of the simplex as possible graph embeddings. [TCER19]. They give empirical results suggesting that this approach is highly effective for link prediction and graph reconstruction.

While this summarizes all the work done explicitly on the graph-simplex correspondence, the more general topic of geometric graph theory has garnered attention from many sources. There is a wide literature on graph embeddings and geometric graph visualizations (e.g., [Tam13, BCD<sup>+</sup>07, KK<sup>+</sup>89, FR91, DFPP90]), an area which typically seeks to represent a graph (sometimes multiple graphs [EKLN05, ELM16, BKR12]) in the plane or  $\mathbb{R}^3$  under certain conditions. For example, we might seek an embedding in which the edges do not cross (a “planar” embedding [Kan93, NR04]), or one in which the vertices are represented as geometric objects [DH97].

Computer scientists have also leveraged graph theory to analyze data. Datum with  $k$  features can naturally be viewed as points in  $k$  dimensional space—the “feature space”. Laplacian Eigenmap methods [BN02] assume that the observed data lies on a lower dimensional manifold within the feature space and seeks to develop useful representations of the data. A distinct approach involves trying to generate a lower dimensional representation of the data given its graph structure (typically represented as an “affinity matrix”). This general approach is usually referred to as *spectral embedding* [BH03, BDR<sup>+</sup>04], and admits different instantiations, including *Principal Component Analysis (PCA)* [Jol11], *Multi-dimensional Scaling (MDS)* [KW78, CC00], and *Local Linear Embedding (LLE)* [RS00]. Related but more general work seeks to apply techniques from topology to find structure in graphs, both from a purely theoretical viewpoint (e.g., topological graph theory [GT01]), and more recently with applications to complex network in mind [SCL18, WMRB15].

There has also been work on graphs arising from general polyhedra, e.g., Steinitz’s theorem [Ste22]. However, this work is not spectral in nature and therefore quite unrelated to the graph-simplex correspondence.

## §1.2. Contribution

We provide a self-contained treatise of the graph-simplex correspondence, accessible to those with only basic knowledge of linear algebra and graph theory. We include Fiedler’s main results on the topic, as well those newly discovered results of Devriendt and Van Mieghem [DVM18]. We

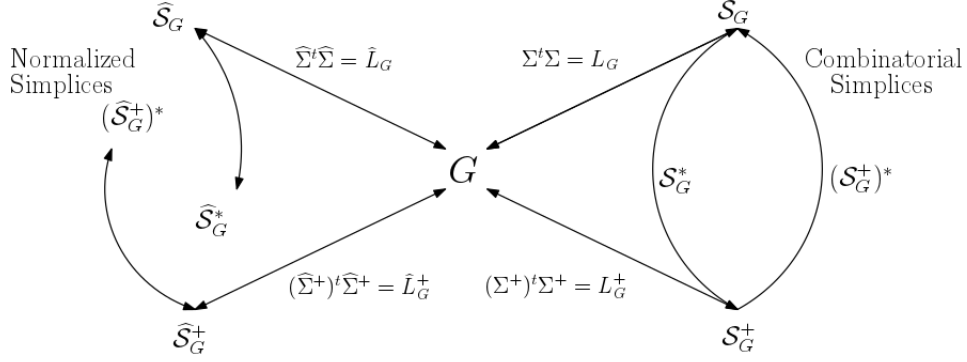


Figure 1.1: An illustration of the various objects and relationships in the graph-simplex correspondence. The combinatorial simplices sit to the right of  $G$ , while the normalized simplices sit to the left. We see that  $\mathcal{S}_G$  and  $\mathcal{S}_G^+$  are duals to one another. The normalized simplices, on the other hand, are not each others duals as exemplified by the discontinuity of the arrows. The arrows between  $G$  and each of its simplices demonstrates how the relationship is formed.

also expand on these results in several ways, enumerated below. For a preliminary taste of the correspondence, see the examples in Figure 1.2.

- Introduction of the dual simplex.** Although at first seemingly unrelated to the correspondence itself, we provide a novel mathematical treatment of an object we call the “dual simplex” of a given simplex. This object was remarked upon by Fiedler in his 2011 book [Fie11], but he did not investigate its properties. We present several general properties of the dual simplex (e.g., Lemmas 2.12, 2.13, 3.23, 4.1) and use it to frame the graph-simplex correspondence, especially of the normalized Laplacian (see below).
- Extension of correspondence to the normalized Laplacian.** While Fiedler (implicitly) and Devriendt and Van Mieghem (explicitly) studied the correspondence by means of the combinatorial Laplacian of a graph, we expand the correspondence to the “normalized” Laplacian. This matrix also describes the complete structure of the graph, but is more intimately related to several of its features, such as describing random walk dynamics [CG97]. We introduce this new mapping along with the original in Section 3.2. We then study the properties of the simplex associated to the normalized Laplacian, which we term the “normalized” simplex. Somewhat surprisingly, the normalized simplex is a significantly different object than the combinatorial simplex. Its analysis also proves more complicated because, as we will show, the inverse normalized simplex is *not* the dual of the normalized simplex in general, whereas the combinatorial simplex and its inverse are duals to one another. We refer the reader to Figure 1.1 for an illustration of the relationship between a graph and its various simplices.
- New graph equations and inequalities.** Combining Fiedler’s block matrix approach with that of Devriendt and Van Mieghem, we are able to uncover several new relationships. For

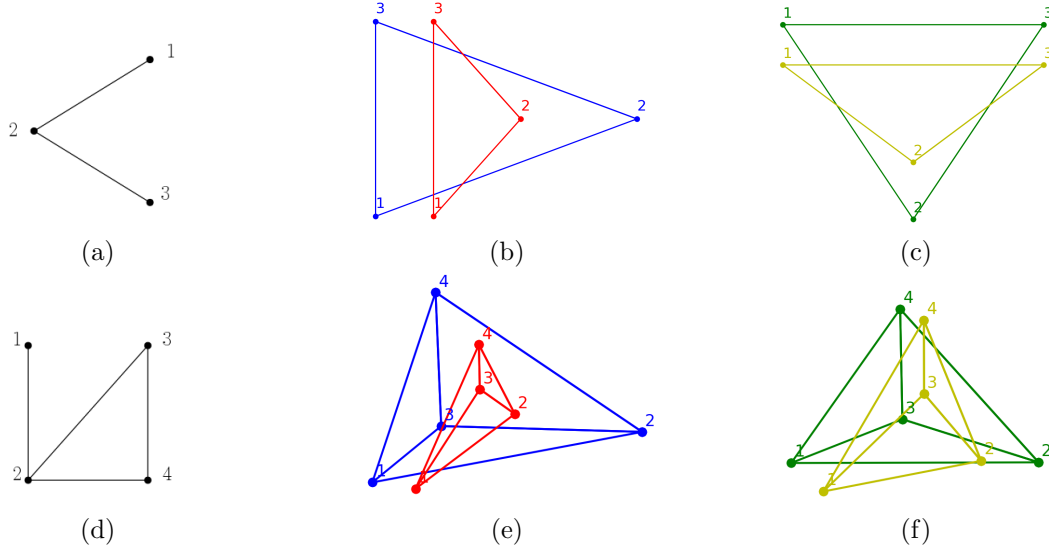


Figure 1.2: Two examples of graphs ((a) and (b)) and their combinatorial and normalized simplices. The combinatorial simplices are figures (b) and (e); the red (lighter) simplex is the inverse combinatorial simplex. The normalized simplices are figures (c) and (f); the yellow (lighter) simplex is the inverse normalized simplex. Observe that the upper graph on three vertices gives rise to simplices in  $\mathbb{R}^2$ , while that on four vertices to simplices in  $\mathbb{R}^3$ . The reader may notice that the inverse simplex seems to be smaller in volume—we will address this relationship in Chapter 3.

example, between the entries of the Laplacian and the total weight of spanning trees in the graph (Lemma 4.8), between the vertices of  $\mathcal{S}_G$  and the volumes of its faces (Equation (4.12)), between the Laplacian and the volumes of facets of  $\mathcal{S}$  (Equation (4.11)). We also obtain new inequalities pertaining to the spanning trees of  $G$  (Lemma 4.13). Figure 1.3 demonstrates how one can utilize the correspondence to translate between specific graph and simplex properties.

- **Link between  $\mathcal{R}_G$  and  $\mathcal{S}_G^+$ .** We also uncover a link between the simplex of a graph and a geometric object related to the effective resistance of the graph, which we call the “resistive polytope”, denoted  $\mathcal{R}_G$ . It seems that the existence of this object has been previously acknowledged (e.g., [Gha15]), but never rigorously studied. This material appears in Section 4.5.
- **Algorithmic analysis of the correspondence.** Perhaps most significantly, we initiate the study of the algorithmic foundations of the correspondence (Chapter 5). This entails three distinct aspects.

1. **Consequences for computational complexity.** We explore several consequences for computational complexity. Owing to the pervasiveness of graphs in theory and application, the complexity classes of many graph-theoretic problems are well established (e.g., computing maximum-cuts and independent sets are “hard”, while spanning trees are “easy”, etc.) If, via the correspondence, such problems have analogues in the simplex then this has implications concerning the difficulty of these geometric problems.

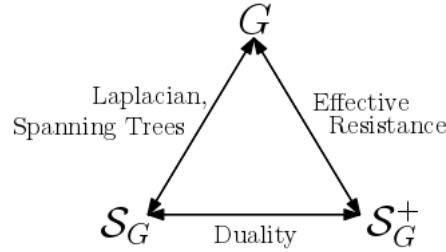


Figure 1.3: A visualization of how the correspondence can be used to apply graph-theoretic knowledge to the geometry of the simplices and vice versa. For example, leveraging that the geometry of  $\mathcal{S}_G^+$  is intimately related to the effective resistances of  $G$  and relating the equations of  $\mathcal{S}_G^+$  to those of  $\mathcal{S}_G$  via duality allows us to, say, express equations of spanning trees in terms of effective resistances.

Moreover, while the analogous problems in the simplex domain may have known to be easy or hard in general convex polytopes, understanding the complexity in (hyperacute) simplices can yield an improved understanding of the hardness “threshold” for such problems. We give several examples of such results in Section 5.2.

2. **Lower bounds on computing the correspondence.** We then explore the natural question of whether various aspects of the correspondence can be computed efficiently. For example, given  $G$  how quickly can we compute  $\mathcal{S}_G$  or  $\mathcal{S}_G^+$ ? What about computing  $\mathcal{S}_G$  given  $\mathcal{S}_G^+$ , or vice versa? Our results in this space are mostly negative; transitioning between many of these objects require time no less than that required to perform an eigendecomposition of a Laplacian matrix. This is perhaps to be expected given that the mapping is based on the eigendecomposition of the Laplacian matrix, but it is not immediate. It is a priori feasible that the various relationships between the eigenvalues and eigenvectors which define the vertices of the simplices are computable more quickly than the eigenvalues and eigenvectors themselves.
3. **Approximations.** Finally, we explore several approximations. Given that the simplex of a graph with  $n$  vertices lives in  $\mathbb{R}^{n-1}$ —a high dimensional space—we might hope that we can “approximately” embed it in lower dimensions. We explore this possibility in Section 5.4.1. We also demonstrate that  $k$ -rank approximations to the Laplacian give rise to convex polyhedra in  $\mathbb{R}^k$ , and that these polyhedra approximate the simplex  $\mathcal{S}_G$  in various ways (with the accuracy depending on the size of the  $k + 1$ -st largest eigenvalue of  $\mathbf{L}_G$ ). We view this work as providing theoretical justification for recent work of Torres *et al.* mentioned in the previous section [TCER19].

We end by noting that while the dissertation is largely theoretical in nature, code implementing various aspects of the graph-simplex correspondence was implemented by the author, and is publicly available [Chu19]. The figures throughout the manuscript were either generated by this software (via PYTHON and MATPLOTLIB), or by the drawing editor IPE [Che14].



### §1.3. Organization

The rest of the thesis will be organized as follows. Chapter 2 will present the relevant background material in the areas of linear algebra, spectral graph theory, and simplex geometry. Here we will also define and make some preliminary explorations of the dual simplex. The background material of Sections 2.1, 2.2, and 2.3.1 is quite standard; the reader familiar with these subject areas should be able to skip them without too much trouble. We encourage all readers to peruse Section 2.5 because, for one, the field of simplex geometry is less well studied in general than the others and secondly, as stated above, we provide a novel treatment of the dual simplex. Chapters 3 and 4 then explore the mathematical aspects of the graph-simplex corresponding, and Chapter 5 presents the algorithmic foundations. In order to conserve space, we have moved those proofs which were presented by either Fiedler or Devriendt and Van Mieghem to the appendix, as well as those which are elementary and not directly related to the material at hand (i.e., those pertaining to background material).

## Background and Fundamentals

*I have got my result, but I do not know yet how to get it.*

— Carl Friedrich Gauss

This chapter is devoted to introducing the pre-requisite knowledge necessary to grapple with the material in subsequent sections. The subject matter of this dissertation lies at the intersection of several mathematical topics, ensuring that any treatment of the material will give rise to notational challenges. Nevertheless, we have strived—courageously, in the author’s unbiased opinion—to use standard notation wherever possible in the hopes that readers familiar with spectral graph theory may skip this background material without losing the plot. Omitted proofs can be found in Appendix A.1.

### §2.1. General Notation

We use the standard notation for sets of numbers:  $\mathbb{R}$  (reals),  $\mathbb{N}$  (naturals),  $\mathbb{Z}$  (integers). We use the subscript  $\geq 0$  (resp.,  $> 0$ ) to restrict a relevant set to its non-negative (resp., positive) elements ( $\mathbb{R}_{\geq 0}$ , for example). We will often introduce new notation or definitions by using the notation  $\stackrel{\text{def}}{=}$ . The complement of a set  $U$  (with respect to what will be clear from context) is denoted  $U^c$ . Given a set of scalars  $K$ , we let  $K^{n \times m}$  denote the set of  $n \times m$  matrices ( $n$  rows and  $m$  columns) with elements in  $K$ . Matrices will typically be denoted by uppercase letters in boldface, e.g.,  $\mathbf{Q} \in K^{n \times m}$ . Matrices will also often be referred to as linear transformations and written, for example, as  $\mathbf{Q} : K^m \rightarrow K^n$ . We let  $\mathbf{Q}(i, \cdot)$  (resp.,  $\mathbf{Q}(\cdot, i)$ ) denote the  $i$ -th row (resp., column) of the matrix  $\mathbf{Q}$ . For a set  $U$ ,  $K^U$  denotes the set of all functions from  $U$  to  $K$ . Elements of  $K^U$  are also called vectors. For any  $n \in \mathbb{N}$ , set  $[n] \stackrel{\text{def}}{=} \{1, 2, \dots, n\}$ . As usual, we let  $K^n = K^{[n]}$ . Vectors will typically be denoted by lowercase boldcase letters. Lowercase greek letters will often be used for scalars. It will often be intuitively useful to identify vectors with their endpoints, rather than the traditional “arrow” originating from the origin. When this is the case, we will often use the word point instead of vector. We emphasize that they are formally the same object.

The standard inner product on  $\mathbb{R}^d$  is denoted as  $\langle \cdot, \cdot \rangle$ , that is,  $\langle \mathbf{x}, \mathbf{y} \rangle = \sum_i x(i)y(i)$ . Elementary properties of the inner product will often be used without justification, such as its bilinearity:

$\langle \mathbf{x}, \alpha \mathbf{y}_1 + \mathbf{y}_2 \rangle = \langle \mathbf{x}, \alpha \mathbf{y}_1 \rangle + \langle \mathbf{x}, \mathbf{y}_2 \rangle$  for  $\alpha \in \mathbb{R}$ . For  $n \in \mathbb{N}$ , let  $\mathbf{0}_n \in \mathbb{R}^n$  and  $\mathbf{1}_n \in \mathbb{R}^n$  be the vectors of all zeroes and all ones. Let  $\mathbf{I}_n$  and  $\mathbf{J}_n$  refer to the  $n \times n$  identity matrix and all-ones matrix respectively (so  $\mathbf{J}_n = \mathbf{1}_n \mathbf{1}_n^t$ ). When the dimension  $n$  is understood from context, will typically omit it as a subscript. We use  $\chi(E)$  or  $\chi_E$  as the indicator of an event  $E$ , i.e.,  $\chi(E) = 1$  if  $E$  occurs, and 0 otherwise. For example,  $\chi(i \in U) = 1$  if  $i \in U$ , and 0 if  $i \in U^c$ . Similarly, for  $U \subseteq K$ ,  $\chi_U \in \mathbb{R}^K$  is the indicator vector of the set  $U$ , so  $\chi_U(i) = \chi(i \in U)$ . By  $\text{diag}(x_1, x_2, \dots, x_n)$  we mean the  $n \times n$  matrix  $\mathbf{Q}$  entries  $\mathbf{Q}(i, i) = x_i$  and  $\mathbf{Q}(i, j) = 0$  for  $i \neq j$ . Given vectors  $\mathbf{v}_1, \dots, \mathbf{v}_n$ , we will often denote by  $(\mathbf{v}_1, \dots, \mathbf{v}_n)$  or  $(\mathbf{v}_i)$  the matrix whose  $i$ -th column is  $\mathbf{v}_i$ . The *Gram matrix* of a set of vectors  $\mathbf{x}_1, \dots, \mathbf{x}_n$  is the matrix with  $(i, j)$ -th entry  $\langle \mathbf{x}_i, \mathbf{x}_j \rangle$ . The  $i$ -th coordinate of a vector  $\mathbf{x}$  will be denoted either by  $\mathbf{x}(i)$  or simply  $x(i)$ . We trust this will not be overly confusing. For  $1 \leq p < \infty$ , the  $p$ -norm of  $\mathbf{x} \in \mathbb{R}^d$  is  $\|\mathbf{x}\|_p = \left( \sum_{i=1}^d x_i^p \right)^{1/p}$ , while the  $0$ -norm of  $\mathbf{x}$  is the number of non-zero entries of  $\mathbf{x}$ , and is denoted by  $\|\mathbf{x}\|_0$ . Given a vector or matrix, we use the superscript  $t$  to denote it's transpose, i.e., given  $\mathbf{Q}$ ,  $\mathbf{Q}^t$  is defined as  $\mathbf{Q}^t(i, j) = \mathbf{Q}(j, i)$ . We will sometimes use the notation  $\perp$  to mean “orthogonal to”, so  $\mathbf{x} \perp \mathbf{y}$  iff  $\langle \mathbf{x}, \mathbf{y} \rangle = 0$ . We will often use the shorthand “iff” to mean “if and only if”. We use  $\delta_{ij}$  to denote the Kronecker delta function, i.e.,  $\delta_{ij} = 1$  if  $i = j$  and 0 otherwise. We may sometimes include a comma and write  $\delta_{i,j}$ .

A set  $\mathcal{X} \subseteq \mathbb{R}^m$  is *convex* if for all  $\mathbf{x}, \mathbf{y} \in \mathcal{X}$  and  $\lambda \in (0, 1)$ ,  $\lambda \mathbf{x} + (1 - \lambda) \mathbf{y} \in \mathcal{X}$ . The *convex hull* of a finite set of points  $X = \{\mathbf{x}_1, \dots, \mathbf{x}_k\} \subseteq \mathbb{R}^n$  is

$$\text{conv}(\mathcal{X}) \stackrel{\text{def}}{=} \left\{ \sum_{\ell} \alpha_{\ell} \mathbf{x}_{\ell} : \sum_{\ell} \alpha_{\ell} = 1, \alpha_{\ell} \geq 0 \right\}, \quad (2.1)$$

or equivalently, the smallest convex set containing  $X$  [GKPS67]. We will often denote the *squared distance matrix* of  $\mathcal{X}$  by  $\mathbf{D}(\mathcal{X}) \in \mathbb{R}^{|\mathcal{X}| \times |\mathcal{X}|}$ , whose entries are given by  $\mathbf{D}(\mathbf{x}, \mathbf{y}) = \|\mathbf{x} - \mathbf{y}\|_2^2$ .

## §2.2. Linear Algebra

We assume familiarity with the basic linear algebraic notions—determinants, dimension, span, etc. We use the standard notation for these— $\det$ ,  $\dim$ ,  $\text{span}$ , etc. All relevant background material can be found in a standard reference, e.g. [Ax197]. We begin by stating a well-known but substantial result first proved by Cauchy (see [Haw75] for the relevant history), which initiated the systematic study of the spectrum of matrices and which underpins the results in this dissertation.

**THEOREM 2.1** (Spectral Theorem for real matrices). *Every real, symmetric  $n \times n$  matrix has a set of  $n$  orthogonal eigenvectors and real eigenvalues.*

Next we state a result which will underpin our construction of the “dual simplex” in Section 2.5.1.

**LEMMA 2.1.** *Let  $\mathbf{v}_1, \dots, \mathbf{v}_k$  be a set of linearly independent vectors in  $\mathbb{R}^n$ . There exists a set of*

vectors,  $\mathbf{u}_1, \dots, \mathbf{u}_k$  such that  $\langle \mathbf{v}_i, \mathbf{u}_j \rangle = \delta_{ij}$  for all  $i, j \in [k]$ . The collections  $\{\mathbf{v}_i\}$  and  $\{\mathbf{u}_i\}$  are called any of biorthogonal, dual or sister sets (or bases if  $k = n$ ).

We present a simple observation to do with dual bases which will be useful in later sections. As usual, the reader can find the proof in Appendix A.1.

**OBSERVATION 2.1.** Let  $\{\mathbf{v}_1, \dots, \mathbf{v}_n\} \subseteq \mathbb{R}^n$  be a set of linearly independent vectors. The sister basis given by Lemma 2.1 is unique. Moreover, if we let  $\mathbf{M} \in \mathbb{R}^{n \times n}$  have as columns the vectors  $\mathbf{v}_i$ , and  $\mathbf{Q}$  have as columns the vectors of the sister basis, then  $\mathbf{Q}^t = \mathbf{M}^{-1}$ .

Let  $\mathbf{M} \in \mathbb{R}^{n \times n}$ . We recall that a vector  $\boldsymbol{\varphi}$  satisfying  $\mathbf{M}\boldsymbol{\varphi} = \lambda\boldsymbol{\varphi}$  is an *eigenvector* of  $\mathbf{M}$ , and call  $\lambda$  the associated *eigenvalue*. If  $\mathbf{M}$  is real and symmetric, then the spectral theorem dictates that there exists an orthonormal basis consisting of eigenvectors  $\{\boldsymbol{\varphi}_1, \boldsymbol{\varphi}_2, \dots, \boldsymbol{\varphi}_n\}$  of  $\mathbf{M}$  whose corresponding eigenvalues  $\{\lambda_1, \dots, \lambda_n\}$  are all real. Let  $\boldsymbol{\Phi} = (\boldsymbol{\varphi}_1, \boldsymbol{\varphi}_2, \dots, \boldsymbol{\varphi}_n)$  be the matrix whose  $i$ -th column is the  $i$ -th eigenvector of  $\mathbf{M}$ , and set  $\boldsymbol{\Lambda} = \text{diag}(\lambda_1, \dots, \lambda_n)$ . Observe that

$$\mathbf{M}\boldsymbol{\Phi} = \mathbf{M}(\boldsymbol{\varphi}_1, \dots, \boldsymbol{\varphi}_n) = (\mathbf{M}\boldsymbol{\varphi}_1, \dots, \mathbf{M}\boldsymbol{\varphi}_n) = (\lambda_1\boldsymbol{\varphi}_1, \dots, \lambda_n\boldsymbol{\varphi}_n) = \boldsymbol{\Phi}\boldsymbol{\Lambda}. \quad (2.2)$$

Moreover, if  $\{\boldsymbol{\varphi}_i\}_i$  are assumed to be orthonormal then  $\boldsymbol{\Lambda}\boldsymbol{\Lambda}^T = \mathbf{I}$  from which it follows from (2.2) that

$$\mathbf{M} = \boldsymbol{\Phi}\boldsymbol{\Lambda}\boldsymbol{\Phi}^t = \sum_{i \in [n]} \lambda_i \boldsymbol{\varphi}_i \boldsymbol{\varphi}_i^t, \quad (2.3)$$

which is called the *eigendecomposition* of  $\mathbf{M}$ . If  $\mathbf{M}$  obeys  $\mathbf{x}^t \mathbf{M} \mathbf{x} \geq 0$  for all  $\mathbf{x} \in \mathbb{R}^n$ , then we call  $\mathbf{M}$  *positive semidefinite (PSD)*. Importantly, if  $\mathbf{M}$  is PSD, then its eigenvalues are non-negative. Indeed, with the eigendecomposition of  $\mathbf{M}$  as above,

$$0 \leq \boldsymbol{\varphi}_k^t \mathbf{M} \boldsymbol{\varphi}_k = \sum_{i \in [n]} \lambda_i \boldsymbol{\varphi}_k^t \boldsymbol{\varphi}_i \boldsymbol{\varphi}_i^t \boldsymbol{\varphi}_k = \lambda_k \boldsymbol{\varphi}_k^t \boldsymbol{\varphi}_k \boldsymbol{\varphi}_k^t \boldsymbol{\varphi}_k = \lambda_k,$$

for any  $k$  since  $\{\boldsymbol{\varphi}_i\}$  are orthonormal. Thus, if  $\mathbf{M}$  is PSD we define

$$\mathbf{M}^{1/2} \stackrel{\text{def}}{=} \boldsymbol{\Phi} \boldsymbol{\Lambda}^{1/2} \boldsymbol{\Phi}^t = \sum_{i \in [n]} \sqrt{\lambda_i} \boldsymbol{\varphi}_i \boldsymbol{\varphi}_i^t.$$

It's easily verified that  $(\mathbf{M}^{1/2})^2 = \mathbf{M}$ . The following basic result will be useful.

**LEMMA 2.2.** For any  $\mathbf{M} : \mathbb{R}^n \rightarrow \mathbb{R}^m$ ,  $\text{rank}(\mathbf{M}) = \text{rank}(\mathbf{M}^t \mathbf{M})$ .

We conclude with a formula for the determinant of a minor of an invertible matrix. It is often referred to as (a special case of) *Sylvester's identity* [Syl51]. We state the version described by Viktor Prasolov [Pra94].

**LEMMA 2.3.** Let  $\mathbf{Q} \in \mathbb{R}^{n \times n}$  have a non-zero determinant, and let  $\emptyset \neq U \subsetneq [n]$ . Then

$$\det(\mathbf{Q}^{-1}[U, U]) \det(\mathbf{Q}) = \pm \det(\mathbf{Q}[U^c, U^c]). \quad (2.4)$$

### 2.2.1. Pseudoinverse

If  $\mathbf{M}$  is a singular matrix, a natural question to ask is whether there exists a matrix whose relationship to  $\mathbf{M}$  “approximates”, in some relevant sense, the relationship between a matrix and its inverse. This question was asked and answered, on separate occasions, by both Elikam Moore and Sir Roger Penrose. Both discovered—originally Moore in 1921 and later Penrose in the 1950’s—what is now known as the *Moore-Penrose pseudoinverse* of a matrix [Moo20, Pen55, Pen56]. It is defined as follows.

DEFINITION 2.1 (Moore-Penrose pseudoinverse [BH12]). Let  $\mathbf{M} \in \mathbb{R}^{n \times m}$  for some  $n, m \in \mathbb{N}$ . If  $\mathbf{M}^+ \in \mathbb{R}^{m \times n}$  is such that

- (i).  $\mathbf{M}\mathbf{M}^+\mathbf{M} = \mathbf{M}$  and  $\mathbf{M}^+\mathbf{M}\mathbf{M}^+ = \mathbf{M}^+$ ;
- (ii).  $\mathbf{M}\mathbf{M}^+$  and  $\mathbf{M}^+\mathbf{M}$  are hermitian, i.e.,  $\mathbf{M}\mathbf{M}^+ = (\mathbf{M}\mathbf{M}^+)^t$ ,  $\mathbf{M}^+\mathbf{M} = (\mathbf{M}^+\mathbf{M})^t$ ,

we call  $\mathbf{M}^+$  the *Moore-Penrose Pseudoinverse* of  $\mathbf{M}$ .

We will often drop the identifier “Moore-Penrose” and simply write that  $\mathbf{M}^+$  is the pseudoinverse of  $\mathbf{M}$ . It’s not immediate from the definition, but the pseudoinverse of  $\mathbf{M}$  has several desirable properties: When  $\mathbf{M}$  is real, so is  $\mathbf{M}^+$ ;  $(\mathbf{M}^+)^+ = \mathbf{M}$ ;  $(\mathbf{M}^+\mathbf{M})^t = \mathbf{M}^+\mathbf{M}$ . Importantly, when  $\mathbf{M}$  is invertible, then  $\mathbf{M}^+ = \mathbf{M}^{-1}$ . Moreover, the pseudoinverse always exists:

LEMMA 2.4 ([BH12]). Let  $\mathbf{M} \in \mathbb{C}^{n \times m}$ . The pseudoinverse  $\mathbf{M}^+$  of  $\mathbf{M}$  exists and is unique. Moreover, the following properties hold:

- (i).  $\mathbf{M}\mathbf{M}^+$  is an orthogonal projector obeying  $\text{range}(\mathbf{M}\mathbf{M}^+) = \text{range}(\mathbf{M})$ ; and
- (ii).  $\mathbf{M}^+\mathbf{M}$  is an orthogonal projector obeying  $\text{range}(\mathbf{M}^+\mathbf{M}) = \text{range}(\mathbf{M}^+)$ .

Together, Definition 2.1 and Lemma 2.4 do not necessarily yield a way to obtain the pseudoinverse of a matrix  $\mathbf{M}$ . We next demonstrate that when the eigendecomposition is known, we can give a precise expression for the pseudoinverse.

LEMMA 2.5. Suppose  $\mathbf{M} \in \mathbb{C}^{m \times m}$  admits the eigendecomposition  $\mathbf{M} = \sum_{i=1}^k \lambda_i \boldsymbol{\varphi}_i \boldsymbol{\varphi}_i^t$ , where  $\lambda_i$ ,  $1 \leq i \leq k$  are the non-zero eigenvalues of  $\mathbf{M}$  with corresponding orthonormal eigenvectors  $\boldsymbol{\varphi}_1, \dots, \boldsymbol{\varphi}_k$ . Then the pseudoinverse of  $\mathbf{M}$  is

$$\mathbf{M}^+ = \sum_{i=1}^k \frac{1}{\lambda_i} \boldsymbol{\varphi}_i \boldsymbol{\varphi}_i^t. \quad (2.5)$$

## §2.3. Spectral Graph Theory

Similarly to Section 2.2, the results in this section can be found in any self-contained reference on (spectral) graph theory (see e.g., [Spi09, CG97]).

We begin with basic graph theory. We denote a *graph* by a triple  $G = (V, E, w)$  where  $V$  is the *vertex set*,  $E \subseteq V \times V$  is the *edge set* and  $w : V \times V \rightarrow \mathbb{R}_{\geq 0}$  (the non-negative reals) a *weight function*. We let the domain of  $w$  be  $V \times V$  for convenience; for  $(i, j) \notin E$  we have  $w((i, j)) = 0$ . We call  $G$  *unweighted* if  $w((i, j)) = \chi_{(i, j) \in E}$  for all  $i, j$ . In this case, we may omit the weight function and simply write  $G = (V, E)$ . Unless otherwise stated,  $G$  will be undirected (edges do not have directions) and connected (each vertex is reachable from every other vertex). We will typically take  $V = [n]$  for simplicity. For a vertex  $i \in V$ , we denote the set of its neighbours by

$$\partial_G(i) \stackrel{\text{def}}{=} \{j \in V : w(i, j) > 0\}, \quad (2.6)$$

a set we call that *neighbourhood* of  $i$ . The *degree* of  $i$  is  $\deg(i) \stackrel{\text{def}}{=} |\partial(i)|$ . The *weight* of  $i$  is  $w(i) \stackrel{\text{def}}{=} \sum_{j \in \partial(i)} w(i, j)$ . Note that if  $G$  is unweighted, then  $w(i) = \deg(i)$ . If the degree of each vertex in  $G$  is equal to  $k$ , we call  $G$  a *k-regular graph*. We call  $G$  *regular* if it is  $k$ -regular for some  $k$ . If  $U \subseteq V$  contains only vertices with the same degree (resp., weight), we call it *degree (resp., weight) homogeneous*. For a set of subset of vertices  $U$ , the *volume* of  $U$  is

$$\text{vol}_G(U) \stackrel{\text{def}}{=} \sum_{i \in U} w(i), \quad (2.7)$$

and the volume of  $G$  is  $\text{vol}(G) \stackrel{\text{def}}{=} \text{vol}_G(V(G))$ . As usual, we will drop the subscript if the graph is clear from context. Owing to possible mental lapses and above average caffeine intake, we may sometimes abuse notation and extend the weight function  $w$  to sets of edges or vertices by setting  $w(A) = \sum_{a \in A} w(a)$ . Thus, for instance,  $w(U) = \text{vol}(U)$ , for  $U \subseteq V$ . (The more notation the better, right?)

Given a subset  $U \subseteq V$ , we write  $G[U]$  to be the graph induced by  $U$ , i.e.,  $V(G[U]) = V \cap U$  and  $E(G[U]) = E \cap U \times U$ . If a graph is connected and acyclic (i.e., there is a unique path between each pair of vertices) we call it a *tree*. It's well known that a tree on  $n$  nodes has  $n - 1$  edges.

As mentioned above, we will typically work with undirected graphs. In this case, we identify each tuple  $(i, j)$  with its sister pair  $(j, i)$ . This implies, for example, that when summing over all edges  $(i, j) \in E$  we are *not* summing over all vertices and their neighbours. Indeed, this latter summation double counts the edges:  $\sum_{(i, j) \in E} = \frac{1}{2} \sum_i \sum_{j \in \partial(i)}$ . We will often write  $i \sim j$  to denote an edge  $(i, j)$ ; so, for example,  $\sum_{i \sim j} = \sum_{(i, j) \in E}$ .

We will also appeal to the so-called “handshaking lemma” for unweighted graphs, which states that  $\sum_i \deg_G(i) = 2|E(G)|$ ; easily verified with a counting argument.

### 2.3.1. Laplacian Matrices

Here we introduce various matrices of graphs, including the Laplacian. See the survey by Merris [Mer94] for an excellent overview of the Laplacian, and that by Mohar [MACO91] for an overview

of its spectrum.

Let  $G = (V, E, w)$  be a graph, with  $V = [n]$  and  $|E| = m$ . Let  $\mathbf{W}$  be the *weight matrix* of  $G$ , i.e.,  $\mathbf{W} = \text{diag}(w(1), w(2), \dots, w(n))$ . The *degree matrix* of  $G$  is  $\text{diag}(\deg(1), \deg(2), \dots, \deg(n))$ . The *adjacency matrix* of  $G$  encodes the edge relations, namely,  $\mathbf{A}_G(i, j) = w((i, j))$  for all  $i \neq j$ , and  $\mathbf{A}_G(i, i) = 0$  for all  $i$ . Notice that (for undirected graphs)  $\mathbf{A}_G$  is symmetric. Note that if  $G$  is unweighted, then  $\mathbf{W}_G$  and the degree matrix are equivalent. The *combinatorial Laplacian* of  $G$  is the matrix

$$\mathbf{L}_G \stackrel{\text{def}}{=} \mathbf{W}_G - \mathbf{A}_G. \quad (2.8)$$

There are several useful representations of the Laplacian. Let  $\mathbf{L}_{i,j} = w(i, j)(\chi_i - \chi_j)(\chi_i - \chi_j)^t \in \mathbb{R}^{V \times V}$ , i.e.,

$$\mathbf{L}_{i,j}(a, b) = \begin{cases} w(i, j) & a = b \in \{i, j\}, \\ -w(i, j), & (a, b) = (i, j), \\ 0, & \text{otherwise.} \end{cases}$$

Then

$$\mathbf{L}_G = \sum_{i \sim j} \mathbf{L}_{i,j}. \quad (2.9)$$

We associate with  $\mathbf{L}_G$  the quadratic form  $\mathcal{L}_G : \mathbb{R}^V \rightarrow \mathbb{R}$  which acts on functions  $\mathbf{f} : V \rightarrow \mathbb{R}$  as  $f \xrightarrow{\mathcal{L}_G} \mathbf{f}^t \mathbf{L}_G \mathbf{f}$ . The Laplacian quadratic form will be crucial in our study of the geometry of graphs. Luckily for us then, its action on a vector is captured by an elegant closed-form formula. Computing  $\mathbf{L}_{i,j} \mathbf{f} = w(i, j)(\chi_i - \chi_j)(\chi_i - \chi_j)^t \mathbf{f} = w(i, j)(\mathbf{f}(i) - \mathbf{f}(j))(\chi_i - \chi_j)$ , we find that  $\mathbf{f}^t \mathbf{L}_{i,j} \mathbf{f} = w(i, j)(\mathbf{f}(i) - \mathbf{f}(j))^2$ . Therefore, applying Equation 2.9 yields

$$\mathcal{L}_G(\mathbf{f}) = \mathbf{f}^t \left( \sum_{i \sim j} \mathbf{L}_{i,j} \right) \mathbf{f} = \sum_{i \sim j} \mathbf{f}^t \mathbf{L}_{i,j} \mathbf{f} = \sum_{i \sim j} w(i, j)(\mathbf{f}(i) - \mathbf{f}(j))^2. \quad (2.10)$$

Another Laplacian matrix associated with  $G$  is the *normalized Laplacian*, given by

$$\widehat{\mathbf{L}}_G = \mathbf{W}_G^{-1/2} \mathbf{L}_G \mathbf{W}_G^{-1/2} = \mathbf{I} - \mathbf{W}_G^{-1/2} \mathbf{A}_G \mathbf{W}_G^{-1/2}. \quad (2.11)$$

The normalized Laplacian is intimately related to various phenomena, most notable random walks on the graph [CZ07, CG97]. To investigate  $\widehat{\mathbf{L}}_G$  we may carry out a similar procedure to above. In particular, if we define  $\widehat{\mathbf{L}}_{i,j} = \mathbf{W}_G^{-1/2} \mathbf{L}_{i,j} \mathbf{W}_G^{-1/2}$  then we obtain the equivalent of Equation (2.9) for the normalized Laplacian:

$$\widehat{\mathbf{L}}_G = \sum_{i \sim j} \widehat{\mathbf{L}}_{i,j}. \quad (2.12)$$

As we've done here, we will typically emphasize the associate of elements associated to the normalized Laplacian with a hat. Using Equation (2.12), we see that the quadratic form  $\widehat{\mathcal{L}}_G$  associated

with  $\widehat{\mathbf{L}}_G$  acts as

$$\widehat{\mathcal{L}}_G(\mathbf{f}) = \sum_{i \sim j} w(i, j) \left( \frac{\mathbf{f}(i)}{\sqrt{w(i)}} - \frac{\mathbf{f}(j)}{\sqrt{w(j)}} \right)^2. \quad (2.13)$$

We now discuss the spectrum of  $\mathbf{L}_G$  and  $\widehat{\mathbf{L}}_G$ . Both the combinatorial and normalized Laplacian of an undirected graph  $G$  are real, symmetric matrices. By the spectral theorem therefore, they both admit a basis of orthonormal eigenfunctions corresponding to real eigenvalues.

**LEMMA 2.6.** *Let  $G = ([n], E)$  be a connected graph. Then  $\ker \mathbf{L}_G = \text{span}(\mathbf{1})$  and  $\ker \widehat{\mathbf{L}}_G = \text{span}(\sqrt{\mathbf{w}})$ . Moreover, both  $\mathbf{L}_G$  and  $\widehat{\mathbf{L}}_G$  have a single zero eigenvalue (with corresponding eigenvector  $\mathbf{1}$  and  $\sqrt{\mathbf{w}}$ , respectively); all other eigenvalues are strictly positive.*

We end this section by discussing two properties of graph Laplacians. The first is their pseudoinverse relationships, and the second is the remarkable link between the eigenvalues of the combinatorial Laplacian and spanning trees of the graph.

**Pseudoinverse of  $\mathbf{L}_G$  and  $\widehat{\mathbf{L}}_G$ .** Since  $\mathbf{L}_G$  and  $\widehat{\mathbf{L}}_G$  are both symmetric,  $\text{range}(\mathbf{L}^t) = \text{range}(\mathbf{L}) = \mathbb{R}^n \setminus \ker(\mathbf{L}) = \mathbb{R}^n \setminus \text{span}(\{\mathbf{1}\})$ , and  $\text{range}(\widehat{\mathbf{L}}^t) = \text{range}(\widehat{\mathbf{L}}) = \mathbb{R}^n \setminus \ker(\widehat{\mathbf{L}}) = \mathbb{R}^n \setminus \text{span}(\{\mathbf{W}^{1/2}\mathbf{1}\})$ . It follows by Lemma 2.4 that the pseudoinverses of these two Laplacians satisfy

$$\mathbf{L}_G \mathbf{L}_G^+ = \mathbf{L}_G^+ \mathbf{L}_G = \mathbf{I} - \frac{1}{n} \mathbf{1} \mathbf{1}^t, \quad (2.14)$$

i.e., the projection onto  $\text{span}(\mathbf{1})^\perp$  (the orthogonal complement of  $\text{span}(\mathbf{1})$ ), and

$$\widehat{\mathbf{L}}_G \widehat{\mathbf{L}}_G^+ = \widehat{\mathbf{L}}_G^+ \widehat{\mathbf{L}}_G = \mathbf{I} - \frac{1}{\text{vol}(G)} \mathbf{W}_G^{1/2} \mathbf{1} (\mathbf{W}_G^{1/2} \mathbf{1})^t = \mathbf{I} - \frac{1}{\text{vol}(G)} \sqrt{\mathbf{w}} \sqrt{\mathbf{w}}^t, \quad (2.15)$$

the projection onto  $\text{span}(\mathbf{w})^\perp$ , where  $\sqrt{\mathbf{w}} = (\sqrt{w(1)}, \dots, \sqrt{w(n)})$ . Note that the denominator in (2.15) is  $\text{vol}(G)$  instead of  $n$  to ensure the result is a projection matrix.<sup>1</sup>

**Kirchoff's Theorem.** A *spanning tree* of a graph  $G$  is a connected subgraph  $T$  of  $G$  with  $V(T) = V(G)$  and  $|E(T)| = |V(T)| - 1$ . That is,  $T$  contains the minimum number of edges possible to connect all vertices of  $G$ . We will make use of the following Theorem, often called the *Kirchoff Tree Theorem*, named after Gustav Kirchhoff for the work done in [Kir47]. It was first stated in its most familiar form by Maxwell [Max73]. We use the formulation found in [CK78].

**THEOREM 2.2.** *Let  $G = (V, E, w)$  be a connected, undirected graph. Let  $\mathbf{L}$  be  $G$ 's combinatorial*

<sup>1</sup>Indeed, put  $\mathbf{P} = \mathbf{I} - \frac{1}{\text{vol}(G)} \sqrt{\mathbf{w}} \sqrt{\mathbf{w}}^t$ . Then  $\mathbf{P}^2 = \mathbf{I} - \frac{2}{\text{vol}(G)} \sqrt{\mathbf{w}} \sqrt{\mathbf{w}}^t + \frac{1}{\text{vol}(G)^2} \sqrt{\mathbf{w}} \sqrt{\mathbf{w}}^t \sqrt{\mathbf{w}} \sqrt{\mathbf{w}}^t = \mathbf{P}$ , since  $\sqrt{\mathbf{w}}^t \sqrt{\mathbf{w}} = \text{vol}(G)$ .



Laplacian matrix. Then for all  $i, j \in [n]$ ,

$$\Gamma_G = (-1)^i (-1)^j \det(\mathbf{L}_{-i, -j}) = \frac{1}{n} \prod_{i=1}^{n-1} \lambda_i,$$

where  $\lambda_1, \dots, \lambda_{n-1}$  are the non-zero eigenvalues of  $G$ ,  $\mathbf{L}_{-i, -j}$  is the matrix obtained by removing the  $i$ -th row and  $j$ -th column of  $\mathbf{L}_G$ , and  $\Gamma_G$  is the weight of all spanning trees of  $G$ .

*Remark 2.1.* The  $\mathfrak{T}$  be the set of all spanning trees of a graph  $G$ . By the “weight of all spanning trees”, we mean that

$$\Gamma_G = \sum_{T \in \mathfrak{T}} \prod_{i \in V(T)} w_G(i). \quad (2.16)$$

Thus, for  $G$  unweighted,  $\prod_{i \in V(T)} w_G(i) = 1$  so  $\Gamma_G$  simply counts the number of spanning trees.

## §2.4. Electrical Flows

One of the most successful physical interpretations of a graph arises from considering it as an electrical network [Ell11, Tet91]. We imagine placing a resistor of resistance  $1/w(i, j)$  on each edge  $(i, j) \in E(G)$ . Injecting current at one or more of the vertices results in an *electrical flow* in the graph. While this physical interpretation is intuitively useful, it is not necessary for understanding the notions of electrical flows. Consequently, we move a more involved discussion on electrical flows to Appendix B and present only the required definitions and results here. The key concept is that of the “effective resistance” between two vertices:

**DEFINITION 2.2.** The *effective resistance* between nodes  $i$  and  $j$  is  $r^{\text{eff}}(i, j) \stackrel{\text{def}}{=} \mathcal{L}_G^+(\mathbf{x}_i - \mathbf{x}_j)$ , and the *effective resistance matrix* of  $G$  is the matrix  $\mathbf{R}_G$  with entries  $\mathbf{R}_G(i, j) = r^{\text{eff}}(i, j)$ . The *total effective resistance in the graph* is the quantity  $R_G^{\text{tot}} \stackrel{\text{def}}{=} \frac{1}{2} \mathbf{1}^T \mathbf{R}_G \mathbf{1}$ .

We can relate the entries of the pseudoinverse Laplacian with the effective resistance as follows.

**LEMMA 2.7.** For any graph  $G$ ,  $\mathbf{R}_G = \mathbf{1} \Delta^t + \Delta \mathbf{1}^t - 2\mathbf{L}_G^+$  where  $\Delta = \text{diag}(\mathbf{L}_G^+(i, i))$ . Moreover, for all  $i, j$  (including  $i = j$ ),

$$\mathbf{L}_G^+(i, j) = \frac{1}{2n} \left( \sum_{k \in [n]} r^{\text{eff}}(i, k) + r^{\text{eff}}(j, k) \right) - \frac{1}{2} r^{\text{eff}}(i, j) - \frac{R_G^{\text{tot}}}{n^2}. \quad (2.17)$$

Later, we will demonstrate that one of the simplices of a given graph  $G$  is intimately related to the effective resistance. The following block matrix equation will help us generate statements concerning the geometry of this simplex, and eventually, all simplices. The following equation was first given in the following form by Van Mieghem *et al.* [VMDC17] and follows from a more general version proven by Fiedler [Fie93, Fie11].

LEMMA 2.8. For a weighted graph  $G$ , let  $\Delta = \text{diag}(\mathbf{L}_G^+(i, i))$  be the vector containing the diagonal elements of  $\mathbf{L}_G^+$ . Then,

$$-\frac{1}{2} \begin{pmatrix} 0 & \mathbf{1}_n^t \\ \mathbf{1}_n & \mathbf{R} \end{pmatrix} = \begin{pmatrix} \Delta^t \mathbf{L}_G \Delta + \frac{4}{n^2} \mathbf{R}_G^{\text{tot}} & -(\mathbf{L}_G \Delta + \frac{2}{n} \mathbf{1})^t \\ -(\mathbf{L}_G \Delta + \frac{2}{n} \mathbf{1}) & \mathbf{L}_G \end{pmatrix}^{-1}. \quad (2.18)$$

Moreover,  $\mathbf{L}_G \mathbf{R}_G \mathbf{L}_G = -2\mathbf{L}_G$  and for all  $\mathbf{x} \in \text{span}(\mathbf{1})^\perp$ ,  $\mathbf{R}_G \mathbf{L}_G \mathbf{R}_G \mathbf{x} = -2\mathbf{R}_G \mathbf{x}$ .

The proofs of Lemmas 2.7 and 2.8 are, as usual, found in Appendix A.1.

## §2.5. Simplicies

Finally we reach what is our main object of study. We begin by describing a relationship among a set of vertices which, roughly speaking, generalizes the notion of “non-collinearity” to higher dimensions. We are then able to properly define a simplex and its dual. We end the section by briefly discussing several of the angles in a simplex.

**Affine Independence.** In order to properly define simplices, we need to define the notion of “affine independence” between points. In  $\mathbb{R}^2$ , for example, such a relationship characterizes the sets of three points which describe a triangle. See Figure 2.1b for an illustration of affine dependence and independence.

DEFINITION 2.3. A set of points  $\mathbf{x}_1, \dots, \mathbf{x}_k$  are said to be *affinely independent* if the only solution to  $\sum_{i \in [n]} \alpha_i \mathbf{x}_i = \mathbf{0}$  with  $\sum_{i \in [n]} \alpha_i = 0$  is  $\alpha_1 = \dots = \alpha_n = 0$ .

Perhaps a more useful characterization of affine independence is the following.

LEMMA 2.9. The set  $\{\mathbf{x}_1, \dots, \mathbf{x}_k\}$  is affinely independent iff for each  $j$ ,  $\{\mathbf{x}_j - \mathbf{x}_i\}_{i \neq j}$  is linearly independent.

The following lemma demonstrates that if we form a matrix of size  $n - 1 \times n$  from the column vectors of  $n$  affine independent vectors, then this matrix has full rank. Moreover, we may assume that the linear combination of the vectors is in fact an *affine combination*, in the following sense.

LEMMA 2.10. Let  $\{\mathbf{x}_1, \dots, \mathbf{x}_n\} \subseteq \mathbb{R}^{n-1}$  be affinely independent, and let  $\mathbf{y} \in \mathbb{R}^{n-1}$  be arbitrary. Then there exists coefficients  $\{\alpha_i\} \subseteq \mathbb{R}$  obeying  $\sum_{i \in [n]} \alpha_i = 1$  such that  $\mathbf{y} = \sum_{i \in [n]} \alpha_i \mathbf{x}_i$ .

**The simplex.** We jump straight into the definition; see Figure 2.1a for several examples.

DEFINITION 2.4. A *simplex*  $\mathcal{T}$  in  $\mathbb{R}^{n-1}$  is the convex hull of  $n$  affinely independent vectors  $\sigma_1, \dots, \sigma_n$ . That is,  $\mathcal{S} = \text{conv}(\gamma_1, \dots, \gamma_n)$ .

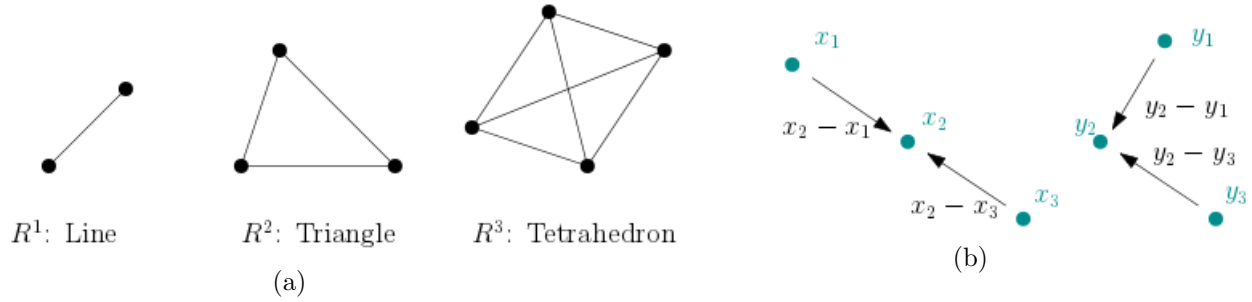


Figure 2.1: (a) Simplices in dimensions one, two, and three. We wish the reader luck in visualizing a simplex (or anything really) in more than three dimensions. (b) Example of affine dependence and independence. Here  $x_1, x_2, x_3$  are not affinely independent, as evidenced by the fact that  $x_2 - x_1$  and  $x_2 - x_3$  are parallel.  $y_1, y_2, y_3$  on the other hand, are affinely independent; one can easily visualize the triangle formed by their convex hull. We emphasize that the arrows representing the difference between two vectors, e.g.,  $x_2 - x_1$ , represent their *direction only* and not their absolute position.

If we gather the vertices of the simplex  $\mathcal{T}$  into the *vertex matrix*  $\Sigma = (\sigma_1, \dots, \sigma_n)$  whose columns are the vertex vectors of  $\mathcal{T}$ , then we can write the simplex as

$$\mathcal{T} = \{\Sigma \mathbf{x} : \mathbf{x} \geq \mathbf{0}, \|\mathbf{x}\|_1 = 1\}.$$

Given a point  $\mathbf{p} = \Sigma \mathbf{x} \in \mathcal{S}$ ,  $\mathbf{x}$  is called the *barycentric coordinate* of  $\mathbf{p}$ .

As is illustrated in two and three dimensions by the triangle and the tetrahedron, the projection of the simplex onto spaces spanned by subsets of its vertices yields simplices of lower dimensions. Let  $U \subseteq [n]$ . The *face* of  $\mathcal{T}$  corresponding to  $U$  is

$$\mathcal{T} \upharpoonright_U \stackrel{\text{def}}{=} \{\Sigma \mathbf{x} : \mathbf{x} \geq \mathbf{0}, \|\mathbf{x}\|_1 = 1, x(i) = 0 \text{ for all } i \in U^c\}. \quad (2.19)$$

If  $|U| = n - 1$ , we call  $\mathcal{T}_U$  a *facet*. Figure 2.2b illustrates a two-dimensional facet and one-dimensional face of a simplex in  $\mathbb{R}^3$ . The following observation demonstrates that  $\mathcal{S} \upharpoonright_U$  is a well-defined simplex.

**OBSERVATION 2.2.** *Any subset of an affinely independent set of vectors is again affinely independent.*

Trusting the reader's capacity for variation, depending on the situation we may adopt different notation for the faces of a simplex. Oftentimes the vertical restriction symbol will be dropped and we will write only  $\mathcal{S}_U$ ; other times we will write  $\mathcal{S}[U]$ , especially when the space reserved a subscript is being used for other purposes.

In our study of simplices we will be mainly concerned with their relative properties (e.g., volume, angles, shape, etc.) as opposed to their absolute positions in space. Thus, it will often be convenient to identify simplices which share the same relative properties, but are simply rotated and/or translated versions of one another. We will call such simplices *congruent*, or occasionally *isomor-*

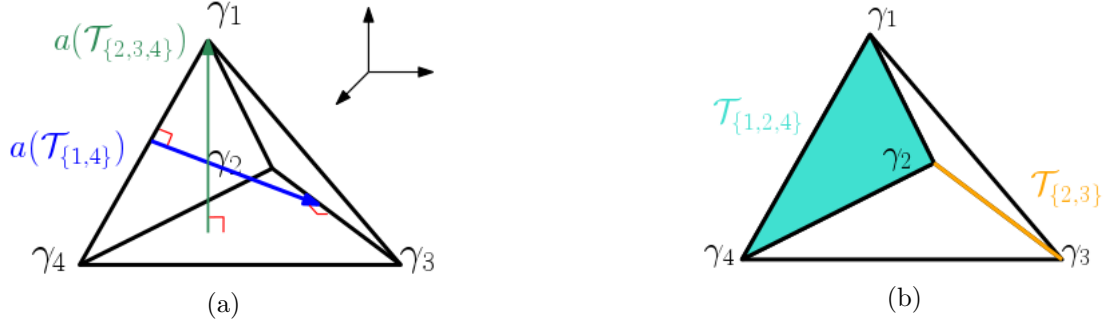


Figure 2.2: (a) The *directions* of altitudes in a simplex. We emphasize that the arrows do not represent the actual altitudes themselves, which are vectors and hence originate at the origin. (b) A one ( $\mathcal{T}_{\{2,3\}}$ ) and two ( $\mathcal{S}_{\{1,2,4\}}$ ) dimensional face of a three dimensional simplex.

*phic*. Unfortunately for notational simplicity's sake, it will be required to sometimes differentiate between simplices which are congruent by translation only, and simplices which are congruent by translation *and* rotation. Let us call the former type of congruence *translational congruence*, and the latter *rotational congruence*. We use the symbol  $\cong$  to denote translational congruency between simplices; so  $\mathcal{T}_1 \cong \mathcal{T}_2$  iff  $\Sigma(\mathcal{S}_1) = \Sigma(\mathcal{S}_2) + \alpha \mathbf{1}^t$  for some  $\alpha \in \mathbb{R}^{n-1}$ . We will also occasionally make use of the following *translational congruence class of simplices*:

$$[\mathcal{T}] \stackrel{\text{def}}{=} \{\mathcal{T}' : \mathcal{T}' \cong \mathcal{T}\}. \quad (2.20)$$

We will not require such notation for rotational congruence.

Two brief notes now on nomenclature. First, we will typically use the symbol  $\mathcal{T}$  to denote an arbitrary simplex. Later, we will use the symbol  $\mathcal{S}$  to denote the simplex associated to a graph. In this way we hope to provide a clear separation between those statements which hold for general simplices and those which hold for simplices of a graph. Secondly, due to possible hypercaffination and apparent lack of conscientiousness, we may write the vertex matrix  $\Sigma$  of a simplex  $\mathcal{T}$  as  $(\gamma_1, \dots, \gamma_n)$ ,  $(\gamma_i)$ , or  $\{\gamma_i\}$  as the case may be. Of course, they should be taken to mean the same thing.

**Centroids and altitudes.** Two fundamental objects related to a simplex are its centroids and altitudes (Figure 2.2). The *centroid* of a simplex is the point

$$\mathbf{c}(\mathcal{T}) \stackrel{\text{def}}{=} \frac{1}{n} \Sigma \mathbf{1} = \frac{1}{n} \sum_{i \in [n]} \gamma_i. \quad (2.21)$$

The centroid of a simplex can be thought of as its centre of mass, assuming that weight is distributed evenly across its surface. We can also of course discuss the centroid of a face  $\mathcal{T}_U$ , which is  $\mathbf{c}(\mathcal{T}_U) = |U|^{-1} \Sigma \chi_U$ . The *altitude between faces  $\mathcal{T}_U$  and  $\mathcal{T}_{U^c}$*  is a vector which lies in the orthogonal complement of both  $\mathcal{S}_U$  and  $\mathcal{S}_{U^c}$  and points from one face to the other. We denote the

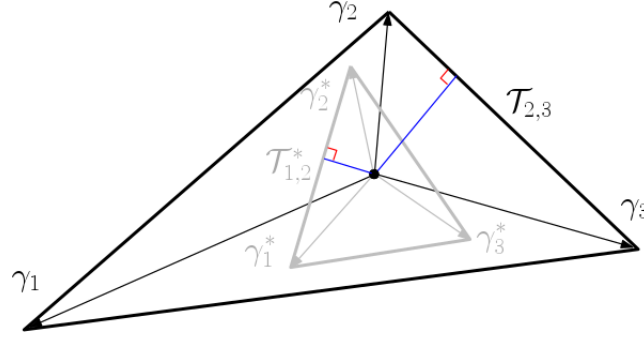


Figure 2.3: An example of a simplex  $\mathcal{T} \subseteq \mathbb{R}^2$  (in black) and its dual,  $\mathcal{T}^*$  (in gray). The blue lines serve to emphasize the fact that the dual vertex  $\gamma_1^*$  is orthogonal to the face  $\mathcal{T}_{2,3}$  just as  $\gamma_3$  is to  $\mathcal{T}_{1,2}^*$ .

altitude pointing from  $\mathcal{S}_{U^c}$  to  $\mathcal{S}_U$  as  $\mathbf{a}(\mathcal{S}_U)$ . We can write the altitude as  $\mathbf{a}_U = \mathbf{p} - \mathbf{q}$  for some  $\mathbf{p} \in \mathcal{S}_{U^c}$  and  $\mathbf{q} \in \mathcal{S}_U$ , and thus as  $\Sigma(\mathbf{x}_{U^c} - \mathbf{x}_U)$  where  $\mathbf{x}_{U^c}$  and  $\mathbf{x}_U$  are the barycentric coordinates of  $\mathbf{p}$  and  $\mathbf{q}$ .

**Nota Bene:** While we conceptualize of the altitude  $\mathbf{a}(\mathcal{T}_U)$  as pointing from  $\mathcal{T}_U$  to  $\mathcal{T}_{U^c}$ , we remark that since we are working in  $\mathbb{R}^{n-1}$  as a vector space,  $\mathbf{a}(\mathcal{T}_U)$  still “begins” at the origin.

**Centred simplex.** In later sections it will be convenient to work with a translated copy of a given simplex which is centred at the origin. Accordingly, given any simplex  $\mathcal{T}$  with vertices  $\{\sigma_i\}$ , we let  $\mathcal{T}_0$  denote the simplex with vertices  $\{\sigma_i - \mathbf{c}(\mathcal{T})\}$ . Note that  $\mathcal{T}_0 \in [\mathcal{T}]$ . It’s clear that the centroid of  $\mathcal{T}_0$  is the origin:

$$\begin{aligned} \mathbf{c}(\mathcal{T}_0) &= \frac{1}{n}(\sigma_1 - \mathbf{c}(\mathcal{T}), \dots, \sigma_n - \mathbf{c}(\mathcal{T}))\mathbf{1} \\ &= \frac{1}{n}(\sigma_1 \dots \sigma_n)\mathbf{1} - \frac{1}{n}(\mathbf{c}(\mathcal{T}) \dots \mathbf{c}(\mathcal{T}))\mathbf{1} = \mathbf{c}(\mathcal{T}) - \mathbf{c}(\mathcal{T}) = \mathbf{0}. \end{aligned}$$

We solidify the concept with a definition.

**DEFINITION 2.5.** Given a simplex  $\mathcal{T}$ , the unique (up to rotation and translation) simplex with vertex matrix  $\Sigma(\mathcal{T}) - (\mathbf{c}(\mathcal{T}) \dots \mathbf{c}(\mathcal{T}))$  centred at the origin is called the *canonical (or centred) simplex corresponding to  $\mathcal{T}$*  and is denoted  $\mathcal{T}_0$ .

We may also refer to  $\mathcal{T}_0$  as the *centred version of  $\mathcal{T}$*  in order spare the author the agony induced by writing out the complete sentence “corresponding to the simplex  $\mathcal{T}$ ”.

### 2.5.1. Dual Simplex

Here we introduce the notion of the dual simplex of a given simplex. Even though we provide a novel treatment of the object, the proofs in this section are relatively elementary. As such, they

have been moved to Appendix A.1.

Let  $\Sigma = (\gamma_1, \dots, \gamma_n) \in \mathbb{R}^{n-1 \times n}$  be the vertex matrix of a simplex  $\mathcal{T} \subseteq \mathbb{R}^{n-1}$ . For each  $i \in [n-1]$ , put  $\mathbf{v}_i = \gamma_n - \gamma_i$ . Then  $\{\mathbf{v}_1, \dots, \mathbf{v}_{n-1}\}$  is a linearly independent set, and thus admits a sister basis  $\{\gamma_1^*, \dots, \gamma_{n-1}^*\}$  which together form biorthogonal bases of  $\mathbb{R}^{n-1}$  (Lemma 2.1). Put  $\gamma_n^* = -\sum_{i=1}^{n-1} \gamma_i^*$ .

CLAIM 2.1. *The set  $\{\gamma_1^*, \dots, \gamma_n^*\}$  is affinely independent.*

Therefore, the set  $\{\gamma_1^*, \dots, \gamma_n^*\}$  determines a simplex, which we call the *dual simplex* of  $\mathcal{T}$ . Of course, it would highly suboptimal if the notion of a dual simplex depended on the labelling of the vertices of  $\mathcal{T}$ . More specifically, we defined the vertices of the dual simplex  $\gamma_i^*$  with respect to the vectors  $\{\gamma_i - \gamma_n\}$ . It is not clear a priori whether the vertices of the dual simplex would change were we to relabel the indices of  $\{\gamma_i\}$ . In fact, they do not—the demonstration of which is the purpose of the following lemma.

LEMMA 2.11. *Let  $\{\gamma_1, \dots, \gamma_n\}$  be a set of affinely independent vectors. Fix  $k \in [n-1]$  and define  $\mathbf{v}_i = \gamma_i - \gamma_n$  for  $i \in [n-1]$  and  $\mathbf{u}_i = \gamma_i - \gamma_k$  for  $i \in [n] \setminus \{k\}$ . If  $\{\gamma_1^*, \dots, \gamma_{n-1}^*\}$  is the sister basis to  $\{\mathbf{v}_1, \dots, \mathbf{v}_{n-1}\}$  and  $\gamma_n^* = -\sum_{i=1}^{n-1} \gamma_i^*$ , then  $\{\gamma_1^*, \dots, \gamma_{k-1}^*, \gamma_{k+1}^*, \dots, \gamma_n^*\}$  is the sister basis to  $\{\mathbf{u}_1, \dots, \mathbf{u}_{k-1}, \mathbf{u}_{k+1}, \dots, \mathbf{u}_n\}$ .*

We also observe that, using the same notation as above,

$$-\sum_{i=1, i \neq k}^n \gamma_i^* = -\left(\sum_{i=1, i \neq k}^{n-1} \gamma_i^*\right) - \gamma_n^* = -\sum_{i=1, i \neq k}^{n-1} \gamma_i^* + \sum_{j=1}^{n-1} \gamma_j^* = \gamma_k^*,$$

hence had we set  $\mathbf{v}_i = \gamma_k - \gamma_i$  and defined  $\gamma_k^* = -\sum_{i \neq k} \gamma_i^*$  (as we did for  $k = n$ ), Lemma 2.11 demonstrates that we would produce the same set of vectors for the dual simplex. What a relief! We honour the fact that the dual simplex is independent of labelling with the following definition.

DEFINITION 2.6 (Dual Simplex). Given a simplex  $\mathcal{T}_1 \subseteq \mathbb{R}^{n-1}$  with vertex set  $\Sigma(\mathcal{S}_1) = (\gamma_1, \dots, \gamma_n)$ , a simplex  $\mathcal{T}_2 \subseteq \mathbb{R}^{n-1}$  with vertex vectors  $\Sigma(\mathcal{T}_2) = (\gamma_1^*, \dots, \gamma_n^*)$  is called a *dual simplex* of  $\mathcal{T}_1$  if for all  $k \in [n]$ ,  $\{\gamma_i^*\}_{i \neq k}$  is the sister basis to  $\{\gamma_i - \gamma_k\}_{i \neq k}$ . We denote the dual of the simplex  $\mathcal{T}$  as  $\mathcal{T}^*$ .

Figure 2.3 illustrates a simplex and its dual. We remark that in light of the previous lemma, in order to determine whether the vertices  $\{\gamma_i^*\}$  are the dual vertices to  $\{\gamma_i\}$  it suffices to check whether  $\langle \gamma_i^*, \gamma_j - \gamma_k \rangle = \delta_{ij}$  for a single  $k \neq i, j$ , as opposed to all  $k \in [n]$ . This will be done henceforth and will not be further remarked upon. We also note that duality between simplices is not a relationship between individual simplices per se, but rather assigns to congruence class  $[\mathcal{T}]$  a centred simplex. Indeed, let  $\mathcal{T}_1 \in [\mathcal{T}]$  and let  $\Sigma(\mathcal{T}^*) = (\gamma_1^*, \dots, \gamma_n^*)$ . We claim that the vertices  $\Sigma(\mathcal{T}^*)$  are also dual to  $\Sigma(\mathcal{T}_1) = (\sigma_1, \dots, \sigma_n)$ . As usual, let  $\Sigma(\mathcal{T}) = (\gamma_i)$ . Let  $\alpha \in \mathbb{R}^{n-1}$  be such that  $\sigma_i = \gamma_i + \alpha$  (such an  $\alpha$  exists by definition of  $[\mathcal{T}]$ ). Then,

$$\langle \gamma_i^*, \sigma_j - \sigma_n \rangle = \langle \gamma_i^*, (\gamma_j + \alpha) - (\gamma_n + \alpha) \rangle = \langle \gamma_i^*, \gamma_j - \gamma_n \rangle = \delta_{ij},$$

meaning that  $\mathcal{T}^*$  is also dual to  $\mathcal{T}_1$ . We encapsulate this in an observation for easy recollection.

**OBSERVATION 2.3.** *A simplex  $\mathcal{T}$  and corresponding centred simplex  $\mathcal{T}_0$  share the same dual, i.e.,  $\mathcal{S}^* = \mathcal{T}_0^*$ .*

Observe that the dual simplex is always centred by construction (since  $\gamma_n^* = -\sum_{i < n} \gamma_i^*$ ). The following lemma demonstrates that, in the language of the preceding paragraph, if  $\mathcal{T}^*$  is the dual of the congruence class  $[\mathcal{T}]$ , then the dual of  $[\mathcal{T}^*]$  is the representative of  $[\mathcal{T}]$  which is centred.

**LEMMA 2.12.** *Let a simplex  $\mathcal{T} \in \mathbb{R}^{n-1}$  have vertices  $(\gamma_i)$ ,  $\mathcal{T}^*$  have vertices  $(\gamma_i^*)$  and  $(\mathcal{T}^*)^*$  have vertices  $(\sigma_i)$ . Then, after potential re-ordering the indices,  $\sigma_i = \gamma_i - \gamma_n$  for  $i < n$ .*

*Remark 2.2.* The notion of the dual simplex expounded here is the same as the object discovered by Fiedler in his book [Fie11, Chapter 5], which he calls the *inverse simplex*. In a covert attempt to confuse the reader, we will reserve the name inverse simplex for a (sometimes) distinct object. Fiedler defines the inverse simplex with respect to the centroid of the given simplex, finding vectors  $\mathbf{u}_i$  such that  $\langle \mathbf{u}_i, \gamma_j - \mathbf{c} \rangle = \delta_{ij} - 1/n$ , where  $\mathbf{c} = \mathbf{c}(\mathcal{S})$ . Such vectors then satisfy  $\langle \mathbf{u}_i, \sigma_j - \gamma_k \rangle = \langle \mathbf{u}_i, \gamma_j - \mathbf{c} - (\gamma_k - \mathbf{c}) \rangle = \delta_{ij} - \delta_{ik} = \delta_{ij}$  for  $i, j \neq k$ , hence are the (unique) dual vertices.

We summarize the discussion with the following theorem.

**THEOREM 2.3.** *Each simplex has a unique dual simplex. Moreover, if  $\mathcal{T}^*$  is the dual of  $\mathcal{T}$ , then  $\mathcal{T}_0$  is the dual of  $\mathcal{T}^*$ , where  $\mathcal{T}_0 \cong \mathcal{T}$  is centred.*

*Proof.* Existence follows from Lemma 2.1 using the construction above. Uniqueness follows from Observation 2.1 and Lemma 2.11. The second part of the statement follows from Lemma 2.12.  $\square$

We end this section on dual simplices by giving a necessary condition of the relationship between a simplex and its dual.

**LEMMA 2.13.** *Let  $\mathcal{T}^*$  be the dual of the simplex  $\mathcal{T} \in \mathbb{R}^{n-1}$ . For all  $U \subseteq [n]$ ,  $\emptyset \neq U \neq [n]$ ,  $\mathcal{T}_U$  is orthogonal to  $\mathcal{S}_{U^c}^*$ .*

### 2.5.2. Angles in a Simplex

There are several angles worth discussing in a simplex. For a simplex  $\mathcal{T}$ , let  $\phi_{ij}^*(\mathcal{T})$  be the angle between the outer normals to  $\mathcal{T}_{\{i\}^c}$  and  $\mathcal{T}_{\{j\}^c}$ . As usual, the paranthetical  $(\mathcal{T})$  will typically be dropped when the simplex is understood from context. Using the notion of the dual simplex introduced in the previous section, we can write

$$\cos \phi_{ij}^*(\mathcal{T}) = \frac{\langle \gamma_i^*, \gamma_j^* \rangle}{\|\gamma_i^*\|_2 \cdot \|\gamma_j^*\|_2},$$

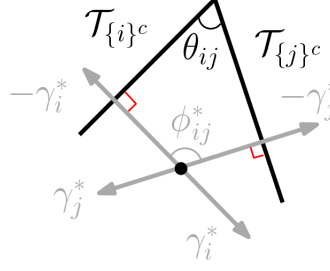


Figure 2.4: The angles in a simplex and its dual. The angle  $\phi_{ij}^*$  between  $\gamma_i^*$  and  $\gamma_j^*$  is the same as that between  $-\gamma_i^*$  and  $-\gamma_j^*$ . From here we see that  $\theta_{ij} + \phi_{ij}^* = \pi$ .

where  $\{\gamma_i^*\}$  are the vertices of  $\mathcal{T}^*$ . The superscript represents the fact that the angle is between the vertices of the dual simplex. Now, define  $\theta_{ij}(\mathcal{T})$  to be the angle between  $\mathcal{T}_{i}^{*c}$  and  $\mathcal{T}_{j}^{*c}$ . Appealing to elementary geometry, we see that the angles  $\phi_{ij}^*$  and  $\theta_{ij}$  are *supplementary*, i.e., their sum is  $\pi$ . Hence,

$$\cos \theta_{ij}(\mathcal{T}) = -\frac{\langle \gamma_i^*, \gamma_j^* \rangle}{\|\gamma_i^*\|_2 \cdot \|\gamma_j^*\|_2}, \quad (2.22)$$

where we've used that  $\cos(\phi_{ij}^*) = \cos(\pi - \theta_{ij}) = -\cos(\theta_{ij})$ . This allows us to define the notion of hyperacuteness in simplices as follows.

**DEFINITION 2.7.** We call the simplex  $\mathcal{T} \subseteq \mathbb{R}^{n-1}$  *hyperacute* if  $\theta_{ij}(\mathcal{T}) \leq \pi/2$  for all  $i, j \in [n]$ . If  $\mathcal{T}$  is not hyperacute, it is called *obtuse*.



## The Graph-Simplex Correspondence

*The right understanding of any matter and a misunderstanding of the same matter do not wholly exclude each other.*

— Franz Kafka, *The Trial*

*Why, sometimes I've believed as many as six impossible things before breakfast.*

— Lewis Carroll, *Alice's Adventures in Wonderland*

In this chapter we introduce the graph-simplex correspondence and explore its mathematical foundations. While the focus of this dissertation is specially on the simplices arising from the Laplacian matrices of graphs, we begin by introducing the more general relationship between matrices and convex polytopes. The correspondence between graphs and simplices will then follow as a consequence.

### §3.1. Convex Polyhedra of Matrices

Here we introduce the polytope associated with a given matrix. Let  $\mathbf{M} \in \mathbb{R}^{n \times n}$  be PSD and admitting of the eigendecomposition  $\mathbf{M} = \sum_{i=1}^d \lambda_i \boldsymbol{\varphi}_i \boldsymbol{\varphi}_i^t$  for some  $d \leq n$  (i.e.,  $\mathbf{M}$  has eigenvalue zero with multiplicity  $n - d$ ) where the eigenvectors  $\{\boldsymbol{\varphi}_i\}_{i=1}^d$  are orthonormal. Writing out the eigendecomposition as

$$\mathbf{M} = \boldsymbol{\Phi}_M \boldsymbol{\Lambda}_M \boldsymbol{\Phi}_M^t = (\boldsymbol{\Phi}_M \boldsymbol{\Lambda}_M^{1/2})(\boldsymbol{\Phi}_M \boldsymbol{\Lambda}_M^{1/2})^t,$$

with  $\boldsymbol{\Phi}_M = (\boldsymbol{\varphi}_1, \dots, \boldsymbol{\varphi}_d)$ ,  $\boldsymbol{\Lambda}_M = \text{diag}(\lambda_1, \dots, \lambda_d)$  (note the respective absences of  $\boldsymbol{\varphi}_{d+1}, \dots, \boldsymbol{\varphi}_n$  and  $\lambda_{d+1}, \dots, \lambda_n$ ), suggests that we might consider  $\boldsymbol{\Lambda}_M^{1/2} \boldsymbol{\Phi}_M$  as a vertex matrix, thus  $\mathbf{M}$  as a gram matrix. Inorexably compelled by this intuition, define the vertices  $\boldsymbol{\sigma}_1, \dots, \boldsymbol{\sigma}_n$  given by the columns of  $\boldsymbol{\Lambda}_M^{1/2} \boldsymbol{\Phi}_M^t$ , i.e.,

$$\boldsymbol{\sigma}_i = (\boldsymbol{\Lambda}_M^{1/2} \boldsymbol{\Phi}_M^t)(\cdot, i) = (\boldsymbol{\varphi}_1(i)\lambda_1^{1/2}, \boldsymbol{\varphi}_2(i)\lambda_2^{1/2}, \dots, \boldsymbol{\varphi}_d(i)\lambda_d^{1/2})^t \in \mathbb{R}^d,$$

where we emphasize that the vertex vector will have real entries since  $\lambda_j > 0$  for all  $j \in [d]$  since  $\mathbf{M}$  is PSD. We may now define the *polytope of the matrix  $\mathbf{M}$*  as the polytope given by their convex hull:

$$\mathcal{P}_{\mathbf{M}} \stackrel{\text{def}}{=} \text{conv}(\boldsymbol{\sigma}_1, \dots, \boldsymbol{\sigma}_n).$$

Letting  $\boldsymbol{\Sigma} = \boldsymbol{\Sigma}(\mathcal{P}_{\mathbf{M}}) = (\boldsymbol{\sigma}_1, \dots, \boldsymbol{\sigma}_n) \in \mathbb{R}^{d \times n}$  be the matrix whose  $i$ -th column is the  $i$ -th vertex  $\boldsymbol{\sigma}_i$ —henceforth called the *vertex matrix of  $\mathcal{P}_{\mathbf{M}}$* —we see that  $\boldsymbol{\Sigma} = \boldsymbol{\Lambda}_M^{1/2} \boldsymbol{\Phi}_M^t = (\boldsymbol{\Phi}_M \boldsymbol{\Lambda}_M^{1/2})^t$ , and

$$\boldsymbol{\Sigma}^t \boldsymbol{\Sigma} = (\boldsymbol{\Phi} \boldsymbol{\Lambda}^{1/2})(\boldsymbol{\Phi} \boldsymbol{\Lambda}^{1/2})^t = \boldsymbol{\Phi} \boldsymbol{\Lambda} \boldsymbol{\Phi}^t = \mathbf{M}.$$

Observe that the polytope  $\mathcal{S}(\mathbf{M})$  is  $d$ -dimensional, i.e., its vertices span a  $d$ -dimensional subspace, since  $\text{rank}(\boldsymbol{\Sigma}) = \text{rank}(\boldsymbol{\Sigma}^t \boldsymbol{\Sigma}) = \text{rank}(\mathbf{M}) = d$ , where we've employed Lemma 2.2 and the fact that  $\mathbf{M}$  has rank  $d$  due to its eigendecomposition. We thus conceptualize  $\mathcal{P}_{\mathbf{M}}$  as a polytope in  $\mathbb{R}^d$ .

*Remark 3.1.* The ordering of the non-zero eigenvalues did not enter our considerations when defining  $\mathcal{P}_{\mathbf{M}}$ . Let us consider re-ordering the indices; take  $\tau : [d] \rightarrow [d]$  to be any permutation and  $\{\boldsymbol{\sigma}_i^\tau\}$  be the vertices as they would be defined under the ordering given by  $\tau$ . Hence  $\boldsymbol{\sigma}_i^\tau(j) = \varphi_{\tau^{-1}(j)}(i) \lambda_{\tau^{-1}(j)}^{1/2}$ . The pairwise distances between these vertices then obey

$$\|\boldsymbol{\sigma}_i^\tau - \boldsymbol{\sigma}_k^\tau\|_2^2 = \sum_{j=1}^d \lambda_{\tau^{-1}(j)} (\varphi_{\tau^{-1}(j)}(i) - \varphi_{\tau^{-1}(j)}(k))^2 = \sum_{j=1}^d \lambda_j (\varphi_j(i) - \varphi_j(k))^2 = \|\boldsymbol{\sigma}_i - \boldsymbol{\sigma}_k\|_2^2,$$

since  $\tau$  is a bijection, hence summing over  $\tau^{-1}(j)$  yields the same result as summing from 1 to  $d$ . Therefore, we see that the polytopes  $\text{conv}(\boldsymbol{\sigma}_1^\tau, \dots, \boldsymbol{\sigma}_n^\tau)$  and  $\text{conv}(\boldsymbol{\sigma}_1, \dots, \boldsymbol{\sigma}_n)$  are congruent. In fact, since they share the same centroid they are simply rotations of one another.

### 3.1.1. The Inverse Polytope

Given that we can associate a polytope with the matrix  $\mathbf{M}$ , it is natural to wonder about the relationship between this polytope and that associated to  $\mathbf{M}^{-1}$  if  $\mathbf{M}$  is invertible, or with its pseudoinverse  $\mathbf{M}^+$  more generally. As illustrated in Section 2.2.1, with the eigendecomposition of  $\mathbf{M}$  as above, we can write the pseudoinverse as

$$\mathbf{M}^+ = \sum_{i=1}^d \lambda_i^{-1} \boldsymbol{\varphi}_i \boldsymbol{\varphi}_i^t = \boldsymbol{\Phi}_M \boldsymbol{\Lambda}_M^{-1/2} \boldsymbol{\Phi}_M.$$

We can thus associate with  $\mathbf{M}^+$  a polytope  $\mathcal{P}_{\mathbf{M}^+}$ , which has as its vertex matrix  $\boldsymbol{\Sigma}(\mathcal{P}_{\mathbf{M}^+}) = (\boldsymbol{\Phi} \boldsymbol{\Lambda}^{-1/2})^t$ ; that is, the vertices  $\{\boldsymbol{\sigma}_i^+\}$  of  $\mathcal{P}_{\mathbf{M}^+}$  are defined by  $\boldsymbol{\sigma}_i^+(j) = \varphi_j(i) / \lambda_j^{1/2}$ . We call  $\mathcal{P}_{\mathbf{M}^+}$  the *inverse polytope of  $\mathbf{M}$* .

Let us observe several properties of the relationship between  $\mathcal{P}_{\mathbf{M}}$  and  $\mathcal{P}_{\mathbf{M}^+}$ . In what follows we drop the subscript  $M$  from the eigenvalue and eigenvector matrix. Note that because of the

orthogonality relationships among eigenvectors of  $\mathbf{M}$ ,

$$\Phi^t \Phi = \begin{pmatrix} \langle \varphi_1, \varphi_1 \rangle & \cdots & \langle \varphi_1, \varphi_d \rangle \\ \vdots & \ddots & \vdots \\ \langle \varphi_d, \varphi_1 \rangle & \cdots & \langle \varphi_d, \varphi_d \rangle \end{pmatrix} = \mathbf{I}_d.$$

Consequently,

$$\mathbf{M}^+ \mathbf{M} = \Phi \Lambda \Phi^t \Phi \Lambda^{-1} \Phi^t = \Phi \Lambda \Lambda^{-1} \Phi^t = \Phi \Phi^t,$$

and similarly  $\mathbf{M} \mathbf{M}^+ = \Phi \Phi^t$ . As it happens, the vertex matrices of  $\mathcal{P}_M$  and  $\mathcal{P}_M^+$  satisfy the same pseudoinverse relation:

$$\Sigma^t \Sigma^+ = \Phi \Lambda^{1/2} \Lambda^{-1/2} \Phi^t = \Phi \Phi^t,$$

and  $(\Sigma^+)^t \Sigma = \Phi \Phi^t$ . Using the properties of the relationship between a matrix and its pseudoinverse immediately yields the following result.

LEMMA 3.1. *Let  $\Sigma = \Sigma(\mathbf{M})$  and  $\Sigma^+ = \Sigma(\mathbf{M}^+)$  by the vertex matrices of  $\mathcal{P}_M$  and  $\mathcal{P}_{M^+}$  where  $\mathbf{M}$  is a real and symmetric matrix. The matrices  $\Sigma^t \Sigma^+$  and  $(\Sigma^+)^t \Sigma$  are equal and moreover*

- (i). *act as the orthogonal projection onto  $\text{range}(\mathbf{M})$ ;*
- (ii).  *$(\mathbf{I} - \Sigma^t \Sigma^+)$  acts as the orthogonal projection onto  $\ker(\mathbf{M})$ .*

*Proof.* Apply Lemma 2.4. \(\square\)

Further exploring the relationships between the vertex matrices, we find that

$$\begin{aligned} \Sigma \Sigma^t &= \begin{pmatrix} \sum_i \sigma_i(1) \sigma_i(1) & \cdots & \sum_i \sigma_i(1) \sigma_i(n) \\ \vdots & \ddots & \vdots \\ \sum_i \sigma_i(n) \sigma_i(1) & \cdots & \sum_i \sigma_i(n) \sigma_i(n) \end{pmatrix} \\ &= \begin{pmatrix} \lambda_1 \langle \varphi_1, \varphi_1 \rangle & \cdots & \lambda_1^{1/2} \lambda_n^{1/2} \langle \varphi_1, \varphi_n \rangle \\ \vdots & \ddots & \cdots \\ \lambda_1^{1/2} \lambda_n^{1/2} \langle \varphi_n, \varphi_1 \rangle & \cdots & \lambda_n \langle \varphi_n, \varphi_n \rangle \end{pmatrix} = \Lambda, \end{aligned} \tag{3.1}$$

and likewise,

$$\widehat{\Sigma}^+ (\widehat{\Sigma}^+)^t = \Lambda^{-1}. \tag{3.2}$$

In summary, any real symmetric  $n \times n$  matrix  $\mathbf{M}$  of rank  $d$  yields a  $d$ -dimensional convex polytope  $\mathcal{P}_M$  in  $\mathbb{C}^{d \times d}$ . If all eigenvalues are positive then the polytope sits in  $\mathbb{R}^{d \times d}$ . The vertex matrices of  $\mathcal{P}_M$  and  $\mathcal{P}_{M^+}$ —the polytope of the pseudoinverse of  $\mathbf{M}$ —when multiplied together are equal to and hence satisfy the projection properties of  $\mathbf{M}^+ \mathbf{M}$ . In the next section we will explore how to apply this result to graphs.

### §3.2. A Bijection Between Graphs and Simplices

This section introduces the graph-simplex correspondence—the core of which is a bijective mapping between the set of all (finite) connected, weighted, and undirected graphs and hyperacute simplices. We begin by exploring the polytopes—and in particular the simplices—associated with a given graph. The subsequent section will then demonstrate how to extract a graph from an arbitrary hyperacute simplex.

#### 3.2.1. The Simplices of a Graph

Fix an undirected, connected and weighted graph  $G = (V, E, w)$ . By means of the graph's adjacency and Laplacian matrices, the previous section yields several polytopes corresponding to  $G$ . The adjacency matrix  $\mathbf{A}_G$ , for instance, yields a complex polytope of dimension  $\text{rank}(\mathbf{A}_G)$ . However, while Theorem 2.1 dictates that  $\mathbf{A}_G$  has real eigenvalues and a set of orthogonal eigenvectors, we do not in general know the rank of  $\mathbf{A}_G$ , nor much of the magnitudes of its eigenvalues. This makes it difficult to explore the structure of  $\mathcal{P}_{\mathbf{A}_G}$ .

We will instead focus on the polytopes generated by  $G$ 's Laplacian matrices;  $\mathcal{S}_G \stackrel{\text{def}}{=} \mathcal{P}_{\mathbf{L}_G}$  and  $\hat{\mathcal{S}}_G \stackrel{\text{def}}{=} \mathcal{P}_{\hat{\mathbf{L}}_G}$  corresponding to the combinatorial and normalized Laplacians, respectively. (The reasoning behind the nomenclature will quickly become apparent.) We let  $\boldsymbol{\Sigma}_G = \boldsymbol{\Sigma}(\mathcal{P}_{\mathbf{L}_G}) = (\boldsymbol{\sigma}_1, \dots, \boldsymbol{\sigma}_n)$  and  $\hat{\boldsymbol{\Sigma}}_G = \boldsymbol{\Sigma}(\mathcal{P}_{\hat{\mathbf{L}}_G}) = (\hat{\boldsymbol{\sigma}}_1, \dots, \hat{\boldsymbol{\sigma}}_n)$  denote the vertices of  $\mathcal{S}_G$  and  $\hat{\mathcal{S}}_G$ , respectively. We recall that  $\boldsymbol{\Sigma} = \mathbf{\Lambda}^{1/2} \boldsymbol{\Phi}^t$  (resp.,  $\hat{\boldsymbol{\Sigma}} = \hat{\mathbf{\Lambda}}^{1/2} \hat{\boldsymbol{\Phi}}^t$ ) where  $\mathbf{\Lambda}$  (resp.,  $\hat{\mathbf{\Lambda}}$ ) is the diagonal matrix containing the non-zero eigenvalues of  $\mathbf{L}_G$  (resp.,  $\hat{\mathbf{L}}_G$ ) and  $\boldsymbol{\Phi}$  (resp.,  $\hat{\boldsymbol{\Phi}}$ ) is the matrix of the corresponding (normalized) eigenvectors. Since  $\text{rank}(\mathbf{L}_G) = \text{rank}(\hat{\mathbf{L}}_G) = n - 1$ , the polytopes  $\mathcal{S}_G$  and  $\hat{\mathcal{S}}_G$  are simplices—a fact which is demonstrated more directly by the following Lemma.

LEMMA 3.2. *The vertices  $\{\boldsymbol{\sigma}_i\}$  and  $\{\hat{\boldsymbol{\sigma}}_i\}$  are affinely independent.*

*Proof.* We provide the proof in the case of  $\{\boldsymbol{\sigma}_i\}$  only. Suppose  $\boldsymbol{\alpha} = (\alpha_1, \dots, \alpha_n)$  is such that  $\sum_{i=1}^n \alpha_i \boldsymbol{\sigma}_i = \mathbf{0}$ , i.e.,  $\boldsymbol{\alpha} \in \ker(\boldsymbol{\Sigma})$ . Since  $\ker(\boldsymbol{\Sigma}) = \ker(\boldsymbol{\Sigma}^t \boldsymbol{\Sigma}) = \ker(\mathbf{L}) = \text{span}(\{\mathbf{1}\})$ , there exists some  $k \in \mathbb{R}$  such that  $\boldsymbol{\alpha} = k\mathbf{1}$ . If  $\langle \boldsymbol{\alpha}, \mathbf{1} \rangle = \langle k\mathbf{1}, \mathbf{1} \rangle = kn = 0$  however, then we must have  $k = 0$ , demonstrating that  $\alpha_i = 0$  for all  $i$ . Hence the vectors  $\{\boldsymbol{\sigma}_i\}$  are affinely independent. Likewise, if  $\boldsymbol{\alpha} \in \ker(\hat{\boldsymbol{\Sigma}}) = \ker(\hat{\mathbf{L}}) = \text{span}(\{\sqrt{w}\})$ , then  $\boldsymbol{\alpha} = k\sqrt{w}$ . But  $\langle k\sqrt{w}, \mathbf{1} \rangle = k \sum_i w(i) = 0$ , so  $\boldsymbol{\alpha} = \mathbf{0}$ .  $\square$

Consequently, we will often refer to  $\mathcal{S}_G$  as the *combinatorial simplex of  $G$*  or simply the *simplex of  $G$* , and to  $\hat{\mathcal{S}}_G$  as the *normalized simplex of  $G$* . If  $G$  is clear from context we will often drop it from the subscript. As per Section 3.1.1, we also introduce the *inverse simplex* and *inverse normalized simplex of  $G$* , which have respective vertex matrices  $\boldsymbol{\Sigma}^+ = \mathbf{\Lambda}^{-1/2} \boldsymbol{\Phi}^t$  and  $\hat{\boldsymbol{\Sigma}}^+ = \hat{\mathbf{\Lambda}}^{-1/2} \hat{\boldsymbol{\Phi}}^t$ .

We will often refer to the pair  $\mathcal{S}_G$  and  $\mathcal{S}_G^+$  as the *combinatorial simplices of  $G$* , and the pair  $\hat{\mathcal{S}}_G$

and  $\widehat{\mathcal{S}}_G^+$  as the *normalized simplices of  $G$* , to avoid the tedious task of constantly referring to, say, the combinatorial simplex and its inverse.

As illustrated by the discussion at the end of Section 3.1.1, the vertex matrices of the polytope of a matrix and its inverse share the same relationship as the matrix and its pseudoinverse (Lemma 3.1). Since this relationship is well understood for the Laplacian and its pseudoinverse, we may explicit compute the relationships between  $\Sigma$ ,  $\Sigma^+$  and  $\widehat{\Sigma}$ ,  $\widehat{\Sigma}^+$ .

Let  $\widetilde{\Phi}$  be the matrix containing all eigenvectors of  $L_G$  (i.e., also containing  $\mathbf{1}/\sqrt{n}$ ). It is well known that  $\widetilde{\Phi}$  is an orthogonal matrix (see e.g., [VM13]), i.e.,  $\widetilde{\Phi}^t \widetilde{\Phi} = \widetilde{\Phi} \widetilde{\Phi}^t = \mathbf{I}$ , a property which is also called *double orthogonality*. When expanded, this second equality implies that

$$\delta_{i,j} = \sum_{k=1}^n \varphi_k(i) \varphi_k(j) = \sum_{k=1}^{n-1} \varphi_k(i) \varphi_k(j) + 1/n. \quad (3.3)$$

From this, it follows that  $\langle \sigma_i^+, \sigma_j \rangle = \delta_{i,j} - 1/n$ , hence,

$$\Sigma^t \Sigma^+ = (\Sigma^+)^t \Sigma = \mathbf{I} - \frac{\mathbf{J}}{n}. \quad (3.4)$$

Beyond simply exemplifying an elegant relationship between  $\Sigma$  and  $\Sigma^+$ , this also demonstrates the following important result.

**OBSERVATION 3.1.** *The dual simplex of  $\mathcal{S}_G$  is equal to the inverse simplex  $\mathcal{S}_G^+$ .*

*Proof.* Recall that the dual simplex is the unique simplex with vertices  $\sigma_i^*$  obeying  $\langle \sigma_i^*, \sigma_j - \sigma_k \rangle = \delta_{ij}$  for  $i, j \neq k$ . The vertices  $\sigma_i^+$  satisfy this property:  $\langle \sigma_i^+, \sigma_j - \sigma_k \rangle = (\delta_{ij} - 1/n) - (\delta_{ik} - 1/n) = \delta_{ij}$  since  $i \neq k$ .  $\square$

Let  $\theta_{ij}^+$  be the interior angle between  $\mathcal{S}_{\{i\}^c}^+$  and  $\mathcal{S}_{\{j\}^c}^+$ . Since  $\mathcal{S}^+$  is dual to  $\mathcal{S}$ , Equation (2.22) gives

$$\cos \theta_{ij}^+ = - \frac{\langle \sigma_i, \sigma_j \rangle}{\|\sigma_i\|_2 \|\sigma_j\|_2} = \frac{w(i,j)}{\sqrt{w(i)w(j)}} \in [0, 1],$$

hence  $\theta_{ij}^+ \in [0, \pi/2]$ , which proves the following observation.

**OBSERVATION 3.2.** *The inverse combinatorial simplex of a graph is hyperacute.*

We turn our attention now to the normalized simplex. Double orthogonality also holds for the eigenvectors of the normalized Laplacian and so, recalling that  $\varphi_n \in \text{span}(\mathbf{W}_G^{1/2} \mathbf{1})$ , (Section 2.3.1) we can write

$$\varphi_n = \frac{\sqrt{w}}{(\text{vol}(G))^{1/2}},$$

where we recall that  $\text{vol}(G) = \sum_{i \in [n]} w(i)$ . Therefore,  $\widehat{\varphi}_n(i) \widehat{\varphi}_n(j) = \sqrt{w(i)w(j)}/\text{vol}(G)$ , implying

that

$$\delta_{i,j} = \sum_{k=1}^n \hat{\varphi}_k(i) \hat{\varphi}_k(j) = \sum_{k=1}^{n-1} \hat{\varphi}_k(i) \hat{\varphi}_k(j) + \frac{\sqrt{w(i)w(j)}}{\text{vol}(G)},$$

and so

$$\hat{\Sigma}^t \hat{\Sigma}^+ = (\hat{\Sigma}^+)^t \hat{\Sigma} = \mathbf{I} - \frac{\sqrt{\mathbf{w}} \sqrt{\mathbf{w}}^t}{\text{vol}(G)}. \quad (3.5)$$

It is worth emphasizing the fact that this inverse relationship is a function of the weights of the graph for the normalized simplex, while it is constant for the combinatorial simplex. As we will see, this dependency on  $\mathbf{w}$  will severely complicate the relationship between  $\hat{S}_G$  and  $\hat{S}_G^+$ , making their study more complicated than that of  $S_G$  and  $S_G^+$ .

### 3.2.2. The Graph of a Simplex

We now proceed to demonstrating that each hyperacute simplex is the inverse simplex of a graph  $G$ . This will constitute the second half of the bijective relationship between graphs and simplices.

LEMMA 3.3. *Given a simplex  $\mathcal{T} \subseteq \mathbb{R}^{n-1}$  centered at the origin, let  $\{\mathbf{u}_i\}$  be vectors describing its outer normal directions, though with no particular length. Let  $\mathbf{Q}$  be their Gram matrix; i.e.,  $\mathbf{Q}(i, j) = \langle \mathbf{u}_i, \mathbf{u}_j \rangle$ . If  $\mathbf{Q}_1 \in \mathbb{R}^{n \times n}$  is the diagonal matrix containing the norms of the outer normals,*

$$\mathbf{Q}_1 = \text{diag}\left(\|\mathbf{u}_1\|_2, \dots, \|\mathbf{u}_n\|_2\right),$$

and  $\mathbf{Q}_2 \in \mathbb{R}^{n \times n}$  describes the angles in the simplex,

$$\mathbf{Q}_2(i, j) = \begin{cases} 1, & \text{if } i = j, \\ -\cos \theta_{i,j}, & \text{otherwise,} \end{cases}$$

where  $\theta_{i,j}$  is the (interior) angle between  $\mathcal{T}_{\{i\}^c}$  and  $\mathcal{T}_{\{j\}^c}$ , then  $\mathbf{Q} = \mathbf{Q}_1 \mathbf{Q}_2 \mathbf{Q}_1$ .

*Proof.* Using Equation 2.22 from the discussion in Section 2.5.2, we can write the entries of  $\mathbf{Q}_2$  as

$$\frac{\langle \gamma_i, \gamma_j \rangle}{\|\gamma_i\|_2 \|\gamma_j\|_2},$$

where  $\{\gamma_i\}$  are the vertices of  $\mathcal{T}^*$  (note that this holds for  $i = j$  as well). Lemma 2.13 implies that these vertices are parallel to the outer normals of  $\mathcal{T}$ , hence  $\gamma_i = \kappa_i \mathbf{u}_i$  where  $\kappa_i \in \mathbb{R}_{>0}$ . Therefore,

$$(\mathbf{Q}_1 \mathbf{Q}_2 \mathbf{Q}_1)(i, j) = \|\mathbf{u}_i\|_2 \frac{\langle \kappa_i \mathbf{u}_i, \kappa_j \mathbf{u}_j \rangle}{\|\kappa_i \mathbf{u}_i\|_2 \|\kappa_j \mathbf{u}_j\|_2} \|\mathbf{u}_j\|_2 = \frac{\kappa_i \kappa_j}{|\kappa_i| |\kappa_j|} \langle \mathbf{u}_i, \mathbf{u}_j \rangle = \langle \mathbf{u}_i, \mathbf{u}_j \rangle = \mathbf{Q}(i, j). \quad \square$$

Let  $\mathcal{T}$  be a hyperacute simplex, and  $\mathcal{T}^*$  its dual. The vertex matrix  $\Sigma^*$  of  $\mathcal{T}^*$  contains the outer normals of  $\mathcal{T}$  (see discussion on dual simplex in Section 2.5.1). Hence, taking  $\mathbf{Q} = (\Sigma^*)^t \Sigma^*$  in the

above Lemma applied to the simplex  $\mathcal{T}$ , we obtain explicit entries for this Gram matrix:

$$((\Sigma^*)^t \Sigma^*)(i, j) = \begin{cases} \|\sigma_i^*\|_2^2, & \text{if } i = j, \\ -\cos \theta_{i,j} \|\sigma_i^*\|_2 \cdot \|\sigma_j^*\|_2, & \text{if } i \neq j. \end{cases}$$

We claim that  $\mathbf{Q}$  is the Laplacian matrix of some graph  $G$ . First, the matrix is symmetric. Second, for each  $i$ ,  $\mathbf{Q}(i, i) = \|\sigma_i^*\|_2^2 > 0$ , and for  $i \neq j$ ,  $\mathbf{Q}(i, j) \leq 0$  since  $\theta_{i,j} \leq \pi/2$  by assumption (note therefore the importance that  $\mathcal{T}$  is hyperacute). Finally, denote  $\Sigma^* = (\sigma_1^*, \dots, \sigma_n^*)$ , and recall from the construction of the dual simplex in Section 2.5.1 that  $\sigma_n^* = -\sum_{i < n} \sigma_i^*$ . Therefore, for  $i \neq n$ ,

$$\sum_{j=1}^n \mathbf{Q}(i, j) = \sum_{j=1}^{n-1} \langle \sigma_i^*, \sigma_j^* \rangle + \langle \sigma_i^*, -\sum_{j < n} \sigma_j^* \rangle = \sum_{j < n} \langle \sigma_i^*, \sigma_j^* \rangle - \sum_{j < n} \langle \sigma_i^*, \sigma_j^* \rangle = 0,$$

hence  $\mathbf{Q}\mathbf{1} = \mathbf{0}$ , meaning that  $\mathbf{Q}(i, i) = -\sum_{j \neq i} \mathbf{Q}(i, j)$ . If we construct a weighted graph  $G = (V, E, w)$  on  $n$  vertices with edge weights  $w(i, j) = -\mathbf{Q}(i, j)$ , it then follows that  $\mathbf{Q} = (\Sigma^*)^t \Sigma^* = \mathbf{L}_G$ . Thus, the simplex  $\mathcal{T}^*$  is congruent to the combinatorial simplex of  $G$  (by virtue of the fact that  $\langle \sigma_i^*, \sigma_j^* \rangle = \mathbf{L}_G(i, j)$ ), and  $\mathcal{T}$  is (congruent to) the dual of the combinatorial simplex of  $G$ .

*Remark 3.2.* All the faffing<sup>1</sup> about with congruence is, unfortunately, necessary. If  $G$  is the graph constructed from the simplex  $\mathcal{T}$  as above, there is no reason that its inverse combinatorial simplex  $\mathcal{S}_G^+$  as constructed in Section 3.2.1 will be precisely  $\mathcal{T}$ . In fact, this is highly unlikely. The construction of  $G$  from  $\mathcal{T}$  and its dual  $\mathcal{T}^*$  used only the magnitudes of the vectors of  $\{\sigma_i^*\}$  and not their absolute position. Thus, any rotation of  $\mathcal{T}$  would produce the same graph. It is for this reason that the relationship between graphs and simplices must deal with congruence relationships.

We summarize the material in Sections 3.2.1 and 3.2.2 with the following theorem.

**THEOREM 3.1.** *There exists a bijection between (the congruence classes of) hyperacute simplices in  $\mathbb{R}^{n-1}$  and connected, weighted graphs on  $n$  vertices.*

Several observations are in order. First, the astute reader may wonder why it was necessary in this section to explore the relation between a given hyperacute simplex  $\mathcal{T}$  and its corresponding graph by means of the dual simplex  $\mathcal{T}^*$ . A second, *more* astute reader will then question the sanity of the first, and point out that in order to demonstrate that  $\mathcal{T}$  is congruent to the inverse simplex of  $G$ , one would have to have a firm grasp of the structure of  $\mathbf{L}_G^+$ , which is much more poorly understood in general than  $\mathbf{L}_G$ . For instance, would one have to argue that there exists a graph  $G$  such that  $\Sigma(\mathcal{T})^t \Sigma(\mathcal{T}) = \mathbf{L}_G^+$ . This seems difficult to do in general since, for example, even the sign of the entries of  $\mathbf{L}_G^+$  aren't known.

Second, considering that Theorem 3.1 was proved using combinatorial simplices, one might wonder whether a similar relationship holds between “normalized” simplices and graphs. That is,

<sup>1</sup>U.K. slang has obviously had its effect on me.

given  $\mathcal{T}$ , when is  $\mathcal{T}^*$  the normalized simplex of a graph? Since the vertices of the normalized simplex lie on the unit sphere, we would require that  $\|\sigma_i^*\|_2 = 1$ , which only holds for a very restricted class of simplex.

### §3.3. Examples & Simplices of Special Graphs

In this section we provide several examples of simplices of graphs in order to give the reader a more intuitive feeling of the correspondence. Fix a connected and undirected graph  $G = (V, E, w)$ . We begin by considering the simplices generated by three special graphs relating to  $G$ —the complement graph  $G^c$ , an arbitrary subgraph of  $G$ , and the case in which  $G$  is a product graph. We then proceed to analyzing several concrete examples.

**Simplex of complement graph,  $G^c$ .** Suppose that  $G$  is unweighted; so  $w(i, j) \in \{0, 1\}$  for all  $i, j$ . The *complement graph of  $G$* , denoted  $G^c$ , is the graph  $G^c = (V, E^c)$  where  $E^c = \{(i, j) : (i, j) \notin E\}$ . That is, it has edges where  $G$  has none and vice versa. Therefore, it has the adjacency matrix  $A^c \stackrel{\text{def}}{=} A_{G^c} = \mathbf{1}\mathbf{1}^t - \mathbf{I} - A_G$  and degree matrix  $D^c \stackrel{\text{def}}{=} D_{G^c} = (n - 1)\mathbf{I} - D_G$  since  $\deg(i)_{G^c} = n - 1 - \deg(i)_G$ . The Laplacian of  $G^c$  thus reads as

$$L^c = D^c - A^c = n\mathbf{I} - D_G - \mathbf{1}\mathbf{1}^t + A_G = n\mathbf{I} - \mathbf{1}\mathbf{1}^t - L_G.$$

Of course,  $\mathbf{1}$  is still an eigenfunction of  $L^c$  ( $G^c$  is, after all, a graph). For  $\varphi \perp \mathbf{1}$ , we have  $L^c \varphi = n\varphi - \mathbf{1}\langle \mathbf{1}, \varphi \rangle - L\varphi = (n - \lambda)\varphi$  from which it follows that  $L^c$  shares the same eigenfunctions as  $L$ , with corresponding eigenvalues  $\{n - \lambda_i\}$ . Consequently, the simplex corresponding to  $G^c$ ,  $\mathcal{S}^c$  has vertices given by  $\sigma_i(j) = \varphi_j(i)\sqrt{n - \lambda_j}$ , and the inverse simplex has vertices  $\sigma_i^+(j) = \frac{\varphi_j(i)}{\sqrt{n - \lambda_j}}$ .

**Subgraphs.** Let  $H \subseteq G$ , in the sense that  $w_H(i, j) \leq w_G(i, j)$  for all  $i, j \in [n]$  (we allow for  $G$  to be weighted once again). Then, for any  $f : V \rightarrow \mathbb{R}$  we see that

$$\mathcal{L}_G(f) = \sum_{i \sim j} w_G(i, j)(f(i) - f(j))^2 \geq \sum_{i \sim j} w_H(i, j)(f(i) - f(j))^2 = \mathcal{L}_H(f).$$

Therefore,

$$\|\Sigma_H f\|_2^2 \leq \|\Sigma_G f\|_2^2.$$

In particular, taking  $f = \chi_i$  for any  $i$ , this yields  $\|\sigma_i(G)\|_2^2 \geq \|\sigma_i(H)\|_2^2$ , where  $\{\sigma_i(G)\}$  are the vertices of  $\mathcal{S}_G$ , and  $\{\sigma_i(H)\}$  those of  $\mathcal{S}_H$ . That is, the length of the vertex vectors of  $G$  is greater than those of  $H$ .

If  $G$  is a multiple of  $H$  such that  $w_G(i, j) = c \cdot w_H(i, j)$  for all  $i, j$ , then we see that  $\mathcal{L}_G(f) = c \cdot \mathcal{L}_H(f)$  so that  $\|\sigma_i(G)\|_2^2 = c \cdot \|\sigma_i(H)\|_2^2$ . This gives us a sense that volume of the simplex of the supergraph is greater than that of the subgraph. This notion will be made more precise in Section



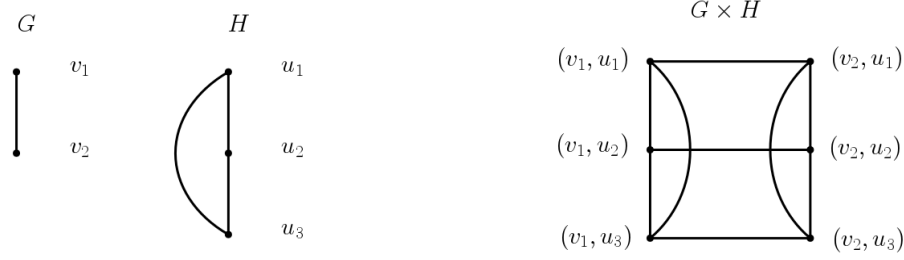


Figure 3.1: Two graphs and their product graph.

4.2.

Meanwhile however, the normalized simplex is unaffected by the re-weighting:

$$\begin{aligned}
 \widehat{\mathcal{L}}_G(\mathbf{f}) &= \sum_{i \sim j} w_G(i, j) \left( \frac{\mathbf{f}(i)}{\sqrt{w_G(i)}} - \frac{\mathbf{f}(j)}{\sqrt{w_G(j)}} \right)^2 \\
 &= \sum_{i \sim j} c \cdot w_H(i, j) \left( \frac{\mathbf{f}(i)}{\sqrt{c \cdot w_H(i)}} - \frac{\mathbf{f}(j)}{\sqrt{c \cdot w_H(j)}} \right)^2 \\
 &= \sum_{i \sim j} w_H(i, j) \left( \frac{\mathbf{f}(i)}{\sqrt{w_H(i)}} - \frac{\mathbf{f}(j)}{\sqrt{w_H(j)}} \right)^2 = \widehat{\mathcal{L}}_H(\mathbf{f}),
 \end{aligned}$$

implying that  $\|\widehat{\sigma}_i(G)\|_2 = \|\widehat{\sigma}_i(H)\|$ .

**Product graphs.** We begin with the definition of a product graph.

**DEFINITION 3.1.** Given two graphs  $G = (V(G), E(G))$  and  $H = (V(H), E(H))$ , the *product graph* of  $G$  and  $H$  is the graph with vertex set  $V(G) \times V(H)$  and edge set  $\{((i_1, j), (i_2, j)) : (i_1, i_2) \in E(G), j \in V(H)\} \cup \{((i, j_1), (i, j_2)) : (j_1, j_2) \in E(H), i \in V(G)\}$ . It is denoted  $G \times H$ .

In order to investigate the simplex of a product graph, we must better understand its eigenstructure.

**LEMMA 3.4.** Let graphs  $G$  and  $H$  be given. Put  $n = |V(G)|$  and  $m = |V(H)|$ . Suppose  $G$  has eigenvalues  $\lambda_1 \geq \dots \geq \lambda_n$  and corresponding eigenvectors  $\varphi_1, \dots, \varphi_n$ , as usual. Let  $H$  have eigenvalues  $\mu_1 \geq \dots \geq \mu_m$  and corresponding eigenvectors  $\psi_1, \dots, \psi_m$ . Then  $G \times H$  has  $mn$  eigenvalues  $\{\lambda_i + \mu_j\}_{(i,j) \in [n] \times [m]}$  with eigenvectors  $\{f_{i,j}\}_{(i,j) \in [n] \times [m]}$  given by  $f_{i,j}(k, \ell) = \varphi_i(k) \psi_j(\ell)$ .

Consequently, with  $G$  and  $H$  as in Lemma 3.4, we see that the product graph yields a simplex  $\mathcal{S}_{G \times H} \in \mathbb{R}^{mn-1}$  with vertices  $\{\sigma_{ij}\}_{(i,j) \in [n] \times [m]}$  given by

$$\sigma_{ij}(k\ell) = f_{k\ell}(ij)(\lambda_k + \mu_\ell)^{1/2}.$$

### 3.3.1. Examples

We now move onto concrete examples of the simplices of particular graphs whose eigenstructures we can compute explicitly. We also compute the graph of perhaps the most well-known simplex: the probability simplex.

**The complete graph,  $K_n$ .** Let us consider the combinatorial simplex  $\mathcal{S} = \mathcal{S}_{K_n}$ . The Laplacian  $L_{K_n}$  has two eigenvalues: 0 with multiplicity 1 and  $n$  with multiplicity  $n - 1$ . To see this, observe that for any  $\varphi$  perpendicular to  $\mathbf{1}$ , we have

$$\begin{aligned} L_{K_n}\varphi &= \left( \varphi(1)(n-1) - \sum_{i \neq 1} \varphi(i), \dots, \varphi(n)(n-1) - \sum_{i \neq n} \varphi(i) \right) \\ &= \left( \varphi(1)n - \sum_i \varphi(i), \dots, \varphi(n)n - \sum_i \varphi(i) \right) \\ &= (\varphi(1)n, \dots, \varphi(n)n) = n\varphi, \end{aligned}$$

since  $\sum_i \varphi(i) = \langle \varphi, \mathbf{1} \rangle = 0$ . Let  $\mathbf{Q}$  described the rotation matrix which rotates each vector by  $\pi/4$  about each axis. Thus  $\mathbf{Q}\mathbf{e}_1 = \mathbf{1}$ , and we can  $n - 1$  orthogonal eigenvectors  $\mathbf{Q}\mathbf{e}_2, \dots, \mathbf{Q}\mathbf{e}_n$ . The vertices of  $\mathcal{S}$  are thus given by  $\sigma_i(j) = \sqrt{n}(\mathbf{Q}\mathbf{e}_{j+1})(i)$ .

**The Cycle graph,  $C_n$ .** The cycle graph  $C_n$  has edge set  $E = \{(i, j) : j = i + 1 \pmod n\}$ . We assume that  $n$  is even for this example. We leave it to the reader to verify by direct computation that the eigenvalues and eigenvectors of  $L_{C_n}$  are given by

$$\varphi_i(j) = \cos\left(\frac{2\pi(i-1)j}{n}\right), \quad \lambda_i = 2 - 2\cos\left(\frac{2\pi(i-1)}{n}\right),$$

for  $i = 1, \dots, n/2 + 1$ , and

$$\varphi_i(j) = \cos\left(\frac{2\pi(i - n/2 - 1)j}{n}\right), \quad \lambda_i = 2 - 2\cos\left(\frac{2\pi(i - n/2 - 1)}{n}\right),$$

for  $i = n/2 + 2, \dots, n$ . Therefore, the vertices of  $\mathcal{S}_{C_n}$  are given by

$$\sigma_i(j) = \begin{cases} \cos\left(\frac{2\pi(i-1)j}{n}\right) \left(2 - \cos\left(\frac{2\pi(i-\chi(j > n/2+1)n/2-1)}{n}\right)\right), & i \leq n/2 + 1, \\ \sin\left(\frac{2\pi(i-n/2-1)j}{n}\right) \left(2 - \cos\left(\frac{2\pi(i-\chi(j > n/2+1)n/2-1)}{n}\right)\right), & i > n/2 + 1. \end{cases}$$

**The probability simplex.** Fix  $n \in \mathbb{N}$ . The *probability simplex* is the simplex  $\tilde{\mathcal{S}}_p = \text{conv}(\{\chi_i\}_{i=1}^n \cup \{\mathbf{0}\})$ . It is most likely the simplex of greatest familiarity to mathematicians and computer scientists, being used to reason geometrically about probability distributions. The probability simplex

has centroid  $\mathbf{1}/n \neq \mathbf{0}$  and we will consider its centred version

$$\mathcal{S}_p \stackrel{\text{def}}{=} \tilde{\mathcal{S}}_p - \frac{\mathbf{J}}{n},$$

which has vertices  $\sigma_i = \chi_i - \mathbf{1}/n$ ,  $i < n$ , and  $\sigma_n = -\mathbf{1}/n$ . Note that  $\sigma_j - \sigma_n = \chi_j$  and so  $\langle \chi_i, \sigma_j - \sigma_n \rangle = \delta_{ij}$ . Taking  $\sigma_i^* = \chi_i$  and  $\sigma_n^* = -\sum_i \chi_i = -\mathbf{1}$  thus gives us the dual vertices. The angles between the facets of  $\mathcal{S}_p$  are thus defined by

$$\cos \theta_{ij}(\mathcal{S}_p) = -\langle \chi_i, \chi_j \rangle = -\delta_{ij},$$

for  $i, j \in [n-1]$  and

$$\cos \theta_{in}(\mathcal{S}_p) = \frac{\langle \chi_i, \mathbf{1} \rangle}{\|\mathbf{1}\|} = 1/\sqrt{n},$$

for all  $i \in [n]$ . This implies that  $\theta_{ij}(\mathcal{S}_p) = 0$  for  $i \neq j$ ,  $i, j \neq n$  and  $\theta_{in}(\mathcal{S}_p) \in (0, \pi/2)$ . Using the construction of Section 3.2.2, we associate to  $\mathcal{S}_p$  the graph with Laplacian matrix  $\Sigma(\mathcal{S}_p^*) \rightarrow \Sigma(\mathcal{S}_p^*)$ , where  $\Sigma(\mathcal{S}_p^*) = (\sigma_1^*, \dots, \sigma_n^*)$ . This matrix has  $(i, j)$ -th entry 1 for  $i = j$ , 1 for  $i = n$  or  $j = n$ , and 0 otherwise. This graph thus has each vertex connected to  $n$ , but to no others. That is, the graph of the probability simplex  $\mathcal{S}_p$  is the star graph on  $n$  vertices.

### §3.4. Properties of $\mathcal{S}_G$ and $\mathcal{S}_G^+$

We now embark on our voyage to understand the mathematical properties of the simplices of a graph. This section is devoted to the study of  $\mathcal{S}_G$  and  $\mathcal{S}_G^+$ , while Section 3.5 is concerned with  $\hat{\mathcal{S}}_G$  and  $\hat{\mathcal{S}}_G^+$ . For bibliographic purposes, we will encode many of the results as Lemmas even if they are relatively simple. There are many results, and this should enable easier accounting. We begin with three basic properties.

LEMMA 3.5. *The following three properties hold:*

1. Both  $\mathcal{S}_G$  and  $\mathcal{S}_G^+$  are centred at the origin;
2. The squared distance between the vertices of  $\mathcal{S}_G^+$  is equal to the effective resistance between the corresponding vertices of  $G$ ;
3. For any non-empty  $U \subsetneq V$ , the faces  $\mathcal{S}_U$  and  $\mathcal{S}_{U^c}^+$  are orthogonal.

*Proof.* For (i) we simply compute  $\mathbf{c}(\mathcal{S}) = n^{-1} \mathbf{\Lambda}^{-1/2} \Phi^t \mathbf{1} = \mathbf{0}$ , since  $\langle \varphi_i, \mathbf{1} \rangle = 0$  for all  $i < n$ . Likewise,  $\mathbf{c}(\mathcal{S}^+) = \mathbf{0}$ . For (ii),

$$\left\| \sigma_i^+ - \sigma_j^+ \right\|_2^2 = \left\| \sigma_i^+ \right\|_2^2 + \left\| \sigma_j^+ \right\|_2^2 - 2 \langle \sigma_i^+, \sigma_j^+ \rangle = L_G^+(i, i) + L_G^+(j, j) - 2L_G^+(i, j) = r^{\text{eff}}(i, j).$$

The third property follows as a result of the fact that  $\mathcal{S}_G^+$  is dual to  $\mathcal{S}_G$  (Observation 3.1) and Lemma 2.13.  $\square$

Property (ii) in the previous lemma was first noticed by Fielder [Fie11, Chapter 6], and was also remarked upon by Van Mieghem *et al.* [VMDC17] who used it in their study of best spreader nodes in electrical networks. We will return to this connection in later sections. We now turn our attention to properties of the angles of a simplex.

LEMMA 3.6. *The combinatorial simplex  $\mathcal{S}_G$  of a graph  $G$  is hyperacute iff  $\mathbf{L}_G^+$  is a Laplacian.*

*Proof.* Using Equation (2.22) and the fact that  $\mathcal{S}_G^+ = \mathcal{S}_G^*$  (Observation 3.1), we have

$$\cos \theta_{ij} = -\frac{\langle \sigma_i^+, \sigma_j^+ \rangle}{\|\sigma_i^+\|_2 \|\sigma_j^+\|_2},$$

where we recall that  $\theta_{ij}$  is the angle between  $\mathcal{S}_{\{i\}^c}$  and  $\mathcal{S}_{\{j\}^c}$ . Thus,  $\mathcal{S}_G$  is hyperacute iff

$$-\langle \sigma_i^+, \sigma_j^+ \rangle / \|\sigma_i^+\|_2 \|\sigma_j^+\|_2 \in [0, 1],$$

which occurs iff  $\langle \sigma_i^+, \sigma_j^+ \rangle \leq 0$ . In this case  $\mathbf{L}_G^+(i, j) \leq 0$ , implying that  $\mathbf{L}_G^+$  is a Laplacian (recall that it already satisfies the other required properties:  $\mathbf{L}_G^+ \mathbf{1} = \mathbf{0}$  and  $\mathbf{L}_G^+(i, i) \geq 0$ ).  $\square$

COROLLARY 3.1. *The combinatorial simplex of the complete graph,  $\mathcal{S}_{K_n}$ , is hyperacute.*

*Proof.* Let  $\mathbf{L} = \mathbf{L}_{K_n}$ . It suffices to show by the previous lemma that  $\mathbf{L}^+ = \mathbf{L}_{K_n}^+$  is a Laplacian. We've already seen that  $\mathbf{L}_G^+ \mathbf{1} = \mathbf{0}$  for any  $G$ , so it remains only to show that  $\mathbf{L}^+(k, k) > 0$  for all  $k \in [n]$  and  $\mathbf{L}^+(k, \ell) \leq 0$  for all  $k \neq \ell$ , i.e., that  $\text{sign}(\mathbf{L}(k, \ell)) = \text{sign}(\mathbf{L}^+(k, \ell))$  for all  $k, \ell$ . Recall from Section 3.3.1 that  $K_n$  has eigenvalue  $n$  with multiplicity  $n - 1$  and a single zero eigenvalue. Hence,  $\mathbf{L} = n \sum_{i < n} \varphi_i \varphi_i^t$  and  $\mathbf{L}^+ = n^{-1} \sum_{i < n} \varphi_i \varphi_i^t$ . Therefore,  $\text{sign}(\mathbf{L}(k, \ell)) = \text{sign}(n \sum_{i < n} \varphi_i(k) \varphi_i(\ell)) = \text{sign}(\sum_{i < n} \varphi_i(k) \varphi_i(\ell)) = \text{sign}(\mathbf{L}^+(k, \ell))$  which implies the result.  $\square$

Before continuing, we make a brief detour to demonstrate how this result combined with the link between  $\mathcal{S}_G^+$  and the effective resistance of  $G$  allows us to uncover the total effective resistance of certain graphs. Recalling that  $R_G^{\text{tot}}$  is the total effective resistance in  $G$ , apply Lemma 3.5 and write

$$\begin{aligned} R_G^{\text{tot}} &= \frac{1}{2} \sum_{i, j \in [n]} r^{\text{eff}}(i, j) = \frac{1}{2} \sum_{i, j \in [n]} \|\sigma_i^+ - \sigma_j^+\|_2^2 \\ &= \frac{n}{2} \sum_{i \in [n]} \|\sigma_i^+\|_2^2 + \frac{n}{2} \sum_{j \in [n]} \|\sigma_j^+\|_2^2 - 2 \sum_{i, j \in [n]} \langle \sigma_i^+, \sigma_j^+ \rangle \\ &= n \sum_{i \in [n]} \|\sigma_i^+\|_2^2 - 2 \sum_{i \in [n]} \langle \mathbf{L}_G(i, \cdot), \mathbf{1} \rangle = n \sum_{i \in [n]} \|\sigma_i^+\|_2^2. \end{aligned}$$

Let  $K_n^\alpha$  denote the complete graph on  $n$  vertices where each edge has weight  $\alpha$ . By Corollary 3.1,  $\mathbf{L}_{K_n^\alpha}^+ = \mathbf{L}_H$  for some graph  $H$ . Therefore,  $\mathbf{L}_{K_n^\alpha} = \mathbf{L}_H^+$  and  $\|\boldsymbol{\sigma}_i^+(H)\|_2^2 = \|\boldsymbol{\sigma}_i(\mathbf{L}_{K_n^\alpha})\|_2^2$ . If  $K_n$  is the unweighted complete graph, we see that  $\mathbf{L}_{K_n^\alpha} = \alpha \mathbf{L}_{K_n}$ . Using that  $\mathbf{L}_{K_n}$  has eigenvalue  $n$  with multiplicity  $n - 1$  (Section 3.3.1) gives  $\mathbf{L}_{K_n^\alpha} = \alpha n \sum_{i < n} \boldsymbol{\varphi}_i \boldsymbol{\varphi}_i^t$ , meaning that  $\mathbf{L}_{K_n^\alpha} = \mathbf{L}_H^+$  has eigenvalue  $\alpha n$  with multiplicity  $n - 1$ . The effective resistance of  $H$  is then

$$R_H^{\text{tot}} = n \text{Tr}(\mathbf{L}_H^+) = \alpha(n - 1).$$

Moreover,  $\mathbf{L}_H$  has eigenvalue  $(\alpha n)^{-1}$  with multiplicity  $n - 1$ , and is therefore a complete graph with weights  $(\alpha n^2)^{-1}$ . We have proven the following:

LEMMA 3.7. *For any complete graph  $H$  on  $n$  vertices with uniform edge weights  $(\alpha n^2)^{-1}$  for any  $\alpha$ ,  $R_H^{\text{tot}} = \alpha(n - 1)$ .*

As Fiedler pointed out [Fie93], the correspondence also allows us to answer questions related to the distribution of angles of simplices. It is not, for example, a priori obvious that all distributions of angles are possible in a hyperacute simplex, in the following sense.

LEMMA 3.8. *For every  $n - 1 \leq k \leq \binom{n}{2}$ , there exists a hyperacute simplex on  $n$  vertices with  $k$  strictly acute interior angles.*

*Proof.* Fix  $k$  and consider a connected graph on  $n$  vertices with  $k$  edges (note the importance that  $k \geq n - 1$ ). The interior angles  $\{\theta_{ij}^+\}_{i,j}$  of  $\mathcal{S}_G^+$  obey  $\cos \theta_{ij} = w(i, j) / \sqrt{w(i)w(j)}$ , hence  $\theta_{ij} = \pi/2$  whenever  $w(i, j) = 0$ , and  $\theta_{ij} \in (0, \pi/2)$  for all  $(i, j) \in E(G)$ . Therefore,  $\mathcal{S}_G^+$  meets the desired criteria.  $\square$

The following lemma presents an alternate characterization of the simplex, and was first proved by Devriendt and Van Mieghem [DVM18]. As they notice, the following representation provides an easy way to check whether a given point lies inside the simplex. As our proof is similar to theirs, we move it to Appendix A.2.

LEMMA 3.9 ([DVM18]). *For a simplex  $\mathcal{S}$  of a graph  $G$ ,*

$$\mathcal{S} = \left\{ \mathbf{x} \in \mathbb{R}^{n-1} : \mathbf{x}^t \boldsymbol{\Sigma}^+ + \frac{\mathbf{1}^t}{n} \geq \mathbf{0}^t \right\}. \quad (3.6)$$

Just as each facet of a tetrahedron is contained in a plane and each edge is contained in an infinite line, each face  $\mathcal{S}_U$  of a simplex  $U$  is contained in a *flat* (i.e., a linear subspace shifted by some constant<sup>2</sup>) of dimension  $|U| - 1$ . The following lemma helps characterize these flats.

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<sup>2</sup>Also called an affine subspace.

LEMMA 3.10. Let  $\mathcal{S}$  be the simplex of a graph  $G = (V, E, w)$ , and fix  $U \subseteq V$ . For any non-empty  $E \subseteq U^c$ ,

$$\mathcal{S}_U \subseteq \left\{ \mathbf{x} \in \mathbb{R}^{n-1} : \sum_{i \in E} \langle \mathbf{x}, \boldsymbol{\sigma}_i^+ \rangle + \frac{|E|}{n} = 0 \right\},$$

and

$$\mathcal{S}_U^+ \subseteq \left\{ \mathbf{x} \in \mathbb{R}^{n-1} : \sum_{i \in E} \langle \mathbf{x}, \boldsymbol{\sigma}_i \rangle + \frac{|E|}{n} = 0 \right\},$$

*Proof.* Let  $\mathbf{x} \in \mathcal{S}_U$  be arbitrary. For any  $i \in U^c$  we have  $\langle \mathbf{x}, \boldsymbol{\sigma}_i^+ \rangle = -1/n$ . Hence, for any  $E \subseteq U^c$

$$\sum_{i \in E} \langle \mathbf{x}, \boldsymbol{\sigma}_i^+ \rangle + \frac{|E|}{n} = \sum_{i \in E} \left( \langle \mathbf{x}, \boldsymbol{\sigma}_i^+ \rangle + \frac{1}{n} \right) = \sum_{i \in E} \left( \frac{1}{n} - \frac{1}{n} \right) = 0,$$

implying that  $\mathbf{x}$  is in the desired set.  $\square$

Lemma 3.10 gives us an alternate way to prove Lemma 3.9. For any  $i$ , taking  $U = N \setminus \{i\}$  and  $E = \{i\}$ , it implies that  $\mathcal{S}_{\{i\}^c}$  is a subset of the hyperplane

$$\mathcal{H}_i \stackrel{\text{def}}{=} \{ \mathbf{x} \in \mathbb{R}^{n-1} : \langle \mathbf{x}, \boldsymbol{\sigma}_i^+ \rangle + 1/n = 0 \}. \quad (3.7)$$

All points in the simplex  $\mathcal{S}$  lie to one side of  $\mathcal{S}_{\{i\}^c}$ , i.e., they lie in the halfspace

$$\mathcal{H}_i^{\geq} \stackrel{\text{def}}{=} \{ \mathbf{x} \in \mathbb{R}^{n-1} : \langle \mathbf{x}, \boldsymbol{\sigma}_i^+ \rangle + 1/n \geq 0 \}.$$

(We know it is this halfspace because  $\mathbf{0} \in \mathcal{S} \cap \mathcal{H}_i^{\geq}$ .) The simplex is the interior of the region defined by the intersection of the faces  $\mathcal{S}_{\{i\}^c}$ , i.e.,

$$\mathcal{S} = \bigcap_i \mathcal{H}_i^{\geq}. \quad (3.8)$$

Moreover,  $\mathbf{x} \in \bigcap_i \mathcal{H}_i^{\geq}$  iff  $\langle \mathbf{x}, \boldsymbol{\sigma}_i^+ \rangle + 1/n \geq 0$  for all  $i$ , i.e.,  $(\langle \mathbf{x}, \boldsymbol{\sigma}_1^+ \rangle, \dots, \langle \mathbf{x}, \boldsymbol{\sigma}_n^+ \rangle) + \mathbf{1}/n \geq \mathbf{0}$ , meaning  $\mathbf{x}$  satisfies (3.6). We emphasize that a very similar discussion applies to  $\mathcal{S}^+$ , in which case one has

$$\mathcal{S}^+ = \bigcap_i (\mathcal{H}_i^+)^{\geq}, \quad (3.9)$$

for  $(\mathcal{H}_i^+)^{\geq} \stackrel{\text{def}}{=} \{ \mathbf{x} \in \mathbb{R}^{n-1} : \langle \mathbf{x}, \boldsymbol{\sigma}_i \rangle + 1/n \geq 0 \}$ .

**Centroids and altitudes.** We now turn to investigating the centroids and altitudes of the simplices, and how they relate to properties of the underlying graph. We begin by exploring the relationships between properties of the simplices themselves.

Recall that the altitude between  $\mathcal{S}[U]$  and  $\mathcal{S}[U^c]$  of a simplex  $\mathcal{S}$  is denoted  $\mathbf{a}(\mathcal{S}_U)$  and is the

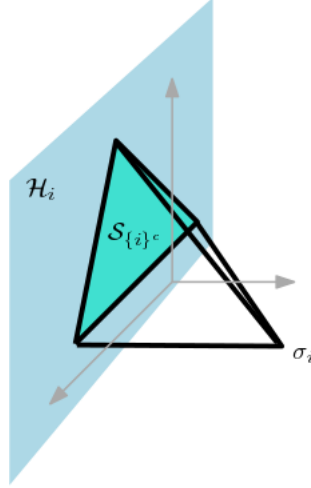


Figure 3.2: An illustration of the combinatorial simplex  $\mathcal{S}_G \subseteq \mathbb{R}^3$  and its face  $\mathcal{S}_{\{i\}^c}$  contained in the hyperplane  $\mathcal{H}_i$ .

unique vector  $\mathbf{p} - \mathbf{q}$  where  $\mathbf{p} \in \mathcal{S}_{U^c}$  and  $\mathbf{q} \in \mathcal{S}_U$  which lies in the orthogonal complement of both  $\mathcal{S}_U$  and  $\mathcal{S}_{U^c}$ . One would thus expect that  $\mathbf{a}(\mathcal{S}_U)$  and  $\mathbf{a}(\mathcal{S}_{U^c})$  to be antiparallel; a fact verified by Lemma 3.11.

In what follows, we will often write  $\mathbf{c}_U$  for  $\mathbf{c}(\mathcal{S}_U)$  (resp.,  $\mathbf{c}_U^+$  for  $\mathbf{c}(\mathcal{S}_U^+)$ ) and  $\mathbf{a}_U$  for  $\mathbf{a}(\mathcal{S}_U)$  (resp.,  $\mathbf{a}_U^+$  for  $\mathbf{a}(\mathcal{S}_U^+)$ ).

LEMMA 3.11 ([DVM18]). *Let  $U \subseteq V$  be non-empty. Then the vectors  $\mathbf{c}(\mathcal{S}_U)$  and  $\mathbf{c}(\mathcal{S}_{U^c})$  are antiparallel. In particular,  $(n - |U|)\mathbf{c}(\mathcal{S}_{U^c}) = |U|\mathbf{c}(\mathcal{S}_U)$  and*

$$\frac{\mathbf{c}(\mathcal{S}_U)}{\|\mathbf{c}(\mathcal{S}_U)\|_2} = -\frac{\mathbf{c}(\mathcal{S}_{U^c})}{\|\mathbf{c}(\mathcal{S}_{U^c})\|_2}.$$

*Proof.* This is a straightforward computation: Observing that  $\chi_U = \mathbf{1} - \chi_{U^c}$  we have

$$\mathbf{c}_U = |U|^{-1} \mathbf{\Sigma} \chi_U = |U|^{-1} \mathbf{\Sigma} (\mathbf{1} - \chi_{U^c}) = -|U|^{-1} \mathbf{\Sigma} \chi_{U^c} = -|U|^{-1} \frac{|U^c|}{|U^c|} \mathbf{\Sigma} \chi_{U^c} = \frac{n - |U|}{|U|} \mathbf{c}_{U^c},$$

where we've used that  $\mathbf{\Sigma} \mathbf{1} = \mathbf{0}$ . This proves the first result; the second follows from normalizing the two vectors.  $\square$

We would now like to examine the relationships between altitudes and centroids in the simplex and its inverse. We will demonstrate that centroids of opposing faces are antiparallel, and that the centroid of the face  $U$  is parallel to the altitude of originating from the face generated by  $U$  in its inverse. First however, we require the following technical result.

LEMMA 3.12. *Any vector perpendicular to  $\mathcal{S}_U$  can be written as  $\mathbf{\Sigma}^+(\mathbf{f}_{U^c} + \alpha \chi_U)$  for some  $\alpha \in \mathbb{R}$  and vector  $\mathbf{f}_{U^c}$  such that  $\mathbf{f}_{U^c}(U) = \mathbf{0}$ .*

*Proof.* Let  $\mathbf{y} \in \mathbb{R}^{n-1}$  be orthogonal to  $\mathcal{S}_U$ . Since  $\text{rank}(\Sigma^+) = n - 1$ , we can find some  $\mathbf{z}$  such that  $\mathbf{y} = \Sigma^+ \mathbf{z} = \sum_{i \in U^c} \sigma_i^+ z(i) + \sum_{j \in U} \sigma_j^+ z(j)$ . Define  $\mathbf{f}$  by  $\mathbf{f}(U^c) = \mathbf{z}(U^c)$  and  $\mathbf{f}(U) = \mathbf{0}$  and  $\mathbf{z}_{U^c}$ . We can then write  $\mathbf{y}$  as  $\Sigma^+ \mathbf{f} + \sum_{j \in U} \sigma_j^+ z(j)$ , so we must show that  $\mathbf{z}(U)$  is a constant vector. The orthogonality of  $\mathbf{y}$  to  $\mathcal{S}_U$  implies that for every two barycentric coordinates  $\mathbf{x}_U$  and  $\mathbf{y}_U$  with  $\mathbf{x}(U^c) = \mathbf{y}(U^c) = \mathbf{0}$ ,

$$\begin{aligned} 0 &= \langle \mathbf{y}, \Sigma \mathbf{x}_U - \Sigma \mathbf{y}_U \rangle \\ &= \sum_{i \in U^c} z(i) \langle \sigma_i^+, \Sigma(\mathbf{x}_U - \mathbf{y}_U) \rangle + \sum_{j \in U} z(j) \langle \sigma_j^+, \Sigma(\mathbf{x}_U - \mathbf{y}_U) \rangle \\ &= \sum_{j \in U} z(j) \langle \sigma_j^+, \Sigma(\mathbf{x}_U - \mathbf{y}_U) \rangle, \end{aligned} \quad (3.10)$$

where the final inequality follows because  $\sigma_i^+$  is orthogonal to  $\mathcal{S}_U$  for  $i \in U^c$  by Lemma 3.5. Now, for  $j \in U$ ,

$$\langle \sigma_j^+, \Sigma(\mathbf{x}_U - \mathbf{y}_U) \rangle = \chi_j^t \Sigma^+ \Sigma(\mathbf{x}_U - \mathbf{y}_U) = \chi_j^t \left( \mathbf{I} - \frac{\mathbf{J}}{n} \right) (\mathbf{x}_U - \mathbf{y}_U) = \chi_j^t (\mathbf{x}_U - \mathbf{y}_U). \quad (3.11)$$

Suppose for contradiction that  $z(k) \neq z(j)$  for some  $k, j \in U$ . Put  $\mathbf{x}_U = \chi_k$  and  $\mathbf{y}_U = \chi_j$ . Using Equation (3.11) write (3.10) as

$$z(k) \chi_k^t (\chi_k - \chi_j) + z(j) \chi_j^t (\chi_k - \chi_j) + \sum_{\ell \in U^c, \ell \neq j, k} z(\ell) \chi_\ell^t (\chi_k - \chi_j) = z(k) - z(j) \neq 0,$$

a contradiction.  $\square$

We can now proceed to the main result.

LEMMA 3.13. *For a simplex  $\mathcal{S}$  of a graph  $G = (V, E)$  and any  $U \subseteq V$ ,  $U \neq \emptyset$ ,*

$$\frac{\mathbf{a}(\mathcal{S}_U)}{\|\mathbf{a}(\mathcal{S}_U)\|_2} = \frac{\mathbf{c}^+(\mathcal{S}_{U^c})}{\|\mathbf{c}^+(\mathcal{S}_{U^c})\|_2} = -\frac{\mathbf{c}^+(\mathcal{S}_U)}{\|\mathbf{c}^+(\mathcal{S}_U)\|_2}, \quad (3.12)$$

and

$$\frac{\mathbf{a}^+(\mathcal{S}_U)}{\|\mathbf{a}^+(\mathcal{S}_U)\|_2} = \frac{\mathbf{c}(\mathcal{S}_{U^c})}{\|\mathbf{c}(\mathcal{S}_{U^c})\|_2} = -\frac{\mathbf{c}(\mathcal{S}_U)}{\|\mathbf{c}(\mathcal{S}_U)\|_2}.$$

*Proof.* We prove the first set of equalities only; the second is obtained similarly. By definition,  $\mathbf{a}_U$  is orthogonal to both  $\mathcal{S}_U$  and  $\mathcal{S}_{U^c}$ . Lemma 3.12 then implies both that

$$\mathbf{a}_U = \Sigma^+ \mathbf{f} + \alpha \Sigma^+ \chi_U,$$

and

$$\mathbf{a}_U = \Sigma^+ \mathbf{g} + \beta \Sigma^+ \chi_{U^c},$$



for some  $\alpha, \beta \in \mathbb{R}$ , and vectors  $\mathbf{f}, \mathbf{g}$  with  $\mathbf{f}(U) = \mathbf{0}$  and  $\mathbf{g}(U^c) = \mathbf{0}$ . In particular then,

$$\frac{\Sigma^+(\mathbf{f} + \alpha\chi_U)}{\|\Sigma^+(\mathbf{f} + \alpha\chi_U)\|_2} = \frac{\Sigma^+(\mathbf{g} + \beta\chi_{U^c})}{\|\Sigma^+(\mathbf{g} + \beta\chi_{U^c})\|_2}. \quad (3.13)$$

By Lemma 3.11, taking  $\mathbf{f} = \pm\chi_{U^c}/|U^c|$ ,  $\mathbf{g} = \mp\chi_U/|U|$ , and  $\alpha = \beta = 0$  yield solutions to the above equation. We have thus obtained Equation (3.12) up to its sign; it remains to determine whether  $\mathbf{a}(\mathcal{S}_U)$  is parallel to antiparallel to  $\mathbf{c}(\mathcal{S}_U)$ . Since it is one of the two, we have

$$\frac{\langle \mathbf{a}_U, \mathbf{c}_U^+ \rangle}{\|\mathbf{a}_U\|_2 \|\mathbf{c}^+ U\|_2} \in \{1, -1\},$$

hence to see that they are antiparallel it suffices to show that  $\langle \mathbf{a}_U, \mathbf{c}^+ U \rangle < 0$ . Let  $\mathbf{a}_U = \Sigma \mathbf{y}_{U^c} - \Sigma \mathbf{z}_U$  for barycentric coordinates  $\mathbf{y}_{U^c}$  and  $\mathbf{z}_U$  representing the faces  $\mathcal{S}_{U^c}$  and  $\mathcal{S}_U$ . Then,

$$\begin{aligned} \langle \mathbf{a}_U, \mathbf{c}_U^+ \rangle &= \frac{1}{n} \langle \Sigma(\mathbf{y}_{U^c} - \mathbf{z}_U), \Sigma \chi_U^+ \rangle \\ &= \frac{1}{n} (\mathbf{y}_{U^c}^t - \mathbf{z}_U^t) \left( \mathbf{I} - \frac{\mathbf{J}}{n} \right) \chi_U \\ &= -\frac{1}{n} \mathbf{z}_U^t \chi_U - \frac{1}{n^2} (\mathbf{y}_{U^c}^t - \mathbf{z}_U^t) \mathbf{1} \mathbf{1}^t \chi_U \\ &= -\frac{1}{n} < 0. \end{aligned}$$

Therefore,  $\mathbf{a}_U$  is indeed antiparallel to  $\mathbf{c}_U^+$ , meaning that the correct signage is  $\mathbf{f} = \chi_{U^c}/|U^c|$  and  $\mathbf{g} = -\chi_U/|U|$ . Thus,

$$\frac{\mathbf{a}_U}{\|\mathbf{a}_U\|_2} = \frac{\Sigma^+ \chi_{U^c}}{\|\Sigma^+ \chi_{U^c}\|_2} = -\frac{\Sigma^+ \chi_U}{\|\Sigma^+ \chi_U\|_2},$$

which is Equation (3.12).  $\square$

*Remark 3.3.* We note that there are no other solutions, up to scaling, of the system of equations for  $\mathbf{a}_U$  in the previous proof. Indeed, let  $\mathbf{f}, \mathbf{g}, \alpha, \beta$  satisfy the equations. Then

$$\Sigma^+(\mathbf{f} - \beta\chi_{U^c}) + \Sigma^+(\alpha\chi_U - \mathbf{g}) = \mathbf{0},$$

so  $\mathbf{f} - \beta\chi_{U^c} + \alpha\chi - \mathbf{g} \in \ker(\Sigma^+) = \text{span}(\mathbf{1})$ , implying that  $\mathbf{f} - \beta\chi_{U^c} = k\chi_{U^c}$  and  $\alpha\chi_U - \mathbf{g} = k\chi_U$  for some  $k \in \mathbb{R}$ , which yields the same solution as in the proof.

Whereas the previous few lemmas explored relationships among  $\mathcal{S}_G$  and  $\mathcal{S}_G^+$  only, we now begin to observe several connections between the geometry of the simplices and properties of the graph. We begin by recalling that given  $U \subseteq V(G)$  the *cut-set* of  $U$  is

$$\partial U \stackrel{\text{def}}{=} (U \times U^c) \cap E(G) = \{(i, j) \in E(G) : i \in U, j \in U^c\}.$$

Noting that  $|\chi_U(i) - \chi_U(j)| = \chi_{(i,j) \in \partial U}$ , we see that

$$w(\partial U) = \sum_{i,j \in E} w(i,j) |\chi_U(i) - \chi_U(j)| = \sum_{i,j \in E} w(i,j) (\chi_U(i) - \chi_U(j))^2 = \mathcal{L}(\chi_U).$$

Moreover,  $\|\mathbf{c}(\mathcal{S}_U)\|_2^2 = \langle |U|^{-1} \Sigma \chi_U, |U|^{-1} \Sigma \chi_U \rangle = |U|^{-2} \mathcal{L}(\chi_U)$  and so

$$\|\mathbf{c}(\mathcal{S}_U)\|_2^2 = \frac{w(\partial U)}{|U|^2}. \quad (3.14)$$

Via the same process we can also obtain an equivalent expression for the centroid of the inverse simplex:

$$\|\mathbf{c}(\mathcal{S}_U^+)\|_2^2 = \frac{w(\partial^+ U)}{|U|^2}, \quad (3.15)$$

where we follow the notation of [DVM18] and define

$$w(\partial^+ U) \stackrel{\text{def}}{=} \langle \Sigma^+ \chi_U, \Sigma^+ \chi_U \rangle = \langle \chi_U, \mathbf{L}^+ \chi_U \rangle = \mathcal{L}^+(\chi_U). \quad (3.16)$$

Equations (3.14) and (3.15) were also given in [DVM18]. As a sanity check, we note that the equations are consistent with the facts that  $\|\sigma_i\|_2^2 = w(i)$  and  $\|\sigma_i^+\|_2^2 = \mathbf{L}^+(i, i) = \hat{\mathcal{L}}^+(\chi_i)$ . These equations allow us to give an interesting correspondence between the sizes of the altitudes and cut-sets of  $G$ .

LEMMA 3.14. *For any non-empty  $U \subseteq V$ ,  $\|\mathbf{a}_U^+\|_2^2 = 1/w(\partial U)$  and  $\|\mathbf{a}_U\|_2^2 = 1/w(\partial^+ U)$ .*

*Proof.* By definition of the altitude there exists barycentric coordinates  $\mathbf{x}_U$  and  $\mathbf{x}_{U^c}$  such that  $\mathbf{a}_U^+ = \Sigma^+(\mathbf{x}_U - \mathbf{x}_{U^c})$ . Combining this representation of  $\mathbf{a}_U^+$  with that given by Lemma 3.13, write

$$\|\mathbf{a}_U^+\|_2 = \frac{\langle \mathbf{a}_U^+, \mathbf{a}_U^+ \rangle}{\|\mathbf{a}_U^+\|_2} = \frac{\langle \Sigma^+(\mathbf{x}_{U^c} - \mathbf{x}_U), c_{U^c} \rangle}{\|c_{U^c}\|_2} = \frac{\langle \Sigma^+(\mathbf{x}_{U^c} - \mathbf{x}_U), \Sigma \chi_{U^c} \rangle}{\sqrt{w(\partial U^c)}},$$

where the final equality comes from using the definition of the centroid in the numerator, and Equation (3.14) in the denominator. Recalling the relation between  $\Sigma$  and  $\Sigma^+$  given by Equation (3.4) and that  $\mathbf{x}_U$  and  $\mathbf{x}_{U^c}$  are barycentric coordinates, we can rewrite the above as

$$\frac{(\mathbf{x}_{U^c} - \mathbf{x}_U)^t (\mathbf{I} - \mathbf{1}\mathbf{1}^t/n) \chi_{U^c}}{\sqrt{w(\partial U^c)}} = \frac{1}{\sqrt{w(\partial U^c)}}.$$

Squaring both sides while noting that  $\partial U = \partial U^c$  completes the proof of the first equality. For the second, we proceed in precisely the same manner to obtain  $\|\mathbf{a}_U\|_2^2 = 1/w(\partial^+ U^c)$ . However, it's not immediately obvious that  $w(\partial^+ U^c) = w(\partial^+ U)$ . To see this, first recall that  $\Sigma^+ \mathbf{1} = \mathbf{L}^{-1/2} \Phi^t \mathbf{1} = \mathbf{0}$ , and so

$$w(\partial^+ U^c) = \langle \Sigma^+ \chi_{U^c}, \Sigma^+ \chi_{U^c} \rangle$$

$$\begin{aligned} &= \langle \Sigma^+(\mathbf{1} - \chi_U), \Sigma^+(\mathbf{1} - \chi_U) \rangle \\ &= \langle \Sigma^+ \chi_U, \Sigma^+ \chi_U \rangle = w(\partial^+ U). \end{aligned} \quad \boxtimes$$

The aforementioned astute reader may have noticed that the above result implies something about the computational difficulty of determining the length of the minimum and maximum altitudes in hyperacute simplices. We tell this reader to “hold their horses”—this result and others like it will be presented in Chapter 5.

The next two lemmas were both proven by Devriendt and Van Mieghem [DVM18], extending work done by Fiedler. The following lemma gives an explicit expression for the altitudes in terms of graph properties and the inverse centroid.

LEMMA 3.15. *For any non-empty  $U \subseteq V$ ,*

$$\mathbf{a}_U = \frac{n - |U|}{w(\partial^+ U)} \mathbf{c}_{U^c}^+, \quad \text{and} \quad \mathbf{a}_U^+ = \frac{n - |U|}{w(\partial U)} \mathbf{c}_{U^c}.$$

*Proof.* This is a consequence of identities (3.14) and (3.15) and Lemmas 3.13 and 3.14. Applying the latter and then the former, observe that

$$\mathbf{a}_U = \frac{\|\mathbf{a}_U\|_2}{\|\mathbf{c}_{U^c}^+\|_2} \mathbf{c}_{U^c}^+ = \left( \frac{1}{\sqrt{w(\partial^+ U^c)}} \Big/ \frac{\sqrt{w(\partial^+ U)}}{|U^c|} \right) \mathbf{c}_{U^c}^+ = \frac{n - |U|}{w(\partial^+ U)} \mathbf{c}_{U^c}^+,$$

where we’ve once against used that  $w(\partial^+ U^c) = w(\partial^+ U)$ . A similar computation holds for  $\mathbf{a}_U^+$ .  $\boxtimes$

Just as one generalizes the incidence of a vertex to the neighbourhood of a set of vertices, one can generalize an edge to the incidence between groups of vertices, as

$$\partial U_1 \cap \partial U_2 = \{(i, j) \in E(G), i \in U_1, j \in U_2\},$$

for  $U_1, U_2 \subseteq V(G)$ . The final lemma gives an expression for the weight (or size) of this set in terms of the altitudes and centroids of the simplices.

LEMMA 3.16. *Let  $U_1, U_2 \subseteq V$  with  $U_1 \cap U_2 = \emptyset$ . Then*

$$\langle \mathbf{c}(\mathcal{S}_{U_1}), \mathbf{c}(\mathcal{S}_{U_2}) \rangle = -\frac{w(\partial U_1 \cap \partial U_2)}{|U_1||U_2|}, \quad \text{and} \quad \langle \mathbf{a}_{U_1}^+, \mathbf{a}_{U_2}^+ \rangle = -\frac{w(\partial U_1^c \cap \partial U_2^c)}{w(\partial U_1)w(\partial U_2)}.$$

*Proof.* For  $i, j \in V$ ,  $i \sim j$ , observe that

$$\chi_{U_1}^t \mathbf{L}_{i,j} \chi_{U_2} = \begin{cases} -w(i, j), & i \in U_1, j \in U_2 \text{ or } i \in U_2, j \in U_1, \\ 0, & \text{otherwise.} \end{cases}$$

Therefore,

$$\begin{aligned} \langle \mathbf{c}_{U_1}, \mathbf{c}_{U_2} \rangle &= \langle |U_1|^{-1} \boldsymbol{\Sigma} \boldsymbol{\chi}_{U_1}, |U_2|^{-1} \boldsymbol{\Sigma} \boldsymbol{\chi}_{U_2} \rangle = |U_1|^{-1} |U_2|^{-1} \boldsymbol{\chi}_{U_1}^t \mathbf{L}_G \boldsymbol{\chi}_{U_2} \\ &= |U_1|^{-1} |U_2|^{-1} \sum_{i \sim j} \boldsymbol{\chi}_{U_1}^t \mathbf{L}_{(i,j)} \boldsymbol{\chi}_{U_2} = |U_1|^{-1} |U_2|^{-1} \sum_{(i,j) \in \partial U_1 \cap \partial U_2} -w(i,j), \end{aligned}$$

which proves the first equality. The second is shown similarly by employing Lemma 3.15 and the previous identity:

$$\langle \mathbf{a}_{U_1}^+, \mathbf{a}_{U_2}^+ \rangle = \frac{|U_1^c| |U_2^c|}{w(\partial U_1) w(\partial U_2)} \langle \mathbf{c}_{U_1^c}, \mathbf{c}_{U_2^c} \rangle = -\frac{w(\partial U_1^c \cap \partial U_2^c)}{w(\partial U_1) w(\partial U_2)}. \quad \boxtimes$$

Given the number of—often related and interacting—results in this section, it may be worth providing a brief summary. The important takeaways are that (i) the geometry of the inverse simplex  $\mathcal{S}^+$  is intimately related to the effective resistance of the graph (Lemma 3.5) and (ii) the lengths of the altitudes and centroids of  $\mathcal{S}$  and  $\mathcal{S}^+$  are proportional to the weights of cuts (Equations (3.14), (3.15), Lemmas 3.14, 3.15, 3.16).

### §3.5. Properties of $\widehat{\mathcal{S}}_G$ and $\widehat{\mathcal{S}}_G^+$

Here we study the normalized simplex  $\widehat{\mathcal{S}}_G$  of the connected graph  $G = (V, E, w)$ —which we again fix throughout this section—a somewhat less accessible object than its unnormalized counterpart. The normalized simplex is, roughly speaking, distorted by the weights of the vertices. Consequently, many of the relationships between  $\mathcal{S}_G$  and  $\mathcal{S}_G^+$  are lost between  $\widehat{\mathcal{S}}_G$  and  $\widehat{\mathcal{S}}_G^+$ . The first issue is that, in general,  $\widehat{\mathcal{S}}_G$  and its inverse are not centred at the origin. Indeed, recall that the zero eigenvector  $\widehat{\boldsymbol{\varphi}}_n$  of  $\widehat{\mathbf{L}}_G$  sits in the space  $\text{span}(\mathbf{W}_G^{1/2} \mathbf{1})$ , which is distinct from  $\text{span}(\mathbf{1})$  unless  $\mathbf{W}_G^{1/2} = d\mathbf{I}$  for some  $d$ , in which case  $G$  is regular. If  $G$  is not regular, we thus have that  $\boldsymbol{\varphi}_i \in \text{span}(\mathbf{W}_G^{1/2} \mathbf{1}) \subseteq \text{span}(\mathbf{1})^\perp$  for all  $i < n$  implying that  $\langle \boldsymbol{\varphi}_i, \mathbf{1} \rangle \neq 0$ . In this case then,

$$\mathbf{c}(\widehat{\mathcal{S}}_G) = \frac{1}{n} \widehat{\mathbf{L}}^{1/2} \widehat{\boldsymbol{\Phi}}^t \mathbf{1} = \frac{1}{n} \begin{pmatrix} \sqrt{\lambda_1} \langle \boldsymbol{\varphi}_1, \mathbf{1} \rangle \\ \vdots \\ \sqrt{\lambda_{n-1}} \langle \boldsymbol{\varphi}_{n-1}, \mathbf{1} \rangle \end{pmatrix} \neq \mathbf{0}.$$

The above argument proves the following.

LEMMA 3.17. *The centroid of  $\widehat{\mathcal{S}}_G$  coincides with the origin of  $\mathbb{R}^{n-1}$  iff  $G$  is regular.*

Given this, one might wonder whether the origin is even a point in the simplex  $\widehat{\mathcal{S}}$ . It is easily seen that it is, however. Consider the barycentric coordinate  $\mathbf{u} = \sqrt{\mathbf{w}} / \|\sqrt{\mathbf{w}}\|_1$ , where  $\sqrt{\mathbf{w}} = (w(1)^{1/2}, \dots, w(n)^{1/2})$ . Since all eigenvectors  $\widehat{\boldsymbol{\varphi}}_i$ ,  $i < n$  are orthogonal to  $\boldsymbol{\varphi}_n \in \text{span}(\mathbf{w}^{1/2})$  it follows that  $\mathbf{0} = \widehat{\boldsymbol{\Sigma}} \mathbf{u} \in \widehat{\mathcal{S}}$ .

The next set of properties which don't hold between  $\widehat{\mathcal{S}}$  and  $\widehat{\mathcal{S}}^+$  are the orthogonality relationships present between a simplex and its dual. That is, in general  $\widehat{\mathcal{S}}_G^+$  is not the dual of  $\widehat{\mathcal{S}}_G$ .

LEMMA 3.18. *The inverse simplex  $\widehat{\mathcal{S}}_G^+$  is the dual of  $\widehat{\mathcal{S}}_G$  iff  $G$  is regular.*

*Proof.* For any  $i, j, k \in \mathbb{N}$  write

$$\langle \widehat{\sigma}_i^+, \widehat{\sigma}_j - \widehat{\sigma}_k \rangle = \delta_{ij} - \delta_{ik} + \frac{\sqrt{w(i)w(k)}}{n} - \frac{\sqrt{w(i)w(j)}}{n}. \quad (3.17)$$

First suppose that  $G$  is regular; so  $w(r) = w(s)$  for all  $r, s$ . Then for  $i \neq k$ , Equation (3.17) becomes  $\langle \widehat{\sigma}_i^+, \widehat{\sigma}_j - \widehat{\sigma}_k \rangle = \delta_{ij}$ . Since  $k$  was arbitrary, we see that  $\{\widehat{\sigma}_i^+\}$  is the sister pair of  $\{\widehat{\sigma}_j - \widehat{\sigma}_k\}$ . Conversely, suppose  $G$  is not regular and let  $i, k$  obey  $0 \neq w(i) \neq w(k)$ . Taking  $i = j \neq k$  in (3.17) we see

$$\langle \widehat{\sigma}_i^+, \widehat{\sigma}_i - \widehat{\sigma}_k \rangle = 1 - \frac{\sqrt{w(i)}}{n}(\sqrt{w(k)} - \sqrt{w(i)}) \neq 1,$$

so  $\{\widehat{\sigma}_i^+\}$  is not the sister set of  $\{\widehat{\sigma}_j - \widehat{\sigma}_k\}$ , completing the argument.  $\square$

A consequence of the previous Lemma is that we can no longer apply Lemma 2.13 (regarding the orthogonality of  $\mathcal{T}_U$  and  $\mathcal{T}_{U^c}^*$ ) to obtain information concerning  $\widehat{\mathcal{S}}_U$  and  $\widehat{\mathcal{S}}_{U^c}^+$ . The following two lemmas and corresponding corollary address the link between these faces, and—rather unfortunately—demonstrate that indeed, they are not orthogonal in general. The first gives sufficient conditions under which the faces are orthogonal, the second provides necessary conditions. Before we state the lemmas, recall from Section 2.3 that a subset of vertices is weight (or degree) homogenous if each vertex in the set has the same weight.

LEMMA 3.19. *Let  $U_1, U_2 \subseteq V(G)$  be two non-empty, weight homogenous subsets such that  $U_1 \cap U_2 = \emptyset$ . Then the faces  $\widehat{\mathcal{S}}^+[U_1]$  and  $\widehat{\mathcal{S}}[U_2]$  are orthogonal.*

*Proof.* Suppose  $w(i) = w_1$  for all  $i \in U_1$  and  $w(i) = w_2$  for all  $i \in U_2$ . Let  $\mathbf{x}_{U_1}$  be the barycentric coordinate of any point in  $\widehat{\mathcal{S}}^+[U_1]$  and  $\mathbf{x}_{U_2}$  that of any point in  $\widehat{\mathcal{S}}[U_2]$ .

$$\begin{aligned} \langle \widehat{\Sigma}^+ \mathbf{x}_{U_1}, \widehat{\Sigma} \mathbf{x}_{U_2} \rangle &= \mathbf{x}_{U_1}^t \left( \mathbf{I} - \frac{\sqrt{\mathbf{w}} \sqrt{\mathbf{w}}^t}{\text{vol}(G)} \right) \mathbf{x}_{U_2} \\ &= \mathbf{x}_{U_1}^t \mathbf{x}_{U_2} - \frac{1}{\text{vol}(G)} \sum_{i \in U_1} \mathbf{x}_{U_1}(i) \sqrt{w(i)} \sum_{j \in U_2} \mathbf{x}_{U_2}(j) \sqrt{w(j)} \\ &= -\frac{1}{\text{vol}(G)} \sqrt{w_1 w_2} \sum_{i \in U_1} \mathbf{x}_{U_1}(i) \sum_{j \in U_2} \mathbf{x}_{U_2}(j) = -\frac{\sqrt{w_1 w_2}}{\text{vol}(G)}, \end{aligned}$$

where the second equality is due to fact that  $U_1 \cap U_2 = \emptyset$ . This demonstrates that  $\langle \widehat{\Sigma}^+ \mathbf{x}_{U_1}, \mathbf{p} - \mathbf{q} \rangle = 0$  for any  $\mathbf{p}, \mathbf{q} \in \widehat{\mathcal{S}}[U_2]$ , completing the proof.  $\square$

LEMMA 3.20. *Suppose  $U_1 \subseteq V(G)$  is not degree homogeneous. Then for all  $U_2 \subseteq V(G)$  then faces  $\widehat{\mathcal{S}}[U_1]$  (resp.,  $\widehat{\mathcal{S}}^+[U_1]$ ) and  $\widehat{\mathcal{S}}^+[U_2]$  (resp.,  $\widehat{\mathcal{S}}[U_2]$ ) are not orthogonal.*

*Proof.* We show that  $\widehat{\mathcal{S}}[U_1]$  and  $\widehat{\mathcal{S}}^+[U_2]$  are not orthogonal; the other case is nearly identical. Let  $i, j \in U_1$  be such that  $w(i) \neq w(j)$  and consider the points  $\mathbf{p} = \widehat{\Sigma}\mathbf{x}_i, \mathbf{q} = \widehat{\Sigma}\mathbf{x}_j \in \widehat{\mathcal{S}}[U_1]$ . For any  $\widehat{\Sigma}^+\mathbf{x} \in \widehat{\mathcal{S}}^+[U_2]$ , performing the usual arithmetic yields

$$\langle \widehat{\Sigma}^+\mathbf{x}, \mathbf{p} - \mathbf{q} \rangle = \frac{1}{\text{vol}(G)} \sum_{k \in U_2} \sqrt{w(k)}x(k)(\sqrt{w(j)} - \sqrt{w(i)}) \neq 0. \quad \boxtimes$$

We state a consequence of Lemmas 3.19 and 3.20 which exemplifies a clear contrast between the combinatorial simplices and the normalized simplices.

**COROLLARY 3.2.** *The vertex  $\widehat{\sigma}_i^+$  (resp.,  $\widehat{\sigma}_i$ ) is orthogonal to  $\widehat{\mathcal{S}}_{\{i\}^c}$  (resp.,  $\widehat{\mathcal{S}}_{\{i\}^c}^+$ ) iff  $G[\{i\}^c] = G[V \setminus \{i\}]$  is regular.*

*Proof.* If  $G[\{i\}^c]$  is regular then  $\{i\}^c$  is weight homogenous. By Lemma 3.19  $\widehat{\mathcal{S}}[\{i\}] = \widehat{\sigma}_i$  (resp.,  $\widehat{\mathcal{S}}^+[\{i\}] = \widehat{\sigma}_i^+$ ) is orthogonal to  $\widehat{\mathcal{S}}[\{i\}^c]$  (resp.,  $\widehat{\mathcal{S}}^+[\{i\}^c]$ ). (Note that the singleton  $\{i\}$  is clearly degree homogeneous.) Conversely, if  $G[\{i\}^c]$  is not regular then by Lemma 3.20  $\widehat{\sigma}_i$  (resp.,  $\widehat{\sigma}_i^+$ ) is not orthogonal to  $\widehat{\mathcal{S}}[\{i\}^c]$  (resp.,  $\widehat{\mathcal{S}}^+[\{i\}^c]$ ).  $\boxtimes$

**Centroids and altitudes.** Let us attempt to parallel the arguments given in Section 3.4 concerning the centroids and altitudes of  $\mathcal{S}_G$  and  $\mathcal{S}_G^+$ . For the normalized Laplacian we have

$$\begin{aligned} \widehat{\mathcal{L}}(\mathbf{x}_U) &= \sum_{i \sim j} w(i, j) \left( \frac{\mathbf{x}_U(i)}{\sqrt{w(i)}} - \frac{\mathbf{x}_U(j)}{\sqrt{w(j)}} \right)^2 \\ &= \sum_{i \in U, j \in U^c} w(i, j) \left( \frac{\mathbf{x}_U(i)}{\sqrt{w(i)}} - \frac{\mathbf{x}_U(j)}{\sqrt{w(j)}} \right)^2 \\ &= \sum_{i \in U, j \in U^c} w(i, j) \frac{\mathbf{x}_U(i)}{w(i)} \\ &= \sum_{i \in U} \frac{1}{w(i)} \sum_{j \in \partial(i) \cap U^c} w(i, j) \\ &= \sum_{i \in U} \frac{w_{G[i+U^c]}(i)}{w(i)}, \end{aligned} \quad (3.18)$$

where we've used the shorthand  $i + U^c = \{i\} \cup U^c$  and we recall that  $G[I]$  is the graph restricted to the vertices in  $I$ . To interpret the above quantity, we might define

$$\gamma(i, B) \stackrel{\text{def}}{=} \frac{w_{G[i+B^c]}(i)}{w(i)},$$

as the *fractional weight of  $i$  in  $B$* . Further defining  $\gamma(A, B)$  as the *total fractional weight from  $A$  to  $B$* :

$$\gamma(A, B) \stackrel{\text{def}}{=} \sum_{i \in A} \gamma(i, B),$$

we have  $\widehat{\mathcal{L}}(\chi_U) = \gamma(U, U^c)$ , and so the length of the centroid  $c(\widehat{\mathcal{S}}_U)$  captures the total fraction of weight between  $U$  and  $U^c$ :

$$\|c(\widehat{\mathcal{S}}_U)\|_2^2 = \frac{1}{|U|^2} \langle \widehat{\Sigma}\chi_U, \widehat{\Sigma}\chi_U \rangle = \frac{1}{|U|^2} \widehat{\mathcal{L}}(\chi_U) = \frac{1}{|U|^2} \gamma(U, U^c), \quad (3.19)$$

which is the equivalent to Equation 3.14 for the normalized simplex. Performing a similar computation for  $c(\widehat{\mathcal{S}}_U^+)$  doesn't seem to yield anything overly insightful.

**Alternate descriptions and duals.** As we did for the combinatorial simplices, we now try to formulate a hyperplane representation of the normalized simplices. As the reader will see, however, this is difficult due to the influence of the graph weights on their geometry. We begin with a lemma which is roughly the equivalent of Lemma 3.10 for the normalized simplex.

LEMMA 3.21. *Let  $U \subseteq V$  be non-empty and  $F \subseteq U^c$ . Setting*

$$\beta_i^S = \sqrt{w(i)} \frac{\max_{j \in S} \sqrt{w(j)}}{\text{vol}(G)},$$

for any set  $S$ , we have

$$\widehat{\mathcal{S}}_U \subseteq \widehat{\mathcal{H}}_F^{\geq} \stackrel{\text{def}}{=} \left\{ \mathbf{x} \in \mathbb{R}^{n-1} : \sum_{i \in F} (\langle \mathbf{x}, \widehat{\sigma}_i^+ \rangle + \beta_i^{F^c}) \geq 0 \right\}.$$

Similarly,

$$\widehat{\mathcal{S}}_U^+ \subseteq (\widehat{\mathcal{H}}_F^+)^{\geq} \stackrel{\text{def}}{=} \left\{ \mathbf{x} \in \mathbb{R}^{n-1} : \sum_{i \in F} (\langle \mathbf{x}, \widehat{\sigma}_i \rangle + \beta_i^{F^c}) \geq 0 \right\}.$$

*Proof.* Let  $\mathbf{x} = \widehat{\Sigma}\mathbf{y} \in \widehat{\mathcal{S}}_U$ , where  $\mathbf{y}$  is a barycentric coordinate with  $\mathbf{y}(U^c) = \mathbf{0}$ . For  $i \in U^c$ ,

$$\langle \widehat{\Sigma}\mathbf{y}, \widehat{\sigma}_i^+ \rangle = \mathbf{y}^t \widehat{\Sigma}^t \widehat{\Sigma}^+ \chi_i = \mathbf{y}^t \left( \mathbf{I} - \frac{\sqrt{\mathbf{w}} \sqrt{\mathbf{w}}^t}{\text{vol}(G)} \right) \chi_i = -\frac{1}{\text{vol}(G)} \left( \sum_{j \in U} y(j) \sqrt{w(j)} \right) \sqrt{w(i)}.$$

Since  $\|\mathbf{y}\|_1 = 1$ , and  $F^c \supseteq U$  (since  $F \subseteq U^c$ ) it follows that

$$\sum_{j \in U} y(j) \sqrt{w(j)} \leq \max_{j \in U} \sqrt{w(j)} \leq \max_{j \in F^c} \sqrt{w(j)},$$

hence

$$\langle \widehat{\Sigma}\mathbf{y}, \widehat{\sigma}_i^+ \rangle \geq -\frac{\sqrt{w(i)}}{\text{vol}(G)} \max_{j \in F^c} \sqrt{w(j)} = -\beta_i^{F^c}.$$

Consequently,  $\sum_{i \in F} (\langle \mathbf{x}, \widehat{\sigma}_i^+ \rangle + \beta_i^{F^c}) \geq \sum_{i \in F^c} (-\beta_i^{F^c} + \beta_i^{F^c}) = 0$ , so indeed  $\mathbf{x} \in \widehat{\mathcal{H}}_F$ . The proof for the  $\widehat{\mathcal{S}}_G^+$  and  $\widehat{\mathcal{H}}_F^+$  is almost identical.  $\square$

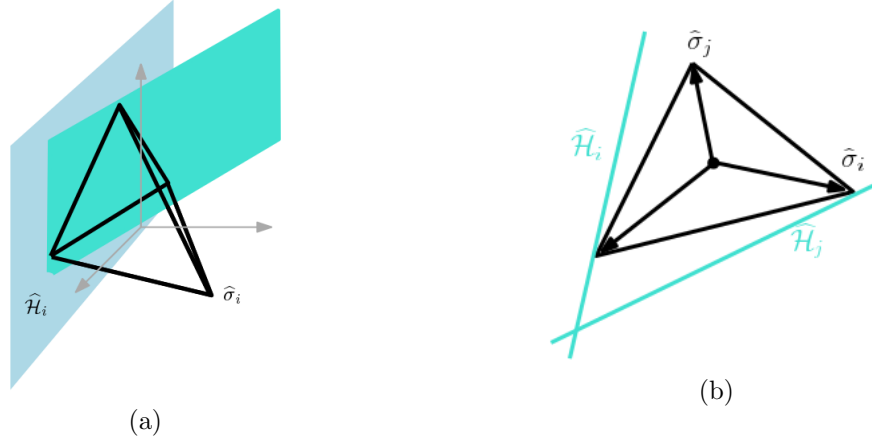


Figure 3.3: An illustration of the fact that, in general,  $\widehat{\mathcal{S}}_{\{i\}^c}$  is not contained in  $\widehat{\mathcal{H}}_i = \{\mathbf{x} : \langle \mathbf{x}, \widehat{\boldsymbol{\sigma}}_i^+ \rangle + \beta_i = 0\}$ .

We might expect that Lemma 3.21 yields a hyperplane representation of the normalized simplex, as did Lemma 3.10 for the combinatorial simplex. Unfortunately however, the issue is once again complicated by the vertex weights and the relation between  $\widehat{\boldsymbol{\Sigma}}^+$  and  $\widehat{\boldsymbol{\Sigma}}$ . Let us illustrate the problem by focusing on  $\widehat{\mathcal{S}}$ .

As opposed to Section 3.4,  $\widehat{\mathcal{S}}_{\{i\}^c}$  is not contained in the hyperplane  $\widehat{\mathcal{H}}_i = \{\mathbf{x} : \langle \mathbf{x}, \widehat{\boldsymbol{\sigma}}_i^+ \rangle + \beta_i = 0\}$ , where we take  $\beta_i = \beta_i^{\{i\}^c} = \sqrt{w(i)} \max_{j \neq i} \sqrt{w(j)} / \text{vol}(G)$ . To see this, take any  $k \notin \arg\max_{j \neq i} \sqrt{w(j)}$  (such a  $k$  exists iff the graph is not regular) and note that while  $\boldsymbol{\sigma}_k \in \widehat{\mathcal{S}}_U$  it is not in  $\widehat{\mathcal{H}}_i$ :

$$\langle \widehat{\boldsymbol{\sigma}}_k, \boldsymbol{\sigma}_i^+ \rangle = \boldsymbol{\chi}_k \widehat{\boldsymbol{\Sigma}}^t \widehat{\boldsymbol{\Sigma}}^+ \boldsymbol{\chi}_i = -\frac{\sqrt{w(k)w(i)}}{\text{vol}(G)} \neq \beta_i,$$

by assumption. The other way to see this is to note that  $\widehat{\boldsymbol{\sigma}}_i^+$  is not perpendicular to  $\widehat{\mathcal{S}}_{\{i\}^c}$  in general by Corollary 3.2. Thus, it is not clear how to generate an analogous description to Equation (3.6) for the normalized simplex. While this may seem relatively inconsequential, it severely complicates finding the dual of  $\widehat{\mathcal{S}}_G$ , which is the question we turn to next.

**What is  $\widehat{\mathcal{S}}_G^*$  and  $(\widehat{\mathcal{S}}_G^+)^*$ ?** Given that  $\widehat{\mathcal{S}}_G^+$  is not the dual of  $\widehat{\mathcal{S}}_G$  in general, it seems appropriate to ask “what on earth *is* the dual of the normalized simplex?”. The question has an interesting implicit answer when asked of  $\widehat{\mathcal{S}}_G^+$ , as demonstrated by the following lemma.

**LEMMA 3.22.** *For any graph  $G$ , there exists a graph  $H$  such that the dual of  $\widehat{\mathcal{S}}_G^+$  is the combinatorial simplex of  $H$ .*

*Proof.* Using the same reasoning which was applied to  $\mathcal{S}_G^+$ , we see that  $\widehat{\mathcal{S}}_G^+$  is also hyperacute. This implies, by Theorem 3.1, that its centred version is the inverse *combinatorial* simplex of some graph  $H$ . That is,  $(\widehat{\mathcal{S}}_G^+)_0 = \mathcal{S}_H^+$ . Since all translationally congruent simplices share the same dual, we



have

$$(\widehat{\mathcal{S}}_G^+)^* = (\widehat{\mathcal{S}}_G^+)_0^* = (\mathcal{S}_H^+)^* = \mathcal{S}_H. \quad \boxtimes$$

Unfortunately, this result is purely existential and does not yield much insight as to actual structure of  $(\widehat{\mathcal{S}}_G^+)^*$ . In the case of  $\widehat{\mathcal{S}}_G$ , somewhat surprisingly, the question is intimately related to the hyperplane representation—or lack thereof—of  $\widehat{\mathcal{S}}_G$ . We can obtain an implicit representation for the dual vertices  $\{\widehat{\sigma}_i^*\}$  by noting that they must satisfy  $\langle \widehat{\sigma}_i^*, \widehat{\sigma}_j - \widehat{\sigma}_n \rangle = \delta_{ij}$  for all  $i, j \neq n$ . This translates to

$$\sum_{\ell=1}^n \widehat{\sigma}_i^*(\ell) (\widehat{\varphi}_k(j) - \widehat{\varphi}_k(n)) \widehat{\lambda}_k^{1/2} = \delta_{ij},$$

but extracting values of  $\widehat{\sigma}_i^*$  which meet this condition is not trivial. We might, however, try a different tactic. Note that in the case of the combinatorial simplices, the dual vertices are encoded in their hyperplane representation by Equation (3.6):  $\mathcal{S}_G = \bigcap_i \{\mathbf{x} : \langle \mathbf{x}, \sigma_i^+ \rangle \geq -1/n\}$ . It is thus natural to wonder whether this relationship holds for every simplex, that is, if given a simplex described as the intersection of halfspaces, say  $\mathcal{T} = \bigcap_i \{\mathbf{x} : \langle \mathbf{z}_i, \mathbf{x} \rangle \geq b_i\}$  are the vectors  $\mathbf{z}_i$  are parallel to the dual vertices of  $\mathcal{T}$ . The following lemma gives sufficient conditions as to when this is the case.

**LEMMA 3.23.** *Let  $\mathcal{T} \subseteq \mathbb{R}^{n-1}$  be a centred simplex with  $\mathcal{T} = \bigcap_{i=1}^n \{\mathbf{x} \in \mathbb{R}^{n-1} : \langle \mathbf{x}, \mathbf{z}_i \rangle \geq \alpha_i\}$ . Then  $\{-\mathbf{z}_i/(\alpha_i n)\}$  are the vertices of  $\mathcal{T}^*$ .*

*Proof.* As usual, let  $\{\sigma_i\}$  be the vertices of  $\mathcal{T}$ . Put  $\gamma_i = -\mathbf{z}_i/(\alpha_i n)$ . We need to show that  $\{\gamma_i\}_{i=1}^{n-1}$  is the sister basis to  $\{\sigma_i - \sigma_n\}_{i=1}^{n-1}$ . Let  $H_i$  be the boundary of the halfspace  $\{\mathbf{x} : \langle \mathbf{x}, \mathbf{z}_i \rangle \geq \alpha_i\}$ , so  $H_i = \{\mathbf{x} : \langle \mathbf{x}, \mathbf{z}_i \rangle = \alpha_i\}$ . Enumerate the vertices  $\{\sigma_i\}$  such that  $\mathcal{S}_{\{i\}^c} \subseteq H_i$ . Fix  $i \in [n-1]$ . We claim that

$$\sigma_i \in \bigcap_{j \neq i} H_j.$$

Indeed,  $\mathcal{S}_{\{j\}^c}$  is the  $n-1$  dimensional simplex with vertices  $\{\sigma_\ell\}_{\ell \neq j}$ . Hence  $\sigma_i \in \mathcal{S}_{\{j\}^c}$  for all  $j \neq i$  and thus also lies in  $\bigcap_{j \neq i} H_j$ . Therefore,  $\langle \sigma_i, \mathbf{z}_j \rangle = \alpha_j$  for all  $j \neq i$ , from which it follows that  $\langle \gamma_j, \sigma_i - \sigma_n \rangle = -\langle \mathbf{z}_j, \sigma_i \rangle/(\alpha_j n) + \langle \mathbf{z}_j, \sigma_n \rangle/(\alpha_j n) = 1/n - 1/n = 0$ . It remains to show that  $\langle \gamma_i, \sigma_i - \sigma_n \rangle = 1$  for all  $i \neq n$ . Since  $\mathcal{T}$  is centred by assumption, we have  $\sigma_i = -\sum_{j \neq i} \sigma_j$ . Consequently,

$$\langle \gamma_i, \sigma_i - \sigma_n \rangle = -\sum_{j \neq i} \langle \gamma_i, \sigma_j \rangle - \langle \gamma_i, \sigma_n \rangle = \frac{1}{n}(n-1) + \frac{1}{n} = 1,$$

as was to be shown. \(\boxtimes\)

Lemma 3.23 allows us to extract the dual given a hyperplane description of a centred simplex. The next natural question is then how the hyperplane description of an arbitrary simplex relates to the hyperplane description of its centred counterpart. This is answered by the following lemma.

LEMMA 3.24. *Let  $\mathcal{T} = \cap_i \{\mathbf{x} : \langle \mathbf{x}, \mathbf{z}_i \rangle \geq \alpha_i\}$  be a simplex. Its centred version,  $\mathcal{T}_0$ , can be written as  $\cap_i \{\mathbf{x} : \langle \mathbf{x}, \mathbf{z}_i \rangle \geq \alpha_i - \langle \mathbf{c}(\mathcal{T}), \mathbf{z}_i \rangle\}$ .*

*Proof.* As usual, take  $\mathcal{H}_i = \{\mathbf{x} : \langle \mathbf{x}, \mathbf{z}_i \rangle = \alpha_i\}$  to be the hyperplanes bounding the simplex. The hyperplanes bounding the centred simplex, are parallel to the hyperplanes  $\mathcal{H}_i$  and can thus be written as

$$\mathcal{H}_{i0} = \{\mathbf{x} : \langle \mathbf{x}, \mathbf{z}_i \rangle = \beta_i\},$$

for some  $\beta_i$ . Moreover, just as  $\boldsymbol{\sigma}_j \in \mathcal{H}_i$  for  $j \neq i$ , we have  $\boldsymbol{\sigma}_j - \mathbf{c}(\mathcal{T}) \in \mathcal{H}_{i0}$ , since  $\{\boldsymbol{\sigma}_j - \mathbf{c}(\mathcal{T})\}$  are the vertices of  $\mathcal{T}_0$ . As such,  $\langle \boldsymbol{\sigma}_j - \mathbf{c}(\mathcal{T}), \mathbf{z}_i \rangle = \beta_i$ , and

$$\langle \boldsymbol{\sigma}_j - \mathbf{c}(\mathcal{T}), \mathbf{z}_i \rangle = \langle \boldsymbol{\sigma}_j, \mathbf{z}_i \rangle - \langle \mathbf{c}(\mathcal{T}), \mathbf{z}_i \rangle = \alpha_i - \langle \mathbf{c}(\mathcal{T}), \mathbf{z}_i \rangle,$$

whence  $\beta_i = \alpha_i - \langle \mathbf{c}(\mathcal{T}), \mathbf{z}_i \rangle$ . It then follows that

$$\mathcal{T}_0 = \bigcap_i \mathcal{H}_{i0}^{\geq},$$

where  $\mathcal{H}_{i0}^{\geq} = \{\mathbf{x} : \langle \mathbf{x}, \mathbf{z}_i \rangle \geq \alpha_i - \langle \mathbf{c}(\mathcal{T}), \mathbf{z}_i \rangle\}$ . \(\boxtimes\)

Taken together, Lemmas 3.23 and 3.24 provide a path to try and determine the dual simplex of  $\widehat{S}_G$ . In particular, if we could determine a hyperplane representation of any simplex congruent to  $\widehat{S}_G$ , then we can obtain a hyperplane representation of its centred version by Lemma 3.24 and to the dual of its centred version by Lemma 3.23. Since the dual is common to all congruent simplices by Observation 2.3, this would yield  $S_G^*$ . Unfortunately, obtaining such a representation is not trivial. We leave the question as an open problem.

## Further Properties of the Correspondence

*Everything is funny, if you can laugh at it.*

— Lewis Carroll

The previous chapter introduced the graph-simplex correspondence and devoted several sections to the basic properties of the simplices associated to a given graph. In this chapter we continue the study of the correspondence and present several of its more significant (but perhaps more complicated) properties. We begin, however, by demonstrating that some of the interplay between  $\mathcal{S}_G$  and  $\mathcal{S}_G^+$  generalizes to an arbitrary simplex and its dual.

### §4.1. General Properties of Dual Simplex

Given that  $\mathcal{S}_G^+$  is the dual of  $\mathcal{S}_G$ , it is natural to wonder whether some aspects of their relationship are common to that between any simplex and its dual. Here we demonstrate that this is indeed the case; in particular, the Gram matrices of any (centred) simplex and its dual enjoy the same pseudoinverse relationship. We begin by investigating the vertices of a simplex and its dual.

**LEMMA 4.1.** *Let  $\mathcal{T} \subseteq \mathbb{R}^{n-1}$  be any simplex, and  $\mathcal{T}^*$  its dual, where  $\Sigma = \Sigma(\mathcal{T}) = (\gamma_i)$  and  $\Sigma^* = \Sigma(\mathcal{T}^*) = (\gamma_i^*)$ . For all  $i, j \in [n]$ ,  $\langle \gamma_i, \gamma_j^* \rangle = \delta_{i,j} - 1/n$ .*

*Proof.* By definition of the dual simplex, for all  $i, j \neq n$ ,  $\langle \gamma_i, \gamma_j^* - \gamma_n^* \rangle = \delta_{ij}$ . Recalling that  $\gamma_n^* = -\sum_{\ell < n} \gamma_\ell^*$ , write

$$\langle \gamma_i, \gamma_n^* \rangle = -\sum_{\ell < n} \langle \gamma_i, \gamma_\ell^* \rangle = -\sum_{\ell < n} \delta_{i,\ell} + \langle \gamma_i, \gamma_n^* \rangle = -1 - (n-1)\langle \gamma_i, \gamma_n^* \rangle.$$

Rearranging the above yields  $\langle \gamma_i, \gamma_j^* \rangle = -1/n$ . Therefore,  $\langle \gamma_i, \gamma_j^* \rangle = \delta_{ij} - 1/n$ . It remains to show that  $\langle \gamma_n, \gamma_n^* \rangle = 1 - 1/n$ . Proceeding as above, we have

$$\langle \gamma_n, \gamma_n^* \rangle = -\sum_{\ell < n} \langle \gamma_n, \gamma_\ell^* \rangle = -\sum_{\ell < n} \frac{-1}{n} = \frac{n-1}{n}. \quad \square$$

We can now proceed to proving the general pseudoinverse relationship between Gram matrices of a simplex and its dual. As we explained in Section 3.5, crucial to many of the proofs pertaining to the combinatorial simplices is the fact that  $\mathbf{L}_G \mathbf{L}_G^+ = \mathbf{L}_G^+ \mathbf{L}_G = \mathbf{I} - \mathbf{J}/n$ . That an equivalent property holds for arbitrary simplices is therefore highly beneficial for their study.

LEMMA 4.2. *Let  $\mathcal{T} \subseteq \mathbb{R}^{n-1}$  be an arbitrary centred simplex, and  $\mathcal{T}^*$  its dual. Put  $\Sigma = \Sigma(\mathcal{T}) = (\gamma_i)$  and  $\Sigma^* = \Sigma(\mathcal{T}^*) = (\gamma_i^*)$  as usual. Then  $\Sigma^* \Sigma^t = \Sigma(\Sigma^*)^t = \mathbf{I}$  and  $(\Sigma^*)^t \Sigma^*$  is the Moore-Penrose pseudoinverse of  $\Sigma^t \Sigma$ .*

*Proof.* First we inquire into the relationship between  $\Sigma$  and  $\Sigma^*$ . Put  $\mathbf{M} = (\gamma_1 - \gamma_n, \dots, \gamma_{n-1} - \gamma_n)$  and  $\mathbf{Q} = (\gamma_1^*, \dots, \gamma_{n-1}^*)$ . By definition,  $\{\gamma_i^*\}$  is the dual basis to  $\{\gamma_i - \gamma_n\}$ . Thus, by Observation 2.1,  $\mathbf{Q}^t = \mathbf{M}^{-1}$  (we are working in  $\mathbb{R}^{n-1}$ ), so  $\mathbf{M} \mathbf{Q}^t = \mathbf{I}$ . The  $(i, j)$ -th component of this matrix product can therefore be expressed as

$$\delta_{ij} = \mathbf{M} \mathbf{Q}^t(i, j) = \sum_{\ell=1}^{n-1} (\gamma_\ell(i) - \gamma_n(i)) \gamma_\ell^*(j) = \delta_{ij} = \sum_{\ell=1}^{n-1} \gamma_\ell(i) \gamma_\ell^*(j) - \gamma_n(i) \sum_{\ell=1}^{n-1} \gamma_\ell^*(j). \quad (4.1)$$

Now, since  $\mathcal{T}^*$  is centred,

$$0 = (\Sigma^* \mathbf{1})(j) = \sum_{\ell \in [n]} \gamma_\ell^*(j),$$

implying that  $\sum_{\ell=1}^{n-1} \gamma_\ell^*(j) = -\gamma_n^*(j)$ . Equation (4.1) can then be written as  $\sum_{\ell=1}^n \gamma_\ell(i) \gamma_\ell^*(j) = \delta_{ij}$ , implying that the components of  $\Sigma^* \Sigma^t$  are

$$(\Sigma^* \Sigma^t)(i, j) = \sum_{\ell=1}^n \gamma_\ell^*(i) \gamma_\ell(j) = \delta_{ij},$$

so that  $\Sigma^* \Sigma^t = \mathbf{I}$ . A similar argument holds for  $\Sigma(\Sigma^*)^t$ , *mutatis mutandis*.

We now proceed to demonstrating the pseudoinverse relation between  $\Sigma^t \Sigma$  and  $(\Sigma^*)^t \Sigma^*$ . Recall that to demonstrate that a matrix  $\mathbf{B}_1$  is the pseudoinverse of  $\mathbf{B}_2$ , we need to show that (i)  $\mathbf{B}_1 \mathbf{B}_2 \mathbf{B}_1 = \mathbf{B}_1$ , (ii)  $\mathbf{B}_2 \mathbf{B}_1 \mathbf{B}_2 = \mathbf{B}_2$ , (iii)  $(\mathbf{B}_1 \mathbf{B}_2)^t = \mathbf{B}_1 \mathbf{B}_2$  and (iv)  $(\mathbf{B}_2 \mathbf{B}_1)^t = \mathbf{B}_2 \mathbf{B}_1$  (Definition 2.4). Using the relationship between  $\Sigma^*$  and  $\Sigma$  given above, these become simple computations. For instance,

$$\Sigma^t \Sigma (\Sigma^*)^t \Sigma^* \Sigma^t \Sigma = \Sigma^t \mathbf{I}^2 \Sigma = \Sigma^t \Sigma,$$

and,

$$((\Sigma^*)^t \Sigma^* \Sigma^t \Sigma)^t = ((\Sigma^*)^t \mathbf{I} \Sigma)^t = \Sigma^t \Sigma^* = \mathbf{I} - \frac{\mathbf{J}}{n} = (\Sigma^*)^t \Sigma = (\Sigma^*)^t \mathbf{I} \Sigma = (\Sigma^*)^t \Sigma^* \Sigma^t \Sigma.$$

Conditions (i) and (iii) therefore hold between  $\Sigma^t \Sigma$  and  $(\Sigma^*)^t \Sigma^*$ ; conditions (ii) and (iv) follow similarly.  $\square$

In the next section, we will demonstrate that this insight allows us to generalize results pertain-

ing to hyperacute simplices to all simplices. We thus witness another benefit of the correspondence: By leveraging knowledge of  $\mathcal{S}_G$  and  $\mathcal{S}_G^+$  we can gain insights into the behaviour of general simplices.

## §4.2. Block Matrix Equations

In this section we are finally able to satisfy those readers who have wondered about the applicability of electrical networks to the graph-simplex correspondence. Applying Lemma 2.8, we are able to develop block matrix equations which relate the structure of  $\mathcal{S}_G$  and  $\mathcal{S}_G^+$ . Then, using the results of the previous section we generalize these equations to arbitrary simplices.

Before we begin, a brief remark on the relationship of the following results and Fiedler's work. Fiedler's derivation of the graph-simplex correspondence relied on a matrix equation—an equation equivalent to our Lemma 4.5, in fact [Fie93, Theorem 3.1]. Conversely, we are obtaining such equations as a *consequence* of the correspondence. It is our belief that different treatments of the material shed light on its different—and hopefully complementary—implications.

Let a centred, hyperacute simplex  $\mathcal{T}$  be given, with  $\Sigma(\mathcal{T}) = \{\gamma_i\}$ . Let  $\bar{d}$  be the average squared distance between all the vertices of  $\mathcal{T}$ , that is

$$\bar{d} \stackrel{\text{def}}{=} \frac{1}{n^2} \sum_{i \leq j} \|\gamma_i - \gamma_j\|_2^2. \quad (4.2)$$

Let  $\xi(i)$  give the average squared distance of vertex  $i$  from other vertices minus the total average distance,

$$\xi(i) \stackrel{\text{def}}{=} \frac{1}{n} \sum_j \|\gamma_i - \gamma_j\|_2^2 - \bar{d}, \quad (4.3)$$

and put  $\xi = (\xi(1), \dots, \xi(n))$ . The following results relates the distance matrix of  $\mathcal{T}$  to the vertex matrix of its dual.

LEMMA 4.3. *Let  $\mathcal{T} \subseteq \mathbb{R}^{n-1}$  be a hyperacute simplex with squared distance matrix  $D_{\mathcal{T}}$ , and average squared distance vector  $\xi$ . Let  $Q = (\Sigma^*)^t \Sigma^*$  where  $\Sigma^*$  is the vertex matrix of  $\mathcal{T}^*$ . Then,*

$$-\frac{1}{2} \begin{pmatrix} 0 & \mathbf{1}_n^t \\ \mathbf{1}_n & D_{\mathcal{T}} \end{pmatrix} = \begin{pmatrix} \xi^t Q \xi + 4\bar{d} & -(Q\xi + 2\mathbf{1}/n)^t \\ -(Q\xi + 2\mathbf{1}/n) & Q \end{pmatrix}^{-1}. \quad (4.4)$$

Moreover, the vertices of  $\mathcal{T}^*$  and the distance matrix of  $\mathcal{T}$  are related by the equation

$$QD_{\mathcal{T}}Q = -2Q, \quad (4.5)$$

and in the space  $\text{span}(\mathbf{1})^\perp$  it holds that

$$D_{\mathcal{T}}QD_{\mathcal{T}} = -2D_{\mathcal{T}}.$$

*Proof.* By Theorem 3.1,  $\mathcal{T}$  is the inverse simplex of some graph  $G$  and therefore  $\mathbf{D} = \mathbf{R}$ , where  $\mathbf{R}$  is the effective resistance matrix (Lemma 3.5). Therefore, we can rewrite  $\xi(i)$  as

$$\frac{1}{n} \sum_j r^{\text{eff}}(i, j) - \frac{1}{n^2} \sum_{i < j} r^{\text{eff}}(i, j),$$

whence,

$$\boldsymbol{\xi} = \frac{1}{n} \mathbf{R} \mathbf{1} - \frac{1}{n^2} \mathbf{1} \mathbf{1}^t \mathbf{R} \mathbf{1} = \frac{1}{n} \mathbf{R} \mathbf{1} - \frac{1}{n^2} \mathbf{J} \mathbf{R} \mathbf{1}.$$

Meanwhile, the dual simplex to  $\mathcal{T}$  is the simplex of the graph  $G$ , and hence obeys  $\mathbf{Q} = \mathbf{L}_G$ . Consequently, letting  $\boldsymbol{\Delta} = \frac{1}{n} \mathbf{R} \mathbf{1} - \frac{1}{n^2} \mathbf{J} \mathbf{R} \mathbf{1}$ , we can rewrite Equation (4.4) as the purely graph theoretic statement

$$-\frac{1}{2} \begin{pmatrix} 0 & \mathbf{1}_n^t \\ \mathbf{1}_n & \mathbf{R} \end{pmatrix} = \begin{pmatrix} \boldsymbol{\Delta}^t \mathbf{L}_G \boldsymbol{\Delta} + \frac{4}{n^2} R_G^{\text{tot}} & -(\mathbf{L}_G \boldsymbol{\Delta} + \frac{2}{n} \mathbf{1})^t \\ -(\mathbf{L}_G \boldsymbol{\Delta} + \frac{2}{n} \mathbf{1}) & \mathbf{L}_G \end{pmatrix}^{-1}.$$

This equation is verified by Lemma 2.8. The final two equations in the lemma translate to  $\mathbf{L}_G \mathbf{R}_G \mathbf{L}_G = -2\mathbf{L}_G$  and  $\mathbf{R}_G \mathbf{L}_G \mathbf{R}_G = -2\mathbf{R}_G$  on  $\text{span}(\mathbf{1})^\perp$ . Both of these also hold via Lemma 2.8.  $\square$

While Lemma 4.3 may be interesting, it is unfortunately restricted in its scope. In what follows we demonstrate that it can be generalized to hold for all simplices. Before we begin, we require a generalization of the statement  $\mathbb{R} = \boldsymbol{\Delta} \mathbf{1}^t + \mathbf{1} \boldsymbol{\Delta}^t - 2\mathbf{L}_G^+$  to all distance matrices (recall that  $\mathbb{R}$  is the distance matrix of  $\mathcal{S}_G^+$ ). This is accomplished by the following lemma.

LEMMA 4.4. *For any centred simplex  $\mathcal{T} \subseteq \mathbb{R}^{n-1}$  with distance matrix  $\mathbf{D}_{\mathcal{T}}$  and vertex matrix  $\boldsymbol{\Sigma}$ , it holds that  $\mathbf{D}_{\mathcal{T}} = \mathbf{1} \boldsymbol{\xi}^t + \boldsymbol{\xi} \mathbf{1}^t - 2\boldsymbol{\Sigma}^t \boldsymbol{\Sigma}$ .*

*Proof.* Fix  $k, \ell \in [n]$ . The proof purely computational. We have

$$(\boldsymbol{\xi} \mathbf{1}^t)(k, \ell) = \frac{1}{n} \sum_j \|\gamma_k - \gamma_j\|_2^2 - \bar{d}, \quad (\mathbf{1} \boldsymbol{\xi}^t)(k, \ell) = \frac{1}{n} \sum_j \|\gamma_\ell - \gamma_j\|_2^2 - \bar{d},$$

and  $-2\boldsymbol{\Sigma}^t \boldsymbol{\Sigma} = -2\langle \gamma_k, \gamma_\ell \rangle$ . Expanding the norm in terms of dot products, write

$$\begin{aligned} (\boldsymbol{\xi} \mathbf{1}^t + \mathbf{1} \boldsymbol{\xi}^t - 2\boldsymbol{\Sigma}^t \boldsymbol{\Sigma})(k, \ell) &= \frac{1}{n} \left( \sum_j \|\gamma_k - \gamma_j\|_2^2 + \sum_j \|\gamma_\ell - \gamma_j\|_2^2 \right) - \frac{2}{n^2} \sum_{i < j} \|\gamma_i - \gamma_j\|_2^2 - 2\langle \gamma_k, \gamma_\ell \rangle \\ &= \frac{1}{n} \sum_j \left( \|\gamma_k\|_2^2 + \|\gamma_j\|_2^2 + \|\gamma_\ell\|_2^2 + \|\gamma_j\|_2^2 - 2\langle \gamma_k, \gamma_j \rangle - 2\langle \gamma_\ell, \gamma_j \rangle \right) \\ &\quad - \frac{1}{n^2} \sum_{i, j} \left( \|\gamma_i\|_2^2 + \|\gamma_j\|_2^2 - 2\langle \gamma_i, \gamma_j \rangle \right) - 2\langle \gamma_k, \gamma_\ell \rangle. \end{aligned}$$

$$\begin{aligned}
 &= \|\gamma_k\|_2^2 + \|\gamma_\ell\|_2^2 - 2\langle\gamma_k, \gamma_\ell\rangle + 2\left(\frac{1}{n} \sum_j \|\gamma_j\|_2^2 - \frac{1}{n^2} \sum_{i,j} \|\gamma_j\|_2^2\right) \\
 &\quad + \frac{1}{n^2} \sum_{i,j} \langle\gamma_i, \gamma_j\rangle - \frac{2}{n} \sum_j (\langle\gamma_k, \gamma_j\rangle - \langle\gamma_\ell, \gamma_j\rangle).
 \end{aligned}$$

Note that in the second line we removed the factor of two from  $\bar{d}$  by summing over all  $i, j$  rather than simply  $i < j$ . Now, the first three terms in the final equation are equal to  $\|\gamma_k - \gamma_\ell\|_2^2 = \mathbf{D}_\mathcal{T}(k, \ell)$ . Therefore, it remains to show that the final three terms are zero. The first of these,  $\frac{1}{n^2} \sum_{i,j} \|\gamma_j\|_2^2$  is clearly zero after noticing that the final summand is independent of  $i$ . As for the final two, we write them in terms of the centroid of  $\mathcal{T}$  (which is  $\mathbf{0}$ ), as

$$\begin{aligned}
 &\frac{1}{n^2} \sum_{i,j} \langle\gamma_i, \gamma_j\rangle - \frac{2}{n} \sum_j (\langle\gamma_k, \gamma_j\rangle - \langle\gamma_\ell, \gamma_j\rangle) \\
 &= \frac{1}{n^2} \left\langle \sum_i \gamma_i, \sum_j \gamma_j \right\rangle - \frac{2}{n} \left( \left\langle \gamma_k, \sum_j \gamma_j \right\rangle - \left\langle \gamma_\ell, \sum_j \gamma_j \right\rangle \right) \\
 &= \frac{1}{n^2} \langle n\mathbf{c}(\mathcal{T}), n\mathbf{c}(\mathcal{T}) \rangle - \frac{2}{n} (\langle \gamma_k, n\mathbf{c}(\mathcal{T}) \rangle - \langle \gamma_\ell, n\mathbf{c}(\mathcal{T}) \rangle) \\
 &= 0,
 \end{aligned}$$

as was to be shown.  $\square$

We can now strengthen Lemma 4.3 to all simplices, even those which are not centred.

LEMMA 4.5. *The equations of Lemma 4.3 hold for any simplex  $\mathcal{T} \subseteq \mathbb{R}^{n-1}$ .*

*Proof.* Let us first assume that  $\mathcal{T}$  is centred. The proof proceeds very much as does that of Lemma 2.8, by computing the matrix product

$$\begin{pmatrix} 0 & \mathbf{1}^t \\ \mathbf{1} & \mathbf{D}_\mathcal{T} \end{pmatrix} \begin{pmatrix} \xi^t \mathbf{Q} \xi + 4\bar{d} & -(\mathbf{Q} \xi + \frac{2}{n} \mathbf{1})^t \\ -(\mathbf{Q} \xi + \frac{2}{n} \mathbf{1}) & \mathbf{Q} \end{pmatrix},$$

and demonstrating that it equals  $-2\mathbf{I}$ . Instead of leverage the relationship  $\mathbf{R}_G = \mathbf{1}\Delta^t + \Delta\mathbf{1}^t - 2\mathbf{L}_G^+$  as was done in that case, we use the more general equation  $\mathbf{D}_\mathcal{T} = \mathbf{1}\xi^t + \xi\mathbf{1}^t - 2\Sigma^t\Sigma$  given by Lemma 4.4. However, since that proof was given in the appendix we will give this one here. The top left corner of the product of these two matrices is  $-\mathbf{1}^t \mathbf{Q} \xi - 2/n \mathbf{1}^t \mathbf{1} = -2$  as  $\mathbf{1}^t \mathbf{Q} = \mathbf{1}^t (\Sigma^*)^t \Sigma^*$  since  $\mathcal{T}^*$  is centred by definition. Likewise, the top right hand corner is zero. After expanding  $\mathbf{D}_\mathcal{T}$  in accordance with Lemma 4.4 the bottom left corner becomes

$$\mathbf{1}\xi^t \mathbf{Q} \xi + 4\bar{d}\mathbf{1} - (\mathbf{1}\xi^t + \xi\mathbf{1}^t - 2\Sigma^t\Sigma)\mathbf{Q}\xi - \frac{2}{n} \mathbf{D}_\mathcal{T} \mathbf{1} = 4\bar{d}\mathbf{1} + 2\Sigma^t\Sigma\mathbf{Q}\xi - \frac{2}{n} \mathbf{D}_\mathcal{T} \mathbf{1}. \quad (4.6)$$

Lemma 4.2 dictates that  $\mathbf{Q}$  is the pseudoinverse of  $\Sigma^t\Sigma$  so, by Lemma 2.4,  $\Sigma^t\Sigma\mathbf{Q} = \mathbf{I} - \mathbf{J}/n$  (of

course, we're implicitly using that  $\text{span}(\mathbf{1})^\perp = \ker(\mathbf{\Sigma}) = \ker(\mathbf{\Sigma}^t \mathbf{\Sigma})$ . Moreover, after noting that

$$\boldsymbol{\xi} = \frac{1}{n} \mathbf{D}_{\mathcal{T}} \mathbf{1} - \bar{d} \mathbf{1}, \quad \text{and} \quad \bar{d} = \frac{1}{2n^2} \mathbf{1}^t \mathbf{D} \mathbf{1},$$

we can rewrite the right hand side of Equation (4.6) as

$$\begin{aligned} & 4\bar{d} \mathbf{1} + 2 \left( \mathbf{I} - \frac{\mathbf{J}}{n} \right) \left( \frac{1}{n} \mathbf{D}_{\mathcal{T}} \mathbf{1} - \bar{d} \mathbf{1} \right) - \frac{2}{n} \mathbf{D}_{\mathcal{T}} \mathbf{1} \\ &= 2\bar{d} \mathbf{1} - \frac{2}{n^2} \mathbf{J} \mathbf{D}_{\mathcal{T}} \mathbf{1} + \frac{2}{n} \mathbf{J} \bar{d} \mathbf{1} \\ &= \frac{1}{n^2} \mathbf{J} \mathbf{D}_{\mathcal{T}} \mathbf{1} - \frac{2}{n^2} \mathbf{J} \mathbf{D}_{\mathcal{T}} \mathbf{1} + \frac{1}{n^3} \mathbf{J}^2 \mathbf{D}_{\mathcal{T}} \mathbf{1} \\ &= \frac{1}{n^2} \mathbf{J} \mathbf{D}_{\mathcal{T}} \mathbf{1} - \frac{2}{n^2} \mathbf{J} \mathbf{D}_{\mathcal{T}} \mathbf{1} + \frac{1}{n^2} \mathbf{J} \mathbf{D}_{\mathcal{T}} \mathbf{1} = \mathbf{0}. \end{aligned}$$

Carrying out a similar procedure for the bottom right corner, we obtain

$$\begin{aligned} -\mathbf{1} \boldsymbol{\xi}^t \mathbf{Q} - \frac{2}{n} \mathbf{J} + \mathbf{D}_{\mathcal{T}} \mathbf{Q} &= -\mathbf{1} \boldsymbol{\xi}^t \mathbf{Q} - \frac{2}{n} \mathbf{J} + (\mathbf{1} \boldsymbol{\xi}^t + \boldsymbol{\xi} \mathbf{1}^t - 2\mathbf{\Sigma}^t \mathbf{\Sigma}) \mathbf{Q} \\ &= -\frac{2}{n} \mathbf{J} - 2 \left( \mathbf{I} - \frac{\mathbf{J}}{n} \right) = -2\mathbf{I}. \end{aligned}$$

The final two equations follow via similar computations:

$$\mathbf{Q} \mathbf{D}_{\mathcal{T}} \mathbf{Q} = \mathbf{Q} (\mathbf{1} \boldsymbol{\xi}^t + \boldsymbol{\xi} \mathbf{1}^t - 2\mathbf{\Sigma}^t \mathbf{\Sigma}) \mathbf{Q} = -2\mathbf{Q} \mathbf{\Sigma}^t \mathbf{\Sigma} \mathbf{Q} = -2\mathbf{\Sigma}^t \mathbf{\Sigma},$$

due to properties of the pseudoinverse (Lemma 2.4), and if  $\mathbf{x} \perp \mathbf{1}$  then

$$\mathbf{D}_{\mathcal{T}} \mathbf{Q} \mathbf{D}_{\mathcal{T}} \mathbf{x} = \mathbf{D}_{\mathcal{T}} \mathbf{Q} (\mathbf{1} \boldsymbol{\xi}^t + \boldsymbol{\xi} \mathbf{1}^t - 2\mathbf{\Sigma}^t \mathbf{\Sigma}) \mathbf{x} = -2\mathbf{D}_{\mathcal{T}} \mathbf{Q} \mathbf{\Sigma}^t \mathbf{\Sigma} \mathbf{x} = -2\mathbf{D}_{\mathcal{T}} \left( \mathbf{I} - \frac{\mathbf{J}}{n} \right) \mathbf{x} = -2\mathbf{D}_{\mathcal{T}} \mathbf{x},$$

which completes the proof if  $\mathcal{T}$  is centred. If  $\mathcal{T}$  is not centred, then we need only apply the relationship to its centred version  $\mathcal{T}_0$ , and note that the quantities  $\mathbf{D}_{\mathcal{T}}$ ,  $\boldsymbol{\xi}$ ,  $\bar{d}$  and  $\mathbf{Q}$  are the same for  $\mathcal{T}_0$  and  $\mathcal{T}$ . The first three are the same because they deal with distances between vertices, which are invariant under linear transformations.  $\mathbf{Q}$  is the same due to Observation 2.3.  $\square$

*Remark 4.1.* We have thus recovered Fiedler's block matrix relation [Fie93], although he does not give the same explicit interpretation of the entries as we do. As discussed above, it is interesting that Fiedler used the equation as the basis for the correspondence while our approach is the reverse.

#### 4.2.1. Applications

We now discuss several uses of the equations developed above. One consequence is a relation between the volume of the simplex and the effective resistances in the graph. To see this, we need to introduce a particular object from the field of distance geometry. Let  $\mathbf{D}(\mathcal{X})$  be the distance



matrix of a set  $\mathcal{X}$  of  $d$  points. The matrix

$$\begin{pmatrix} 0 & \mathbf{1}^t \\ \mathbf{1} & \mathbf{D}(\mathcal{X}) \end{pmatrix} \in \mathbb{R}^{(d+1) \times (d+1)}, \quad (4.7)$$

is called the *Menger matrix* of  $X$ , the determinant of which is called the *Cayley-Menger determinant*, named after Arthur Cayley and Karl Menger [Cay41, Men28]. The Cayley-Menger determinant is related to the volume of the underlying set of points as follows.

LEMMA 4.6 ([Men31]). *Let  $\mathbf{D}(\mathcal{X})$  be the distance matrix of a set  $\mathcal{X}$  of  $d$  points. The squared  $d - 1$  dimensional volume<sup>1</sup> of the convex hull of  $\mathcal{X}$  is proportional to the root of the determinant of the Menger matrix:*

$$\text{vol}^2(\text{conv}(\mathcal{X})) = \frac{(-1)^d}{((d-1)!)^2 2^{d-1}} \det \begin{pmatrix} 0 & \mathbf{1}^t \\ \mathbf{1} & \mathbf{D}(\mathcal{X}) \end{pmatrix}. \quad (4.8)$$

The relation between the Menger matrix and the volume combined with the matrix equations above, allows us to give a concise formula for the volume of any hyperacute simplex. This was first pointed out in [VMDC17].

LEMMA 4.7. *Let  $\mathcal{T} \subseteq \mathbb{R}^{n-1}$  be a hyperacute simplex, and let  $G$  be its associated graph. Then  $\mathcal{T}$ 's  $n - 1$  dimensional volume is*

$$\text{vol}(\mathcal{T}) = \frac{1}{(n-1)! \cdot \Gamma_G^{1/2}}, \quad (4.9)$$

where  $\Gamma_G$  is the total weight of all spanning trees of  $G$ .

We remind the reader that  $\Gamma_G$  was discussed in Section 2.3.1; see Equation (2.16) in particular. The proof of Lemma 4.7 may be found in Appendix A.3.

We can use these results to produce a surprising equation concerning the diagonal entries of the Laplacian. In particular,  $\mathbf{L}_G(i, i)$  is proportional to the ratio of the weight of spanning trees in  $G$  to this weight when the vertex  $i$  is removed.

LEMMA 4.8. *Let  $G$  be a connected graph and fix  $i \in V(G)$ . Put  $G_{\{i\}^c} = G[V \setminus \{i\}]$ . The diagonal entries of the combinatorial Laplacian are given by*

$$\mathbf{L}_G(i, i) = \frac{\Gamma_G}{\Gamma_{G_{\{i\}^c}}}. \quad (4.10)$$

Moreover, if  $\mathcal{S}^+ \subseteq \mathbb{R}^{n-1}$  is the inverse combinatorial simplex of  $G$  then the volumes of  $\mathcal{S}_{\{i\}^c}^+$  and  $\mathcal{S}^+$  are related as

$$\frac{\text{vol}^2(\mathcal{S}_{\{i\}^c}^+)}{\text{vol}^2(\mathcal{S}^+)} = (n-1)^2 \mathbf{L}_G(i, i). \quad (4.11)$$

---

<sup>1</sup>That is, the volume as calculated in  $\mathbb{R}^{d-1}$ .

*Proof.* We will begin with Equation (4.11). Let  $\mathcal{S}^+$  have vertices  $\sigma_1^+, \dots, \sigma_n^+$ , and let  $\mathbf{M}$  be the Menger matrix associated with  $\mathcal{S}^+$ . Sylvester's formula (Lemma 2.3) gives us that

$$\mathbf{M}^{-1}(i+1, i+1) = \det \mathbf{M}^{-1}(i+1, i+1) = \pm \frac{\det \mathbf{M}(U, U)}{\det \mathbf{M}},$$

where  $U = \{i+1\}^c$ . Observe that  $\mathbf{M}(U, U)$  is the Menger matrix of the simplex  $\mathcal{S}_{\{i\}^c}$ ; we are simply removing the row and column corresponding to the  $i$ -th vertex. Translating the determinants of Menger matrices into statements about volumes of simplices via Equation (4.9) gives

$$\begin{aligned} \mathbf{M}^{-1}(i+1, i+1) &= \pm \frac{[(n-2)!]^2 2^{n-2} \text{vol}^2(\mathcal{S}_{\{i\}^c}^+)}{(-1)^{n-1}} \bigg/ \frac{[(n-1)!]^2 2^{n-1} \text{vol}^2(\mathcal{S}^+)}{(-1)^n} \\ &= \mp \frac{1}{2(n-1)^2} \frac{\text{vol}^2(\mathcal{S}_{\{i\}^c}^+)}{\text{vol}^2(\mathcal{S}^+)}. \end{aligned}$$

Via the block matrix equation (??) we have  $\mathbf{M}^{-1}(i+1, i+1) = -\frac{1}{2} \mathbf{L}_G(i, i)$ . Plugging this into the above equation and noting that both  $\mathbf{L}_G(i, i)$  and  $\text{vol}^2(\mathcal{S}_{\{i\}^c}^+) / (2n^2 \text{vol}^2(\mathcal{S}^+))$  are positive gives the desired result. Equation (4.10) now comes from writing out the simplex volumes  $\text{vol}(\mathcal{S}_{\{i\}^c}^+)$  and  $\text{vol}(\mathcal{S}^+)$  in terms of spanning trees of  $G$  by (4.9), after using (4.11):

$$\mathbf{L}_G(i, i) = \frac{\text{vol}^2(\mathcal{S}_{\{i\}^c}^+)}{(n-1)^2 \text{vol}^2(\mathcal{S}^+)} = \frac{1}{(n-2)!^2 \cdot \Gamma_{G[\{i\}^c]}} \bigg/ \frac{(n-1)^2}{(n-1)!^2 \cdot \Gamma_G} = \frac{\Gamma_G}{\Gamma_{G[\{i\}^c]}}. \quad \boxtimes$$

**COROLLARY 4.1.** *For all  $i \in [n]$ , the length of the vertex vector  $\sigma_i$  of  $\mathcal{S}_G$  obeys*

$$\|\sigma_i\|_2^2 = \frac{\Gamma_G}{\Gamma_{G[\{i\}^c]}} = \frac{\text{vol}^2(\mathcal{S}_{\{i\}^c}^+)}{(n-1)^2 \text{vol}^2(\mathcal{S}^+)}. \quad (4.12)$$

*Proof.* Follows immediately from Lemma 4.8.  $\boxtimes$

Next, we investigate the volumes of the facets in more detail.

**LEMMA 4.9.** *For any hyperacute simplex  $\mathcal{T} \subseteq \mathbb{R}^{n-1}$  and  $i \in [n]$ , the following equations hold:*

1.  $\text{vol}(\mathcal{T}_{\{i\}^c}) = \sum_{j \neq i} \text{vol}(\mathcal{T}_{\{j\}^c}) \cos \theta_{ij}(\mathcal{T})$ ;
2.  $\text{vol}^2(\mathcal{T}_{\{i\}^c}) = \sum_{j \neq i} \text{vol}^2(\mathcal{T}_{\{j\}^c}) - \sum_{j, k \neq i, j \neq k} \text{vol}(\mathcal{T}_{\{j\}^c}) \text{vol}(\mathcal{T}_{\{k\}^c}) \cos \theta_{jk}(\mathcal{T})$ ; and
3.  $(n-1) \text{vol}(\mathcal{T}_{\{i, j\}^c}) \text{vol}(\mathcal{T}) = (n-2) \text{vol}(\mathcal{T}_{\{i\}^c}) \text{vol}(\mathcal{T}_{\{j\}^c}) \sin \theta_{ij}(\mathcal{T})$  for all  $j \neq i$ .

Here, as usual,  $\theta_{ij}(\mathcal{T})$  is the angle between  $\mathcal{T}_{\{i\}^c}$  and  $\mathcal{T}_{\{j\}^c}$ .

*Remark 4.2.* One might expect that the second equation in the above lemma follows immediately from squaring the first. However, performing the computation demonstrates that this is not the case. Hence the second equation is in fact providing new information.

*Proof.* It suffices to take  $\mathcal{T} = \mathcal{S}^+$ , the inverse combinatorial simplex of some graph  $G$ . Let  $\{\sigma_i\}$  be the vertices of  $\mathcal{S}_G$ , the combinatorial simplex of  $G$ . We have  $L_G(i, j) = \langle \sigma_i, \sigma_j \rangle = \|\sigma_i\|_2 \|\sigma_j\|_2 \cos \phi_{ij}$ , where  $\phi_{ij}$  is the angle between  $\sigma_i$  and  $\sigma_j$ . Since the vertices  $\{\sigma_i\}$  are dual to those of  $\mathcal{S}_G^+$ , we have  $\cos \phi_{ij} = -\cos \theta_{ij}^+$  where  $\theta_{ij}^+$  is the angle between  $\mathcal{S}_{\{i\}^c}^+$  and  $\mathcal{S}_{\{j\}^c}^+$ . (We are applying the same reasoning here as in Sections 2.5.2 and 3.2.2.) Combining this with the fact that  $L_G \mathbf{1} = \mathbf{0}$  and Equation (4.12) gives

$$\begin{aligned} 0 &= \sum_{j \in [n]} L_G(i, j) = \|\sigma_i\|_2^2 - \sum_{j \neq i} \|\sigma_i\|_2 \|\sigma_j\|_2 \cos \theta_{ij}^+ \\ &= \frac{\text{vol}(\mathcal{S}_{\{i\}^c}^+)}{n^2 \text{vol}^2(\mathcal{S}^+)} \left( \text{vol}(\mathcal{S}_{\{i\}^c}^+) - \sum_{j \neq i} \text{vol}(\mathcal{S}_{\{j\}^c}^+) \cos \theta_{ij}^+ \right), \end{aligned}$$

which proves the first equation. To see the second, note that  $L_G(i, k) = -\sum_{j \neq k} L_G(i, j)$  (again using that  $L_G \mathbf{1} = \mathbf{0}$ ). Applying this twice, we obtain

$$L_G(i, i) = -\sum_{j \neq i} L_G(i, j) = \sum_{j \neq i} \sum_{k \neq i} L_G(k, j) = \sum_{j \neq i} L_G(j, j) + \sum_{j, k \neq i, k \neq j} L_G(k, j).$$

As above, translating this to expressions involving the volumes of facets of  $\mathcal{S}^+$  and then multiplying through by  $n^2 \text{vol}(\mathcal{S}^+)$  gives

$$\text{vol}^2(\mathcal{S}_{\{i\}^c}^+) = \sum_{j \neq i} \text{vol}^2(\mathcal{S}_{\{j\}^c}^+) - \sum_{j, k \neq i, k \neq j} \text{vol}(\mathcal{S}_{\{k\}^c}^+) \text{vol}(\mathcal{S}_{\{j\}^c}^+) \cos \theta_{kj}^+.$$

It remains to prove the third equation. Let  $M$  be the Menger matrix of  $\mathcal{S}^+$ , and let  $U = \{i, j\}$  and  $U_1 = \{i+1, j+1\}$  for any  $i \neq j$ . Without loss of generality assume  $i < j$ . Notice that  $M(U_1^c, U_1^c)$  is the Menger matrix of the vertices  $\{\sigma_k\}_{k \neq i, j}$ . Combining Sylvester's equation and our usual block matrix relation gives

$$\begin{aligned} \frac{\det M(U_1^c, U_1^c)}{\det M} &= \pm \det \left( -\frac{1}{2} L_G(U, U) \right) \\ &= \pm \frac{1}{4} \det \begin{pmatrix} \|\sigma_i\|_2^2 & \langle \sigma_i, \sigma_j \rangle \\ \langle \sigma_i, \sigma_j \rangle & \|\sigma_j\|_2^2 \end{pmatrix} \\ &= \pm \frac{1}{4} \|\sigma_i\|_2^2 \|\sigma_j\|_2^2 - \langle \sigma_i, \sigma_j \rangle^2 \\ &= \pm \frac{1}{4} \|\sigma_i\|_2^2 \|\sigma_j\|_2^2 (1 - \cos^2 \phi_{ij}) \end{aligned}$$

where  $\phi_{ij}$  is the angle between  $\sigma_i$  and  $\sigma_j$  (Section 2.5.2). Since the vertices  $\{\sigma_i\}$  are the duals to those in  $\mathcal{S}^+$ , we have  $\cos \phi_{ij} = -\cos \theta_{ij}^+$  so

$$\|\sigma_i\|_2^2 \|\sigma_j\|_2^2 (1 - \cos^2 \phi_{ij}) = \|\sigma_i\|_2^2 \|\sigma_j\|_2^2 (1 - \cos^2 \theta_{ij}^+) = \|\sigma_i\|_2^2 \|\sigma_j\|_2^2 \sin^2 \theta_{ij}^+.$$

Writing  $\det \mathbf{M}(U_1^c, U_1^c)$  in terms of  $\text{vol} \mathcal{S}_{U^c}^+$  and  $\det \mathbf{M}$  in terms of  $\text{vol} \mathcal{S}^+$  by means of Equation (4.8), and using Equation (4.12) to relate  $\|\sigma_i\|_2^2$  and  $\|\sigma_j\|_2^2$  to the volumes of  $\mathcal{S}_{\{i\}^c}^+$  and  $\mathcal{S}_{\{j\}^c}^+$  then yields

$$\frac{1}{4(n-1)^2(n-2)^2} \frac{\text{vol}^2 \mathcal{S}_{U^c}^+}{\text{vol}^2 \mathcal{S}^+} = \frac{\text{vol}^2 \mathcal{S}_{\{i\}^c}^+}{(n-1)^2 \text{vol}^2 \mathcal{S}^+} \frac{\text{vol}^2 \mathcal{S}_{\{j\}^c}^+}{(n-1)^2 \text{vol}^2 \mathcal{S}^+} \sin^2 \theta_{ij}^+.$$

Notice that we have rid ourselves of the ambiguity in sign because we see that both sides are the square of some quantity, hence are positive. Simplifying and taking the square root of both sides of the above expression gives the third equation.  $\square$

Our next set of results demonstrate the the inverse relation can be used not only to infer geometric properties of simplices, but also graph-theoretic properties. A variant of the following was proved by Fiedler [Fie11].

LEMMA 4.10. *For a weighted and connected tree  $T = (V, E, w)$  on  $n$  vertices let the matrix  $\mathbf{S}_T$  describe the inverse distances between vertices, i.e., for  $(i, j) \in E$ ,  $\mathbf{S}_T(i, j) = 1/w(i, j)$  and for  $(i, j) \notin E$ ,  $\mathbf{S}_T(i, j) = \sum_{\ell=1}^{k-1} 1/w(v_\ell, v_{\ell+1})$  where  $i = v_1, v_2, \dots, v_k = j$  is the unique path between  $i$  and  $j$ . Then,*

$$-\frac{1}{2} \begin{pmatrix} 0 & \mathbf{1}^t \\ \mathbf{1} & \mathbf{S}_T \end{pmatrix} \begin{pmatrix} \sum_{i \sim j} 1/w(i, j) & (\mathbf{d} - 2\mathbf{1})^t \\ \mathbf{d} - 2\mathbf{1} & \mathbf{L}_T \end{pmatrix} = \mathbf{I}, \quad (4.13)$$

where  $\mathbf{d} = (\deg(1), \dots, \deg(n))$ .

COROLLARY 4.2. *Let  $T$  be a weighted and connected tree. Then*

$$\Delta^t \mathbf{L}_T \Delta + \frac{4R_T}{n^2} = \sum_{i,j} \frac{1}{w(i, j)}, \quad \text{and} \quad \mathbf{L}_G \Delta = \left(2 - \frac{2}{n}\right) \mathbf{1} - \mathbf{d},$$

where  $\Delta = \text{diag}(\mathbf{L}_T^+(i, i)) = \frac{1}{n} \mathbf{R} \mathbf{1} - \frac{1}{n^2} \mathbf{J} \mathbf{R} \mathbf{1}$  and  $\mathbf{d} = (\deg(1), \dots, \deg(n))$ .

*Proof.* Let  $\mathbf{S}_T$  be as it was in Lemma 4.10. It's well known that in trees, the effective resistance between nodes  $i, j$  is equal to  $\sum_{s=1}^{r-1} 1/w(v_s, v_{s+1})$  where  $i = v_1, \dots, v_r = j$  is the shortest path between  $i$  and  $j$  in  $T$  (see e.g., [Ell11]). That is,  $\mathbf{R}_T = \mathbf{S}_T$ . Since matrix inverses are unique, combining Equations (4.13) and (2.18) yields

$$\begin{pmatrix} \sum_{i \sim j} 1/w(i, j) & (\mathbf{d} - 2\mathbf{1})^t \\ \mathbf{d} - 2\mathbf{1} & \mathbf{L}_T \end{pmatrix} = \begin{pmatrix} \Delta^t \mathbf{L}_T \Delta + 4R_T/n^2 & -(\mathbf{L}_T \Delta + \frac{2}{n} \mathbf{1})^t \\ -(\mathbf{L}_T \Delta + \frac{2}{n} \mathbf{1}) & \mathbf{L}_T \end{pmatrix},$$

from which the claim follows.  $\square$

### §4.3. Inequalities

In this section we demonstrate how the correspondence may be used to obtain both geometric and graph-theoretic inequalities. We begin with an inequality relating the quadratic form  $\mathcal{L}$  to the “weight” of the cuts associated with the pseudoinverse. It was first proved by Devriendt and Van Mieghem [DVM18]. Interestingly, a parallel result for the normalized Laplacian form does not seem to exist. As usual, omitted proofs are found in the appendix.

LEMMA 4.11. *For any  $f$  with  $\langle f, \mathbf{1} \rangle = 0$ ,  $\mathcal{L}(f) \geq \|f\|_1^2 / 4w(\partial^+ F^+)$ , for  $F^+ \stackrel{\text{def}}{=} \{i : f(i) \geq 0\}$ .*

Next we give an (admittedly, somewhat undecipherable) inequality relating the centroids of  $\mathcal{S}_G$  to the vertex matrix of  $\hat{\mathcal{S}}$ . The motivation is simply to demonstrate the potential uses of known graph-theoretic inequalities in the simplex domain.

Using Cheeger’s inequality [CG97],

$$\kappa_G \geq \hat{\lambda}_{n-1} \geq \frac{\kappa_G^2}{2},$$

where  $\hat{\lambda}_1 \geq \hat{\lambda}_{n-1} > \hat{\lambda}_n = 0$  are the eigenvalues of the normalized Laplacian of  $G$ , and  $\kappa_G$  is the conductance of  $G$ ,

$$\kappa_G \stackrel{\text{def}}{=} \min_{U: \text{vol}(U) \leq \text{vol}(G)/2} \frac{\text{vol}(\partial U)}{|U|},$$

we can relate the centroids of  $\mathcal{S}_G$  to  $\hat{\mathcal{S}}_G$  as follows.

OBSERVATION 4.1.

$$\min_{U: \text{vol}(U) \leq \text{vol}(G)/2} \|\mathbf{c}(\mathcal{S}_U)\|_2^4 |U|^2 \leq \min_{i=1}^n (\hat{\Sigma} \hat{\Sigma}^t)(i, i) \leq \min_{U: \text{vol}(U) \leq \text{vol}(G)/2} \|\mathbf{c}(\mathcal{S}_U)\|_2^2 |U|.$$

*Proof.* Use that  $\|\mathbf{c}(\mathcal{S}_U)\|_2^2 = |U|^{-2} \chi_U \mathbf{L}_G \chi_U$  (Section 3.4) and that  $\hat{\Sigma} \hat{\Sigma}^t = \hat{\mathbf{A}}$  (Equation (3.1)) and apply Cheeger’s inequality.  $\square$

We can translate several of the results obtained in the previous section on volumes and spanning into inequalities.

LEMMA 4.12. *For any hyperacute simplex  $\mathcal{T} \subseteq \mathbb{R}^{n-1}$  and  $i \in [n]$ , the following equations hold:*

1.  $\text{vol}(\mathcal{T}_{\{i\}^c}) \leq \sum_{j \neq i} \text{vol}(\mathcal{T}_{\{j\}^c})$ ;
2.  $\sum_{j \neq i} \text{vol}^2 \mathcal{T}_{\{j\}^c} \geq \text{vol}^2 \mathcal{T}_{\{i\}^c} \geq \sum_{j \neq i} \text{vol}^2(\mathcal{T}_{\{j\}^c}) - \sum_{j, k \neq i, j \neq k} \text{vol}(\mathcal{T}_{\{j\}^c}) \text{vol}(\mathcal{T}_{\{k\}^c})$ ; and
3.  $(n-1) \text{vol} \mathcal{T}_{\{i, j\}^c} \text{vol}(\mathcal{T}) \leq (n-2) \text{vol}(\mathcal{T}_{\{i\}^c}) \text{vol}(\mathcal{T}_{\{j\}^c})$  for all  $j \neq i$ .

*Proof.* Follows immediately from Lemma 4.9 after recalling that because  $\mathcal{T}$  is hyperacute all interior angles are at most  $\pi/2$ . We remark that for the second equation we have simply provided the easy upper bound provided by Equation 2 of Lemma 4.12.  $\square$

More interestingly however, we can use the relation between volume of a graph's inverse combinatorial simplex and the weight of its spanning trees (Equation (4.9)) to give inequalities pertaining to the latter.

LEMMA 4.13. *For any weighted, connected graph  $G$  and all  $i \in V(G)$ ,*

1.  $\Gamma_{G_{\{i\}^c}}^{-1/2} \leq \sum_{j \neq i} \Gamma_{G_{\{j\}^c}}^{-1/2}$ ;
2.  $\sum_{j \neq i} \Gamma_{G_{\{j\}^c}}^{-1} \geq \Gamma_{G_{\{i\}^c}}^{-1} \geq \sum_{j \neq i} \Gamma_{G_{\{j\}^c}}^{-1} - \sum_{j, k \neq i, j \neq k} \Gamma_{G_{\{j\}^c}}^{-1/2} \Gamma_{G_{\{k\}^c}}^{-1/2}$ ; and
3.  $\Gamma_{G_{\{i\}^c}} \Gamma_{G_{\{j\}^c}} \leq \Gamma_{G_{\{i, j\}^c}} \Gamma_G$  for all  $j \neq i$ .

*Proof.* All equations follow from applying Lemma 4.12 together with Equation 4.9 and simplifying.  $\square$

#### §4.4. Quadrics

Here we explore several quadrics associated with the simplices of  $G$ . We remind the reader that a *quadric* in  $\mathbb{R}^d$  is a hypersurface of dimension  $d - 1$  of the form

$$\{\mathbf{x} \in \mathbb{R}^d : \mathbf{x}^t \mathbf{Q} \mathbf{x} + \mathbf{r}^t \mathbf{x} + s = 0\},$$

for some  $\mathbf{Q} \in \mathbb{R}^{d \times d}$ ,  $\mathbf{r} \in \mathbb{R}^d$  and  $s \in \mathbb{R}$ . In  $\mathbb{R}^3$ , typical examples of quadrics are spheroids and ellipsoids ( $\mathbf{r} = \mathbf{0}$  in these cases), paraboloids, hyperboloids, and cylinders. In what follows we focus on ellipsoids, in particular on *circumscribed* ellipsoids. Such a quadric of interest in simplex geometry is the following.

DEFINITION 4.1 ([Kra83]). The *Steiner Circumscribed Ellipsoid*, or simply the *Steiner Ellipsoid* of a simplex  $\mathcal{S}$  with vertices  $\{\sigma_i\}$  is a quadric which contains the vertices and whose tangent plane at  $\sigma_i$  is parallel to the affine plane spanned by  $\{\sigma_j\}_{j \neq i}$ .

Figure 4.1 illustrates the Steiner ellipsoid of a generic simplex. Its existence and uniqueness is guaranteed by the following theorem.

THEOREM 4.1 ([Fie05]). *The Steiner ellipsoid of a simplex  $\mathcal{S}$  is unique and moreover, is the ellipsoid with minimum volume which contains  $\mathcal{S}$ .*

Owing to its uniqueness, we denote the Steiner ellipsoid of the simplex  $\mathcal{S}$  by  $\mathcal{E}(\mathcal{S})$ . The following lemma gives an explicit representation of the circumscribed ellipsoid of the combinatorial simplex

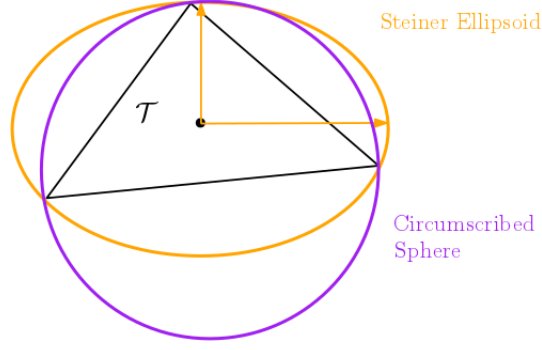


Figure 4.1: A simplex  $\mathcal{T} \subseteq \mathbb{R}^2$  and its corresponding Steiner circumscribed ellipsoid in orange (light) and circumscribed sphere in purple (dark). The arrows illustrate the semi-axes of the ellipsoid.

of  $G$ —which we will henceforth call the *(Steiner) circumscribed ellipsoid of  $G$* —and of its inverse, which we call the *inverse (Steiner) circumscribed Ellipsoid of  $G$* .

LEMMA 4.14 ([Fie05]). *The Steiner circumscribed ellipsoid of  $G$  and its inverse are described by*

$$\mathcal{E}(\mathcal{S}_G) = \left\{ \mathbf{x} : \mathbf{x}^t \boldsymbol{\Sigma}^+ (\boldsymbol{\Sigma}^+)^t \mathbf{x} - \frac{n-1}{n} = 0 \right\}, \quad (4.14)$$

and

$$\mathcal{E}(\mathcal{S}_G^+) = \left\{ \mathbf{x} : \mathbf{x}^t \boldsymbol{\Sigma} \boldsymbol{\Sigma}^t \mathbf{x} - \frac{n-1}{n} = 0 \right\}. \quad (4.15)$$

Perhaps a more insightful representation of  $\mathcal{E}(\mathcal{S})$  comes from appealing to Equation (3.2), i.e.,  $\boldsymbol{\Sigma} \boldsymbol{\Sigma}^t = \boldsymbol{\Lambda}^{-1/2}$ . Hence, by (4.14),

$$\mathcal{E}(\mathcal{S}) = \left\{ \mathbf{x} : \mathbf{x}^t \boldsymbol{\Lambda}^{-1} \mathbf{x} = \frac{n-1}{n} \right\}. \quad (4.16)$$

This allows us to give explicit formulas for the semi-axes of  $\mathcal{E}(\mathcal{S})$ . The *semi-axes* of an ellipsoid written in the standard form  $\mathbf{x}^t \mathbf{D}^2 \mathbf{x} = 1$  with  $\mathbf{D} \in \mathbb{R}^{d \times d}$  a diagonal matrix are the  $d$  vectors  $\mathbf{e}_i \cdot \mathbf{D}(i, i)^{-1}$ . They are the unique vectors  $\mathbf{u}_i$  such that any point  $\mathbf{x}$  on the ellipsoid can be written as  $\mathbf{x} = \sum_i \mathbf{u}_i \alpha_i$  with  $\sum_i \alpha_i^2 = 1$  [DVM18].

LEMMA 4.15. *The semi-axes of the Steiner Circumscribed Ellipsoid  $\mathcal{E}(\mathcal{S}_G)$  of the graph  $G$  are*

$$\frac{\mathbf{e}_i}{\sqrt{\lambda_i}} \cdot \left( \frac{n}{n-1} \right)^{1/2},$$

for  $i = 1, \dots, n-1$ .

*Proof.* The diagonal matrix  $\mathbf{D} = \boldsymbol{\Lambda}^{-1/2} \left( \frac{n}{n-1} \right)^{1/2}$  has entries  $D(i, i) = \mathbf{e}_i \left( \frac{n}{(n-1)\lambda_i} \right)^{1/2}$ , and equation (4.16) demonstrates that  $\mathcal{E}(\mathcal{S}_G) = \{ \mathbf{x} : \mathbf{x}^t \mathbf{D}^2 \mathbf{x} = 1 \}$ . Apply the definition of semi-axes.  $\square$

Next we investigate the circumscribed sphere of the combinatorial simplex. Similarly to the circumscribed ellipsoid, the *circumscribed sphere of a convex body*  $\mathcal{P}$  is the sphere whose boundary contains all the vertices of  $\mathcal{P}$ . The circumscribed sphere does not exist in general. However, just as it is possible to always draw a circle containing the endpoints of a triangle, so the circumscribed sphere of a hyperacute simplex always exists as is demonstrated by the following lemma.

LEMMA 4.16 ([Fie93]). *Let  $\mathcal{S}^+ \subseteq \mathbb{R}^{n-1}$  be a hyperacute simplex. The circumscribed sphere of  $\mathcal{S}^+$  exists and is given by the set of points  $\{\mathbf{x} : \mathbf{x} = \mathbf{\Sigma}\boldsymbol{\alpha}, \langle \boldsymbol{\alpha}, \mathbf{1} \rangle = 1, \langle \boldsymbol{\alpha}, \mathbf{D}\boldsymbol{\alpha} \rangle = 0\}$ , which is a sphere centred at the point  $\frac{1}{2}\mathbf{\Sigma}(\mathbf{L}_G\boldsymbol{\xi} + \mathbf{1}/n)$  with radius  $\frac{1}{2}\sqrt{\boldsymbol{\xi}^t \mathbf{L}_G \boldsymbol{\xi} + 4R_G/n^2}$  where  $G$  is  $\mathcal{S}^+$ 's associated graph, and  $\boldsymbol{\xi} = \text{diag}(\mathbf{L}_G^+(i, i))$ .*

Until this point, we have been examining only the quadrics associated with the combinatorial simplices. We now consider the normalized simplices. Since all the vertices of the normalized simplex lie on the unit sphere, it's clear that the circumscribed sphere of  $\widehat{\mathcal{S}}_G$  is precisely  $\{\mathbf{x} : \mathbf{x}^t \mathbf{x} = 1\}$ . It's not as straightforward to see what they circumscribed ellipsoid,  $\mathcal{E}(\widehat{\mathcal{S}})$ , is on the other hand. One might suspect that it obeys the equation  $\mathbf{x}^t \widehat{\mathbf{\Sigma}}^+ (\widehat{\mathbf{\Sigma}}^+)^t \mathbf{x} = 1 - 1/n$ , as this is the natural analogue of (4.14). However, because  $\widehat{\mathbf{\Sigma}}^+$  and  $\widehat{\mathbf{\Sigma}}$  obey a non-constant pseudoinverse relation, this equation fails the first test:  $\widehat{\boldsymbol{\sigma}}_i^t \widehat{\mathbf{\Sigma}}^+ (\widehat{\mathbf{\Sigma}}^+)^t \widehat{\boldsymbol{\sigma}}_i = \boldsymbol{\chi}_i^t (\mathbf{I} - \sqrt{\mathbf{w}} \sqrt{\mathbf{w}}^t / \text{vol}(G)) \boldsymbol{\chi}_i = 1 - \sqrt{w(i)w(j)} / \text{vol}(G)$  is non-constant. However, at this point we recall that beyond being simply the inverse simplex of  $\mathcal{S}$ ,  $\mathcal{S}^+$  is also its dual. We might thus hazard a guess that the correct matrix is  $\widehat{\mathbf{\Sigma}}^* (\widehat{\mathbf{\Sigma}}^*)^t$ , where  $\widehat{\mathbf{\Sigma}}^*$  is the vertex matrix of  $\widehat{\mathcal{S}}^*$ . The following lemma confirms this hypothesis.

COROLLARY 4.3. *The normalized Steiner ellipsoid of  $G$  is*

$$\mathcal{E}(\widehat{\mathcal{S}}) = \left\{ \mathbf{x} : \mathbf{x}^t \widehat{\mathbf{\Sigma}}^* (\widehat{\mathbf{\Sigma}}^*)^t \mathbf{x} = \frac{n-1}{n} \right\},$$

and the inverse is

$$\mathcal{E}(\widehat{\mathcal{S}}) = \left\{ \mathbf{x} : \mathbf{x}^t (\widehat{\mathbf{\Sigma}}^+)^* ((\widehat{\mathbf{\Sigma}}^+)^*)^t \mathbf{x} = \frac{n-1}{n} \right\}.$$

where  $\widehat{\mathbf{\Sigma}}^*$  contains the vertices of  $\widehat{\mathcal{S}}_G^*$  and  $(\widehat{\mathbf{\Sigma}}^+)^*$  those of  $(\widehat{\mathcal{S}}_G^+)^*$ .

*Proof.* The computation is almost identical to that in the proof of Lemma 4.14. □

## §4.5. Resistive Polytope

In this section we explore the relationship between the inverse combinatorial simplex of  $G$  and another geometric object related to the effective resistance of the graph. Consider the vertices  $\boldsymbol{\mu}_i = \mathbf{L}_G^{+/2} \boldsymbol{\chi}_i \in \mathbb{R}^n$ , for  $i \in [n]$ . This yields  $n$  points in  $\mathbb{R}^n$ , also with pairwise squared distances equal to the effective resistance of the graph:

$$\|\boldsymbol{\mu}_i - \boldsymbol{\mu}_j\|_2^2 = \left\| \mathbf{L}_G^{+/2} (\boldsymbol{\chi}_i - \boldsymbol{\chi}_j) \right\|_2^2 = (\boldsymbol{\chi}_i - \boldsymbol{\chi}_j)^t \mathbf{L}_G^+ (\boldsymbol{\chi}_i - \boldsymbol{\chi}_j) = r^{\text{eff}}(i, j).$$



This embedding has been referred to as a *resistive embedding* [Gha15, DLP11], and is an example of an  $\ell_2^2$  metric [ARV09] owing to the well known fact that the effective resistance is a metric (e.g., [KR93]). That being said however, while the mapping seems to be known [GBS08], there is very little literature on its properties.

We set

$$\mathcal{R}_G \stackrel{\text{def}}{=} \text{conv}(\{\mu_i\}), \quad (4.17)$$

and call  $\mathcal{R}_G$  the *resistive polytope of  $G$* . Note that  $\mathbf{L}_G^{+/2}$  is  $\mathcal{R}_G$ 's vertex matrix. As usual, we may omit the subscript  $G$  for convenience. We emphasize that while the vertices  $\{\mu_i\}$  obey the same pairwise distances as those of the inverse simplex  $\mathcal{S}_G^+$ ,  $\mathcal{R}_G$  is not the same object as  $\mathcal{S}_G^+$ . First, of course, there is the fact that it sits in  $\mathbb{R}^n$ . However, we also note that the entries of  $\mu_i$  (the first  $n-1$ , at least) do not match those of  $\sigma_i^+$ . Indeed,

$$\mu_i(\ell) = \mathbf{L}_G^{+/2}(\ell, i) = \sum_{j \in [n]} \lambda_j^{-1/2} \varphi_j \varphi_j^t(\ell, i) = \sum_{j \in [n]} \lambda_j^{-1/2} \varphi_j(\ell) \varphi_j(i).$$

Recalling the formula for the vertices of the inverse simplex  $\mathcal{S}^+$  demonstrates that

$$\mu_i(\ell) = \sum_{j \in [n]} \sigma_\ell^+(j) \varphi_j(i) = \sum_{j \in [n]} \sigma_i^+(j) \varphi_j(\ell).$$

Hence, in general,  $\mu_i(\ell) \neq \sigma_i^+(\ell)$ . However, the dot products between the vertices of  $\mathcal{R}_G$  does respect the same relationships as those between the vertices of  $\mathcal{S}_G^+$ :

$$\begin{aligned} \langle \mu_i, \mu_j \rangle &= \sum_{\ell \in [n]} \mathbf{L}_G^{+/2}(\ell, i) \mathbf{L}_G^{+/2}(\ell, j) \\ &= \langle \mathbf{L}_G^{+/2}(\cdot, i), \mathbf{L}_G^{+/2}(\cdot, j) \rangle \\ &= \langle \mathbf{L}_G^{+/2}(\cdot, i), \mathbf{L}_G^{+/2}(j, \cdot) \rangle = \mathbf{L}_G^+(i, j), \end{aligned}$$

since  $\mathbf{L}_G^{+/2}$  is symmetric and  $\mathbf{L}_G^{+/2} \mathbf{L}_G^{+/2} = \mathbf{L}_G^+$ . We can also see this from recalling that

$$r^{\text{eff}}(i, j) = \mathbf{L}_G^+(i, i) + \mathbf{L}_G^+(j, j) - \frac{1}{2} \mathbf{L}_G^+(i, j),$$

combined with the facts that  $\|\mu_i - \mu_j\|_2^2 = r^{\text{eff}}(i, j)$  and  $\|\mu_i\|_2^2 = \mathbf{L}_G^+(i, i)$ . Moreover, the centroid of  $\mathcal{R}_G$  also coincides with the origin of  $\mathbb{R}^n$ :

$$c(\mathcal{R}_G) = \frac{1}{n} \mathbf{L}_G^{+/2} \mathbf{1} = \frac{1}{n} \sum_{i \in [n-1]} \lambda_i^{-1/2} \varphi_i \varphi_i^t \mathbf{1} = \mathbf{0}.$$

One therefore begins to suspect that  $\mathcal{R}_G$  is the same object of  $\mathcal{S}_G^+$ , simply projected onto some

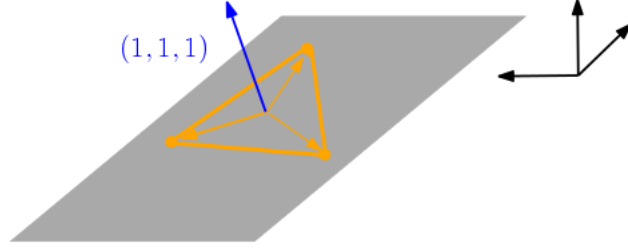


Figure 4.2: The resistive embedding (in orange; light) of a graph with three nodes sits in a plane (gray) which is parallel to the all ones vector.

hyperplane of  $\mathbb{R}^n$ . The following lemma demonstrates that this is indeed the case, and that the hyperplane is that which has  $\text{span}(\mathbf{1})$  as its orthogonal complement.

LEMMA 4.17. *The all ones vector is orthogonal to  $\mathcal{R}_G$ .*

*Proof.* We need to show that for all  $\mathbf{p}, \mathbf{q} \in \mathcal{R}_G$ ,  $\langle \mathbf{1}, \mathbf{p} - \mathbf{q} \rangle = 0$ . As usual, let  $\mathbf{x}$  and  $\mathbf{y}$  be the barycentric coordinates of  $\mathbf{p}$  and  $\mathbf{q}$  so that  $\mathbf{p} = \mathbf{L}_G^{+/2} \mathbf{x}$  and  $\mathbf{q} = \mathbf{L}_G^{+/2} \mathbf{y}$ . We have

$$\langle \mathbf{1}, \mathbf{p} \rangle = \sum_{\ell \in [n]} (\mathbf{L}_G^{+/2} \mathbf{x})(\ell) = \sum_{\ell \in [n]} \sum_{j \in [n]} \mathbf{L}_G^{+/2}(\ell, j) x(j) = \sum_{j \in [n]} x(j) \sum_{\ell \in [n]} \mathbf{L}_G^{+/2}(\ell, j),$$

where for any  $j$ ,

$$\sum_{\ell \in [n]} \mathbf{L}_G^{+/2}(\ell, j) = \mathbf{1}^t \mathbf{L}_G^{+/2} \chi_j = \sum_{\ell \in [n-1]} \lambda_\ell^{-1/2} \mathbf{1}^t \varphi_\ell \varphi_\ell^t \chi_j = 0,$$

since  $\varphi_i \in \text{span}(\mathbf{1})^\perp$  for all  $i < n$ . Hence  $\langle \mathbf{1}, \mathbf{p} \rangle = 0$  meaning that  $\langle \mathbf{1}, \mathbf{p} - \mathbf{q} \rangle = 0$  as well.  $\square$

The relationship between  $\mathcal{R}$  and  $\mathcal{S}$  gives us an alternate way to prove equalities such as (3.14): There exists an isometry<sup>2</sup> between  $\mathcal{R}$  and  $\mathcal{S}$ , so

$$\|\mathbf{c}(\mathcal{S}_U^+)\|_2^2 = \|\mathbf{c}(\mathcal{R}_U)\|_2^2 = \frac{1}{|U|^2} \left\| \mathbf{L}_G^{+/2} \chi_U \right\|_2^2 = \frac{1}{|U|^2} w(\delta^+ U).$$

Additionally, just as  $\mathcal{S}_G^+$  has the inverse  $\mathcal{S}_G$ ,  $\mathcal{R}_G$  has an inverse which respects the same relationships. As one might guess, this inverse has vertex matrix  $\mathbf{L}_G^{1/2}$ . To see this, for any  $i, j \neq k$ , we have

$$\langle \mathbf{L}_G^{1/2} \chi_i, \mathbf{L}_G^{+/2} \chi_j - \mathbf{L}_G^{+/2} \chi_k \rangle = \chi^t \mathbf{L}_G^{1/2} \mathbf{L}_G^{+/2} (\chi_j - \chi_k),$$

where

$$\mathbf{L}_G^{1/2} \mathbf{L}_G^{+/2} = \sum_{r,s=1}^{n-1} \lambda_r^{1/2} \lambda_s^{-1/2} \varphi_r \varphi_r^t \varphi_s \varphi_s^t = \sum_{r=1}^{n-1} \varphi_r \varphi_r^t,$$

<sup>2</sup>A distance preserving map.

and

$$\sum_{r=1}^{n-1} \chi_i \varphi_r \varphi_r^t \chi_j = \sum_{r=1}^{n-1} \varphi_r(i) \varphi_r(j) = \delta_{ij} - \frac{1}{n},$$

using Equation (3.3). Hence,

$$\chi_i^t \mathbf{L}_G^{1/2} \mathbf{L}_G^{+/2} (\chi_j - \chi_k) = \delta_{ij} - \frac{1}{n} - (\delta_{ik} - \frac{1}{n}) = \delta_{ij}.$$

To conclude, there exists an isometry between the inverse combinatorial simplex of a graph  $G$  (which lies in  $\mathbb{R}^{n-1}$ ) and the effective polytope,  $\mathcal{R}_G$  of  $G$  (which lies in  $\mathbb{R}^n$ ). The resistive polytope lies in a hyperplane orthogonal to the all-ones vector.

#### §4.6. Continuous Time Random Walks

This current section is for the reader who is less interested in the mathematics behind the graph-simplex correspondence, and is reading only for the vague hope that some of the underlying geometry will be aesthetically pleasing. While the content has certainly failed in this vein thus far, this section is the closest we will come to remedying the situation.

Consider a random walk on a graph. The probability distribution governing the dynamics is a barycentric coordinate: each coordinate is non-negative and they sum to one. Therefore, we can represent the probability distribution as a point in the simplex and the probability distribution as a function of time as a path in the simplex. See Figure 4.3 for an illustration. In what follows we give equations which determine the dynamics of the path in the simplex as a function of the eigenvalues and eigenvectors of the graph.

We will examine a continuous time random walk which obeys the equation

$$\frac{d\pi(t)}{dt} = -\mathbf{L}_G \mathbf{W}_G^{-1/2} \pi(t),$$

which has the solution  $\pi(t) = \exp(-\mathbf{L}_G \mathbf{W}_G^{-1/2} t) \pi(0)$ . This, however, is relatively unsightful in terms of analyzing the dynamics of  $\pi(t)$  in terms of the graph. Instead, in what follows we seek to develop a solution to  $\pi(t)$  in terms of the eigendecomposition of  $G$ . Define  $\pi_1(t) = \mathbf{W}^{-1/2} \pi(t)$  and  $\pi_2(t) = \hat{\Phi}^t \pi_1(t)$ , where we recall that  $\hat{\Phi}^t$  is the eigenvector matrix of  $\hat{\mathbf{L}}_G$ . Then

$$\frac{d\pi_1(t)}{dt} = \mathbf{W}^{-1/2} \frac{d\pi(t)}{dt} = -\mathbf{W}^{-1/2} \mathbf{L}_G \mathbf{W}^{-1/2} \mathbf{W}^{-1/2} \pi(t) = -\hat{\mathbf{L}}_G \pi_1(t),$$

and, using the eigendecomposition of  $\hat{\mathbf{L}}_G$ ,

$$\frac{d\pi_2(t)}{dt} = \hat{\Phi}^t \frac{d\pi_1(t)}{dt} = -\hat{\Phi}^t \hat{\mathbf{L}}_G \pi_1(t) = -\hat{\Phi}^t \hat{\Phi} \hat{\Lambda} \hat{\Phi}^t \pi_1(t) = -\hat{\Lambda} \pi_2(t),$$

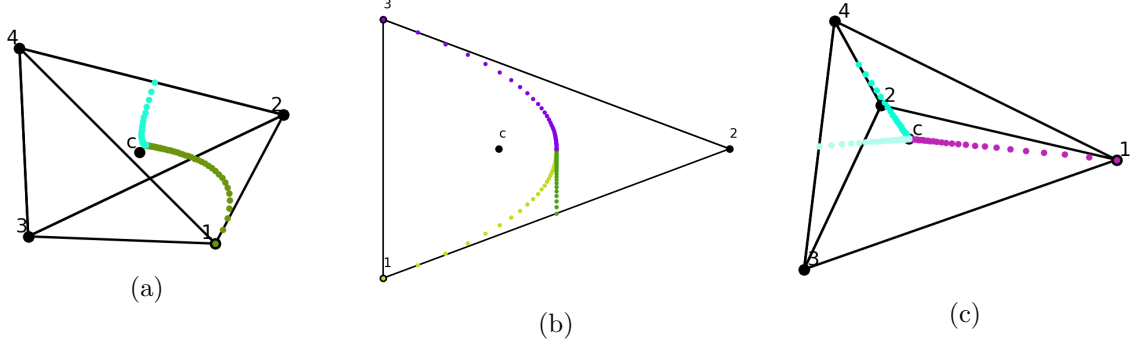


Figure 4.3: Random walk dynamics plotted as points in the simplex. Figures (a) and (b) are plotted using the normalized simplex; figure (c) uses the normalized simplex. The underlying graph of Figure (a) has edges  $(1, 2)$ ,  $(2, 3)$ ,  $(3, 4)$ ,  $(2, 4)$ , that underlying (b) edges  $(1, 2)$  and  $(2, 3)$  and that of (c) is the complete graph  $K_4$ .

since  $\hat{\Phi}^t \hat{\Phi} = \mathbf{I}$ . This equation has the solution

$$\pi_2(t) = \exp(-\hat{\Lambda}t) \pi_2(0) = \begin{pmatrix} e^{-\lambda_1 t} & & \\ & \ddots & \\ & & e^{-\lambda_{n-1} t} \end{pmatrix} \pi_2(0).$$

Combining the definitions of  $\pi_1$  and  $\pi_2$  gives  $\pi_2(t) = \hat{\Phi}^t \pi_1(t) = \hat{\Phi}^t \mathbf{W}^{-1/2} \pi(t)$ , hence  $\pi(t) = \mathbf{W}^{1/2} \hat{\Phi} \pi_2(t)$ . As a point in the simplex this gives

$$p(t) = \Sigma \pi(t) = \Lambda^{1/2} \Phi^t \mathbf{W}^{1/2} \hat{\Phi} \pi_2(t) = \mathbf{Y} \pi_2(t),$$

after defining  $\mathbf{Y} \stackrel{\text{def}}{=} \Lambda^{1/2} \Phi^t \mathbf{W}^{1/2} \hat{\Phi}$ . As a point in the normalized simplex, we have

$$q(t) = \hat{\Sigma} \pi(t) = \hat{\Lambda}^{1/2} \hat{\Phi}^t \mathbf{W}^{1/2} \hat{\Phi} \pi_2(t) = \hat{\mathbf{Y}} \pi_2(t),$$

where  $\hat{\mathbf{Y}} = \hat{\Lambda}^{1/2} \hat{\Phi}^t \mathbf{W}^{1/2} \hat{\Phi}$ . We thus see that the matrices

$$\mathbf{Y} = \begin{pmatrix} \lambda_1^{1/2} \sum_{i \in [n]} \varphi_1(i) \hat{\varphi}_1(i) w_i^{1/2} & \cdots & \lambda_1^{1/2} \sum_{i \in [n]} \varphi_1(i) \hat{\varphi}_{n-1}(i) w_i^{1/2} \\ \vdots & \ddots & \vdots \\ \lambda_{n-1}^{1/2} \sum_{i \in [n]} \varphi_{n-1}(i) \hat{\varphi}_1(i) w_i^{1/2} & \cdots & \lambda_{n-1}^{1/2} \sum_{i \in [n]} \varphi_{n-1}(i) \hat{\varphi}_{n-1}(i) w_i^{1/2} \end{pmatrix},$$

and

$$\hat{\mathbf{Y}} = \begin{pmatrix} \hat{\lambda}_1^{1/2} \sum_{i \in [n]} \hat{\varphi}_1(i) \hat{\varphi}_1(i) w_i^{1/2} & \cdots & \hat{\lambda}_1^{1/2} \sum_{i \in [n]} \hat{\varphi}_1(i) \hat{\varphi}_{n-1}(i) w_i^{1/2} \\ \vdots & \ddots & \vdots \\ \hat{\lambda}_{n-1}^{1/2} \sum_{i \in [n]} \hat{\varphi}_{n-1}(i) \hat{\varphi}_1(i) w_i^{1/2} & \cdots & \hat{\lambda}_{n-1}^{1/2} \sum_{i \in [n]} \hat{\varphi}_{n-1}(i) \hat{\varphi}_{n-1}(i) w_i^{1/2} \end{pmatrix},$$

govern the dynamics of the random walk in  $\mathcal{S}_G$  and  $\hat{\mathcal{S}}_G$ , respectively. More specifically, letting

$\mathbf{Y} = (\mathbf{y}_1 \dots \mathbf{y}_n)$  we have

$$\mathbf{p}(t) = \sum_{i \in [n-1]} \mathbf{y}_i (\pi_2(t))(i) = \sum_{i \in [n-1]} \mathbf{y}_i e^{-\lambda_i t} \hat{\mathbf{\Phi}}^t \mathbf{W}^{-1/2} \boldsymbol{\pi}(0)(i),$$

and a similar equation for  $\mathbf{q}(t)$ .

## Algorithmics

*I'm smart enough to know that I'm dumb.*

— Richard Feynman

This final technical chapter will discuss some of the algorithmic foundations and consequences of the graph-simplex correspondence. Vis-à-vis foundations, we will chiefly be concerned with transitioning between a graph and its various simplices. We will explore lower bounds for how quickly this can be done if we wish to obtain the precise result<sup>1</sup>, and whether we can “approximate” any of the constructions (e.g., given the graph  $G$  can we quickly obtain a simplex which serves as an approximation<sup>2</sup> to  $\mathcal{S}_G$ .) With respect to algorithmic consequences on the other hand, we will attempt to leverage knowledge we have in the hitherto relatively unrelated areas of computational graph theory and high-dimensional computational geometry to draw new conclusions about the complexity of several problems in these areas. For instance, if a graph theoretic problem has an analogue in the simplex, any fact regarding the problems difficulty—whether it’s NP-complete, say—translates to an immediate result about its geometric counterpart. In particular, since the simplex of a graph can be generate in polynomial time given the graph (due to the fact that an eigendecomposition can be computed in polynomial time) and vice versa, problems which are solvable in polynomial in either the simplex or graph domain translate to polynomial (yet perhaps not optimal!) problems in the other domain and likewise, problems which are NP-hard in one domain have analogues which are NP-hard in the other.

For the benefit of the (undoubtedly confused) reader unfamiliar with computational complexity and reductions, we begin the chapter with a short section containing this background material. We will also discuss computational representations of a simplex therein.

### §5.1. Preliminaries

**Asymptotics.** We begin with asymptotic notation which will be used to analyze the running time of various algorithms. We use the standard definitions—see any reference text on algorithm

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<sup>1</sup>Ignoring issues of floating point number accuracy

<sup>2</sup>The notion of approximating a simplex is rather ambiguous and will be expounded upon at a later time.

design for more background (e.g., [KT06]). Let  $f, g : U \subseteq \mathbb{R} \rightarrow \mathbb{R}$  be functions. Write  $f = O(g)$  (or  $f(n) = O(g(n))$ ) if  $\limsup_{x \rightarrow \infty} |f(x)/g(x)| < \infty$ , and  $f = \Omega(g)$  if  $g = O(f)$ . Write  $f = o(g)$  as  $x \rightarrow c$  if  $\lim_{x \rightarrow \infty} |f(x)/g(x)| = 0$  and  $f = \omega(g)$  if  $g = o(f)$ . If  $f = O(g)$  and  $f = \Omega(g)$  we write  $f = \Theta(g)$ . We will also use the tilde to hide polylog factors. Say  $f = \tilde{O}(g)$  if  $f(n) = O(g(n) \log^c n)$  and  $f = \tilde{\Omega}(g)$  if  $f(n) = \Omega(g(n) \log^{-c} n)$ , for some  $c \geq 0$ .

**Simplex representations.** In order to discuss the algorithmics pertaining to simplices and convex polyhedra in general, we must discuss how such objects are represented by a machine. Clearly, we cannot simply enumerate all the points enclosed by a body in high-dimensional space. Instead we must concisely represent the boundaries of the polytope. The two most common such descriptions are

- *V-description*, in which we are given the vertex vectors of the polytope;
- *H-description*, in which we are given the parameters of the half-spaces whose intersection defines the polytope. That is, if  $\mathcal{T} = \bigcap_i \{\mathbf{x} : \langle \mathbf{z}_i, \mathbf{x} \rangle \geq b_i\}$ , then an H-description of  $\mathcal{T}$  would be the vectors  $\{\mathbf{z}_i\}$  and the scalars  $\{b_i\}$ .

It's not at all clear whether these descriptions are equivalent in the sense that one can easily generate one from the other. Indeed, the complexity of vertex enumeration (generating a V-description from an H-description) and facet enumeration (generating an H-description from a V-description) remains an open problem for general polytopes [KP03], although there exist polynomial time algorithms when the polytopes are simplices (e.g., [BFM98]). We will return to this fact later on.

**Reductions.** Some background on computational models and reductions will also be useful. For more details see [KT06] or [Knu11]. We will use the typical computational model for analyzing algorithms. Without diving too far into the minutiae, we assume that single arithmetic operations require  $O(1)$ -time, i.e., constant. We will analyze the runtime of an algorithm as a function of how many bits it takes to represent the input. A common tool for providing upper bounds on the runtime of an algorithm is to “reduce” it to a problem for which a bound is already known. Assume problem  $P$  requires time  $\Omega(f_P(n))$  to solve—meaning that *any* algorithm requires time  $\Omega(f_P(n))$ —where  $n$  represents the size of the input and  $f_P(n)$  is some function of  $n$ , e.g.,  $f_P(n) = n^2 \log n$ . Let  $Q$  be a distinct problem and suppose that for every instance of  $P$  we can transform the input of  $P$  to a valid input for  $Q$ , and transform the output of  $Q$  to a valid output of  $P$ , both in time  $O(f_P(n))$ . We have then established that  $f_Q(n) = \Omega(f_P(n))$ , where  $f_Q$  the runtime required to solve  $Q$ , since we can solve  $P$  in time  $f_Q(n) + O(f_P(n))$  by transforming any input to  $P$  to the input of  $Q$ , solving  $Q$ , and transforming the output back. Such a technique will be used extensively throughout the next few sections.

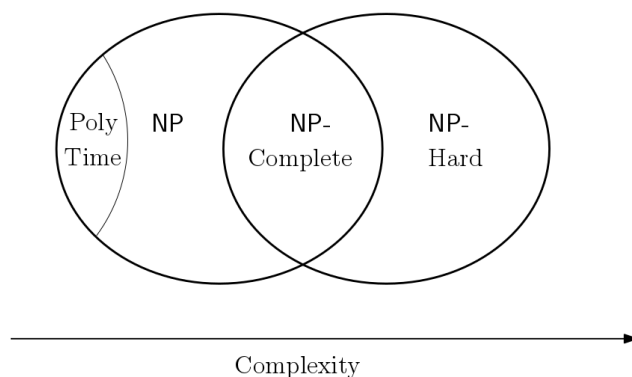


Figure 5.1: Illustration of the relationships between the classes NP, NP-hard, and NP-complete. “Poly-time” refers to problems with polynomial time solutions. Such algorithms can trivially be verified in polynomial time, hence are a subset of problems in NP. We emphasize that the diagram is for intuitive purposes only, and may not reflect the true relationships between these classes. For example, in the unlikely case that  $P=NP$  (i.e., all problems in NP are solvable in polynomial time), then the regions “Poly time”, NP and NP-complete coincide.

**The complexity classes NP, NP-hard, and NP-Complete.** For brevity, we restrict ourselves to a very brief presentation of these concepts. The interested reader can find more background in any reference on computational complexity theory.

The class NP is the set of all decision problems<sup>3</sup> which have solutions which are *verifiable* in polynomial time. It is possible, for example, to check in polynomial time whether a given set is in fact an independent set of a certain size. Thus the decision variant of INDEPENDENT-SET lies in NP. NP stands for “non-deterministic polynomial time”, as it is formally the set of all decision problems solvable by a non-deterministic Turing Machine [Pap03].

The class NP-hard comprises all the problems to which any problem in NP can be reduced in polynomial time (see above). That is,  $P \in \text{NP-hard}$  iff for all  $Q \in \text{NP}$ ,  $Q$  can be reduced to  $P$  in polynomial time. Thus, to show that  $P \in \text{NP-hard}$ , it suffices to reduce another problem  $R \in \text{NP-hard}$  to  $P$  (in polynomial time) since, in this case, if all problems in NP are reducible to  $R$  they are in turn reducible to  $P$ . We tend to think of NP as the set of “hard” problems.

Finally, the class NP-complete is the intersection of the classes NP and NP-hard. Informally then, it is the class of all “hard” decision problems.

## §5.2. Computational Complexity

In this section we investigate the relationships between problems in one domain—either the graph-theoretic or geometric domain—and their analogues in the other. The following result exemplifies the power of the graph-simplex correspondence in yielding results which seem otherwise to be difficult to obtain (certainly more difficult than the following proof, at any rate). The following

<sup>3</sup>That is, problems to which we seek a yes/no answer.



result was first stated by Devriendt and Van Mieghem [DVM18], although it was stated only for inverse simplices of graphs. We observe that it can be generalized as follows.

**LEMMA 5.1.** *Computing the altitude of minimum length in a hyperacute polytope is NP-hard. Consequently, computing the minimum length altitude in general polyhedra is NP-hard.*

*Proof.* The relationship  $\|\mathbf{a}(\mathcal{S}_U^+)\|_2^2 = w(\partial U)^{-1}$  (Lemma 3.15) for the inverse simplex of a graph  $G$  demonstrates that the problem of computing a minimum length altitude in any hyperacute simplex is NP-hard, because computing the maximum weight cut in any weighted graph is NP-hard [Kar72]. Since the class of convex polytopes contains the class of hyperacute simplices, the result follows.  $\square$

*Remark 5.1.* In the above statement and its proof, the description of the polytope and simplex was not specified. This is due to the fact that—as discussed above—for simplices there is a polynomial time algorithm to translate between the various descriptions. With regard to NP-completeness therefore, the description makes no difference. Consequently, we will continue to ignore this distinction for the remainder of this section.

*Remark 5.2.* As exemplified by the statement of Lemma 5.1 the fact that a problem is NP-hard for hyperacute simplices immediately implies that it is so for general polyhedra (since simplices are a subclass of polyhedra). We will still, however, often state a result in terms of general polyhedra because it seems most likely to be useful in this form.

The remainder of this section is dedicated to obtaining more results of this type.

We begin by investigating independent sets. Given a graph  $G = (V, E, w)$ , recall that an *independent set* is a subset  $I \subseteq V$  such that if  $i, j \in I$  then  $(i, j) \notin E$ . The weight of an independent set is nicely described by the Laplacian quadratic form. If  $I$  is an independent set note that

$$\text{vol}(I) = w(\partial I),$$

and so

$$\mathcal{L}(\chi_I) = \sum_{i \sim j} w(i, j)(\chi_I(i) - \chi_I(j))^2 = \sum_{i \in I} \sum_{j: j \sim i} w(i, j) = \sum_{i \in I} w(i) = w(\partial I),$$

where the second and fourth inequalities follows from the fact that  $I$  is an independent set. Now, suppose we assign each vertex  $i$  a weight  $f(i) \geq 0$ . The MAX-WEIGHT INDEPENDENT-SET problem consists of maximizing  $f(I) \stackrel{\text{def}}{=} \sum_{i \in I} f(i)$  over all independent sets  $I$ . Clearly MAX-WEIGHT INDEPENDENT-SET is NP-hard in general, seeing as it reduces to the usual independent set maximization problem by taking  $f(i) = 1$  for all  $i$ . If  $f$  is a linear function of the weights so that  $f(i) = \alpha w(i)$  for all  $i$  and some  $\alpha > 0$ , we call the corresponding problem  $\alpha$ -VERTEX-WEIGHTED INDEPENDENT-SET. We will focus on the case  $\alpha = 1$  for clarity, and call the corresponding problem just VERTEX-WEIGHTED INDEPENDENT-SET. The difficulty of this problem is not immediately

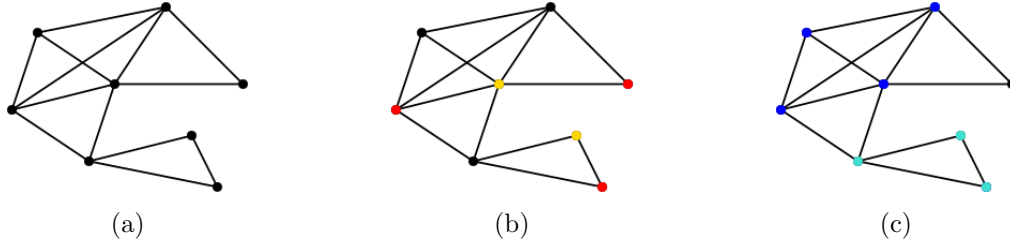


Figure 5.2: (a) A connected graph. (b) Two of its independent sets; one in red (dark) and one yellow (light). The red set constitutes a maximum sized independent set. (c) Two of its cliques; one in blue (dark), one turquoise (light). The blue set constitutes a maximum sized clique.

clear, since it is more structured than simply MAX-WEIGHT INDEPENDENT-SET. The next lemma removes any doubt as to the problem's tractability.

LEMMA 5.2. VERTEX-WEIGHTED INDEPENDENT-SET is NP-Complete.

*Proof.* Given a purported independent  $I$ , it is easily checkable in polynomial time whether  $\text{vol}(I)$  is of a certain size—hence VERTEX-WEIGHTED INDEPENDENT-SET is in NP. To that it is NP-hard, we reduce from INDEPENDENT-SET. Let  $G = (V(G), E(G))$  and  $k \in \mathbb{N}$  be an instance of INDEPENDENT-SET. The intuition behind the following reduction is to create a separate graph  $H$  which, for each independent set  $I \subseteq V(G)$ , has an independent set  $J$  in  $H$  such that  $\text{vol}_H(J) = |I|$  in  $H$  and conversely, for each maximal independent set  $J$  in  $H$  there exists an independent set  $I$  in  $G$  with  $|I| = \text{vol}_H(J)$ . From this relationship it follows that  $G, k$  constitutes a yes instance to INDEPENDENT-SET iff  $H, k$  is a yes instance to MAX-WEIGHT INDEPENDENT-SET. After wordsmithing the intuition, let us proceed to the formal argument.

Construct a graph  $H = (V(H), E(H))$  as follows. For each vertex  $u \in V(G)$ , create  $\deg_G(u) + 1$  vertices  $u_0, u_1, \dots, u_{\deg_G(u)}$  in  $V(H)$ . For  $1 \leq k \leq \deg_G(u)$  set

$$w_H(u_k) = \frac{1}{\deg_G(u)}.$$

Construct the edge set  $E(H)$  such that the neighbours of each vertex are described by

$$\partial_H(u_k) = \{u_0\} \cup \bigcup_{v \in \partial_G(u)} \{v_\ell : 0 \leq \ell \leq \deg_G(v)\}.$$

In words,  $u_k$  is connected to all the vertices representing  $v$  if  $(u, v) \in E(G)$ , and to  $u_0$ . Now, let  $I \subseteq V(G)$  be an independent set in  $G$  and consider the set

$$J = \{v_k : v \in I, 1 \leq k \leq \deg_G(v)\}.$$

We claim that  $J$  is an independent set in  $H$ . Indeed, if  $v_k, u_\ell \in J$  and  $(v_k, u_\ell) \in E(H)$  for some  $k \in [\deg_G(v)]$ ,  $\ell \in [\deg_G(u)]$  then  $v \in d_G(u)$  by definition of  $\partial_H(u)$ . Since  $I$  is an independent

set however, both  $u$  and  $v$  are not in  $I$ , a contradiction. This demonstrates that  $J$  is bonafide independent set. Moreover,

$$\text{vol}_H(J) = \sum_{v \in I} \sum_{k=1}^{\deg_G(u)} w_H(v_k) = \sum_{v \in I} \sum_{k=1}^{\deg_G(u)} \frac{1}{\deg_G(u)} = |I|.$$

Conversely, let  $J$  be an independent set in  $H$ . We claim that there exists an independent  $J'$  in  $H$  with  $\text{vol}_H(J') \geq \text{vol}_H(J)$  containing only vertices of the form  $v_\ell$  for  $\ell \geq 1$ , i.e., not  $v_0$ . Initially, set  $J' = J$  but suppose  $v_0 \in J$ . Replace  $v_0$  by  $v_1, \dots, v_{\deg_G(v)}$  in  $J'$ . None of these vertices share edges, and aside from one another,  $v_\ell$  and  $v_0$  for  $\ell > 0$  have the same edge set. It follows that  $J'$  remains an independent set. Moreover, since  $w_H(v_0) < w_H(v_\ell)$  by construction, we have  $\text{vol}_H(J) < \text{vol}_H(J')$ . Let us remark further that if  $J$  contains vertices  $\{v_\ell\}_{\ell \in F}$  for some  $F \subsetneq [\deg_G(v)]$ , then we may add the missing vertices  $v_k$ ,  $k \in [\deg_G(v)] \setminus F$  while maintaining the property that  $J$  is an independent set (this follows since  $\partial_H(v_k) = \partial_H(v_\ell)$  for all  $\ell, k \geq 1$ ). We have thus argued that every maximal independent set in  $H$  can be written in the form  $J = \cup_{v \in I} \{v_k : 1 \leq k \leq \deg_G(v)\}$  for some set  $I \subseteq V(G)$ . We now claim that  $I$  is an independent set in  $G$ . The argument is similar to above: If not, then  $u, v \in I$  with  $u \sim v$ , but this implies that  $v_k \sim v_\ell$  in  $H$  meaning that  $J$  is not an independent set. Additionally, as above,  $\text{vol}_H(J) = |I|$ . Therefore, there exists an independent set  $J$  in  $H$  with  $\text{vol}_H(J) \geq k$  iff there exists an independent set  $I$  in  $G$  with  $|I| \geq k$ , concluding the argument.  $\square$

This result allows us to conclude that certain optimization problems in hyperacute simplices—thus convex polytopes in general—are NP-hard.

LEMMA 5.3. *Let  $\mathcal{P}$  be a convex polytope with vertex set  $V$ . The optimization problem*

$$\begin{aligned} \min_{I \subseteq V, I \neq \emptyset} \quad & \frac{\|c(\mathcal{P}_I)\|_2^2}{|I|} \\ \text{s.t.} \quad & \langle \sigma_i, \sigma_j \rangle = 0, \quad i, j \in I, \end{aligned}$$

*is NP-hard. In particular, it is NP-hard whenever  $\mathcal{P}$  is the combinatorial simplex of a graph.*

*Proof.* Let  $\mathcal{P}$  be the combinatorial simplex of a graph  $G$ . Using that  $\langle \sigma_i, \sigma_j \rangle = w(i, j)$ , the condition that  $\langle \sigma_i, \sigma_j \rangle = 0$  for all  $i, j \in I$  translates to  $(i, j) \in E(G)$  for all  $i, j \in I$ . Moreover, Equation (3.14) in Section 3.4 gives us

$$\frac{|I|}{\|c(\mathcal{S}_I)\|_2^2} = w_G(\partial I) = \text{vol}(I),$$

for  $I$  an independent set. The above optimization problem can consequently be formulated as

$$\max_{I \subseteq V(G)} \text{vol}_G(I), \quad \text{s.t.} \quad I \text{ is an independent set.}$$

which is precisely the VERTEX-WEIGHTED INDEPENDENT-SET problem.  $\square$

We can play a similar game by using the relationships furnished by the normalized Laplacian as opposed to the combinatorial Laplacian. Doing this removes the normalizing factor of  $|I|$  from the optimization problem in the previous result.

LEMMA 5.4. *Let  $\mathcal{P}$  be a convex polytope with vertex set  $V$ . The optimization problem*

$$\begin{aligned} \min_{I \subseteq V, I \neq \emptyset} \quad & \|c(\mathcal{P}_I)\|_2^2 \\ \text{s.t.} \quad & \langle \sigma_i, \sigma_j \rangle = 0, \quad i, j \in I, \end{aligned}$$

*is NP-hard. In particular, it is hard for those polytopes and simplices with all vertices on the unit sphere.*

*Proof.* The proof is similar to the previous lemma. For  $\mathcal{P}$  the normalized simplex of a graph  $G$ , the condition  $\langle \sigma_i, \sigma_j \rangle = 0$  once again implies that  $I$  must be an independent set. Notice that for such an  $I$ , if  $i \in I$  then  $\partial(i) \cap I^c = \partial(i)$  (none of  $i$ 's neighbours are in  $I$ ). Therefore, Equation (3.18) yields

$$\widehat{\mathcal{L}}(\chi_I) = \sum_{i \in I} \frac{1}{w(i)} \sum_{j \in I^c \cap \partial(i)} w(i, j) = \sum_{i \in I} \frac{w(i)}{w(i)} = |I|.$$

Equation (3.19) then implies that

$$\|c(\mathcal{P}_I)\|_2^2 = \frac{1}{|I|^2} \widehat{\mathcal{L}}_G(\chi_I) = \frac{1}{|I|},$$

so the optimization problem can be formulated as

$$\max_{I \subseteq V(G)} |I|, \quad \text{s.t.} \quad I \text{ is an independent set,}$$

which is the INDEPENDENT-SET problem.  $\square$

A *clique* in a graph  $G$  is a complete subgraph of  $G$ . The MAX-CLIQUE problem asks, given  $G$ , what is the largest  $k$  such that  $G$  has a clique of size  $k$ ? Its decision version variant, K-CLIQUE, has parameters  $G$  and  $k$ , and asks whether  $G$  has a clique of size  $k$ . Karp [Kar72] demonstrated that K-CLIQUE  $\in$  NP and MAX-CLIQUE  $\in$  NP-hard.

LEMMA 5.5. *Given a polytope in either V-description or H-description, consider finding a subset  $U$  of the vertices such that none of the vertices in  $U$  are orthogonal. The optimization version of these problem is NP-hard while the decision variant is NP-complete, even in the case of hyperacute simplices.*

*Proof.* The optimization version corresponds to MAX-CLIQUE while the decision variant corresponds to K-CLIQUE via the correspondence.  $\square$

Next we extract a result based on the most (in)famous problem in computational graph theory: Graph isomorphism. An *isomorphism* between two graphs  $G_1$  and  $G_2$  is a bijection  $f : V(G_1) \rightarrow V(G_2)$  such that  $(u, v) \in E(G_1)$  iff  $(f(u), f(v)) \in E(G_2)$ . We write  $G_1 \cong G_2$  if  $G_1$  is isomorphic to  $G_2$ . The GRAPH-ISOMORPHISM problem asks, given  $G_1, G_2$  whether they are isomorphic. It's clear that GRAPH-ISOMORPHISM  $\in$  NP, but whether it is NP-complete remains an open question [MP14]. László Babai recently claims to have solved the problem in quasipolynomial time [Bab16]; the work is still being verified. Accordingly, we call a problem *Graph Isomorphism Hard* if it can be reduced to GRAPH-ISOMORPHISM. The more general problem of *subgraph* isomorphism, which asks whether  $G_1$  has a subgraph isomorphic to  $G_2$ , is NP-complete [Coo71, Kar72]. We are interested in the relationship between graph isomorphism and polytope congruence.

**THEOREM 5.1.** *Deciding whether two hyperacute simplices are congruent is Graph Isomorphism Hard. Moreover, given two hyperacute simplices  $\mathcal{S}_1 \in \mathbb{R}^d$  and  $\mathcal{S}_2 \in \mathbb{R}^k$ , deciding whether there exists  $k$ -dimensional face of  $\mathcal{S}_1$  congruent to  $\mathcal{S}_2$  is NP-hard.*

*Proof.* Let two graphs  $G_1$  and  $G_2$  be given. Compute their corresponding inverse simplices  $\mathcal{S}_1^+$  and  $\mathcal{S}_2^+$ . We claim that  $\mathcal{S}_1^+ \cong \mathcal{S}_2^+$  iff  $G_1 \cong G_2$ . If  $\mathcal{S}_1^+ \cong \mathcal{S}_2^+$  then because they are both centred at the origin there exists a rotation matrix  $\mathbf{Q}$  such that  $\mathbf{Q}\Sigma_1^+ = \Sigma_2^+$ . Since a rotation matrix does not change the relationship between the inner product of vectors<sup>4</sup>, we see that  $(\Sigma_1^+)^t \Sigma_1^+$  and  $(\Sigma_2^+)^t \Sigma_2^+$  define the same Laplacian. Hence  $G_1$  is isomorphic to  $G_2$ . Conversely, if  $G_1 \cong G_2$ , then there exists a relabelling of the vertices such that their Laplacian matrices are identical, as are the simplices. The second part of the statement follows by a similar reduction, and the fact that SUBGRAPH-ISOMORPHISM  $\in$  NP-complete.  $\square$

Kaibel and Schwarz [KS08] investigated the problem of polytope isomorphism. They define two polytopes is isomorphic if they have the same *face-lattice*—the lattice in which the nodes correspond to subsets of the vertices, and the lattice ordering is by face inclusion. Since congruent simplices share the same face lattice up to labelling, Theorem 5.1 implies their result.

### §5.3. There and Back Again: A Tale of Graphs and Simplices

In this section we investigate the computational aspects of transitioning between the various objects which we've studied thus far. As one should expect given that the mapping between graphs and simplices relies on the eigenvalues and eigenvectors of graph Laplacians, the complexity of these transitions is intimately related with the complexity of computing eigendecompositions. Moreover, as we will see, if we are prepared to compute eigendecompositions (which is essentially cubic), then

<sup>4</sup>A rotation matrix  $\mathbf{Q}$  obeys  $\mathbf{Q}^t \mathbf{Q} = \mathbf{I}$ , hence  $\langle \mathbf{Q}\mathbf{u}, \mathbf{Q}\mathbf{v} \rangle = \mathbf{u}^t \mathbf{Q}^t \mathbf{Q} \mathbf{v} = \langle \mathbf{u}, \mathbf{v} \rangle$ .

we can essentially compute all the objects from one another. We thus begin with a foray into the computational complexity of eigendecompositions, as we will be mostly interested in circumstances in which a transition can be computed in less time than this. Unfortunately, it will become clear that the complexity of computing a Laplacian eigendecomposition is actually a lower bound to many of the transitions.

Let  $M(n)$  denote the complexity of the eigendecomposition problem. It is known that  $M(n) = \tilde{\Omega}(n^3 + n \log^2 \log \epsilon)$  to obtain a relative error<sup>5</sup> of  $2^{-\epsilon}$ , while there exists algorithms which run in time  $O(n^3 + n \log^2 \log \epsilon)$  [PC99]. Let LAPLACIAN EIGENDECOMPOSITION refer to the problem of computing the eigendecomposition of the Laplacian of a graph, i.e., computing its eigenvalues and eigenvectors. The complexity of LAPLACIAN EIGENDECOMPOSITION does not seem to be known, and we thus denote the lower bound by  $\Omega(n^\tau)$  for some  $\tau$ . We will assume, based on the difficulty of general eigendecomposition that  $\tau > 2$ .

Now, observe that given  $G$ , we can compute the combinatorial and normalized Laplacians (and their inverses) by first constructing the combinatorial or normalized Laplacian in  $O(n^2)$ , performing an eigendecomposition in time  $O(n^\tau)$ , and constructing the vertices of the simplices from the eigenvalues and eigenvectors in time  $O(n^2)$ . Using our assumption that  $\tau > 2$ , this takes total time  $O(n^\tau)$ . Moreover, starting with a simplex with vertex set  $\Sigma$ , one can compute  $\Sigma^t \Sigma$  in the time required for matrix multiplication, which is currently  $O(n^{2.3727})$  [Wil12] and whose lower bound is  $\Theta(n^\kappa)$  for some  $2 \leq \kappa \leq 2.3727$  [Sto10]. If the simplex is the simplex of a graph then this yields the Laplacian (or its pseudoinverse) of the graph in time  $O(n^{2.3727})$ , and from here to any of its simplices in time  $O(n^\tau)$ . Hence, we can transition between the various simplices in time  $O(n^{\max\{2.3727, \tau\}})$ . In what follows therefore, we attempt to beat the barrier of  $O(n^\tau)$ .

Another question in which we might be interested is one of *certification*. That is, verifying whether a given simplex is one of the combinatorial or normalized simplices of a graph. We will investigate this possibility at the end of this section.

We begin by investigating the relationship between  $\mathcal{S}$  and  $\hat{\mathcal{S}}$ , when either  $\mathcal{S}$  or  $\hat{\mathcal{S}}$  are given and we are told a priori that they are the simplices of a graph. The results obtained in this section are summarized in Figure 5.3.

**Between  $\mathcal{S}$  and  $\hat{\mathcal{S}}$ .** Let us consider the computational complexity of transitioning between  $\mathcal{S}$  and  $\hat{\mathcal{S}}$  and vice versa. Let  $\phi_{ij}$  (resp.,  $\hat{\phi}_{ij}$ ) be the angle between  $\sigma_i$  and  $\sigma_j$  (resp.,  $\hat{\sigma}_i$  and  $\hat{\sigma}_j$ ). Using the typical formula for the dot product in Euclidean space we have

$$\cos \phi_{ij} = \frac{\langle \sigma_i, \sigma_j \rangle}{\|\sigma_i\|_2 \|\sigma_j\|_2} = \frac{L_G(i, j)}{\sqrt{w(i)w(j)}} = \hat{L}_G(i, j), \quad \text{and} \quad \cos \hat{\phi}_{ij} = \frac{\langle \hat{\sigma}_i, \hat{\sigma}_j \rangle}{\|\hat{\sigma}_i\|_2 \|\hat{\sigma}_j\|_2} = \hat{L}_G(i, j),$$

<sup>5</sup>We note that the relative error is a necessary parameter of any algorithm because eigenvalues may be irrational.

		V				H			
From/To	$G$	$\mathcal{S}_G$	$\mathcal{S}_G^+$	$\widehat{\mathcal{S}}_G$	$\widehat{\mathcal{S}}_G^+$	$\mathcal{S}_G$	$\mathcal{S}_G^+$	$\widehat{\mathcal{S}}_G$	$\widehat{\mathcal{S}}_G^+$
	$G$	—	$\Omega(n^\tau)$	$\Omega(n^\tau)$	$\Omega(n^\tau)$	$\Omega(n^\tau)$	$\Omega(n^\tau)$		
V	$\mathcal{S}_G$	$O(n^3)$	—	$\Omega(n^\tau)$	$O(n^2)$		$\Omega(n^\tau)$	$O(1)$	
	$\mathcal{S}_G^+$		$\Omega(n^\tau)$	—			$O(1)$	$\Omega(n^\tau)$	
	$\widehat{\mathcal{S}}_G$		? / $O(n^2)$		—	$\Omega(n^\tau)$			
	$\widehat{\mathcal{S}}_G^+$				$\Omega(n^\tau)$	—			
H	$\mathcal{S}_G$		$\Omega(n^\tau)$	$O(n^2)$			—	$\Omega(n^\tau)$	
	$\mathcal{S}_G^+$		$O(n^2)$	$\Omega(n^\tau)$			$\Omega(n^\tau)$	—	
	$\widehat{\mathcal{S}}_G$								—
	$\widehat{\mathcal{S}}_G^+$								—

Figure 5.3: Summary of results for precise mappings. A slash refers to a difference in runtimes when the graph is available versus when it isn't. The quantity before the slash indicates the runtime *without* the graph, after the slash the runtime *with* the graph. A question mark indicates that the runtime isn't known.

using that  $\|\widehat{\sigma}_i\|_2 = 1$  for all  $i$ . That is, the angles between vertices in  $\mathcal{S}$  in  $\widehat{\mathcal{S}}$  are the same. Suppose we are given the simplex  $\mathcal{S}$  and told it is the combinatorial simplex of a graph. For each  $\sigma_i = \Sigma(\mathcal{S})$ , define a new vertex

$$\gamma_i = \frac{\sigma_i}{\|\sigma_i\|_2}.$$

Is it evident that the angle between  $\gamma_i$  and  $\gamma_j$  is identical to that between  $\sigma_i$  and  $\sigma_j$ :

$$\frac{\langle \gamma_i, \gamma_j \rangle}{\|\gamma_i\|_2 \|\gamma_j\|_2} = \left\langle \frac{\sigma_i}{\|\sigma_i\|_2}, \frac{\sigma_j}{\|\sigma_j\|_2} \right\rangle = \cos(\phi_{ij}).$$

Therefore, it follows that the simplex with vertices is congruent to  $\widehat{\mathcal{S}}$ . This yields the following result.

LEMMA 5.6. *Given a combinatorial simplex  $\mathcal{S}$ , a simplex congruent to  $\widehat{\mathcal{S}}$  can be computed in time  $O(n^2)$ .*

*Proof.* Given  $\mathcal{S}$ , define the vertices  $\gamma_i$  as above. Computing  $\|\sigma_i\|_2$  takes time  $O(n)$  and must be done for each vertex.  $\boxtimes$

Given the relative ease with which we can transition from  $\mathcal{S}$  to  $\widehat{\mathcal{S}}$ , it is somewhat surprising that it is much more difficult to transition from  $\widehat{\mathcal{S}}$  to  $\mathcal{S}$ , especially if the underlying graph  $G$  is not given. The obvious tactic is, given the vertices  $\{\widehat{\sigma}_i\}$ , to define vertices  $\widehat{\sigma}_i \sqrt{w(i)}$ , which, since

$\sqrt{w(i)} = \|\sigma_i\|_2$ , have the same magnitude as  $\sigma_i$ . As above, the scaling does not affect the angle between the vertices, and thus the simplex with these vertices is congruent to  $\mathcal{S}$ . However, it's not clear how to obtain the value  $\sqrt{w(i)}$  from  $\hat{\mathcal{S}}$ . Using that  $\langle \hat{\sigma}_i, \hat{\sigma}_j \rangle = (w(i)w(j))^{-1/2}$  we can write

$$w(i)^{1/2} = - \sum_{j \neq i} w(j)^{-1/2} \bigg/ \sum_{j \neq i} \langle \hat{\sigma}_i, \hat{\sigma}_j \rangle,$$

which yields a non-linear system of equations.

Of course, if we are given the graph then we have access to  $\sqrt{w(i)}$  and can compute  $\hat{\sigma}_i w(i)^{1/2}$  in time  $O(n)$ . The following result is then immediate.

**LEMMA 5.7.** *Given a graph  $G = (V, E, w)$  and its normalized simplex  $\hat{\mathcal{S}}_G$ , a simplex congruent to the combinatorial simplex  $\mathcal{S}_G$  can be computed in  $O(n^2)$  time.*

**$\mathcal{S}$  and  $\mathcal{S}^+$ .** Let us suppose that we can generate  $\mathcal{S}^+$  from  $\mathcal{S}$  (or vice versa) in time  $O(g(n))$ . Note that for  $i < n$ ,

$$\lambda_i = \frac{\lambda_i^{1/2} \varphi_j(i)}{\lambda_i^{-1/2} \varphi_j(i)} = \frac{\sigma_i(j)}{\sigma_i^+(j)}, \quad \text{and} \quad \varphi_i(j) = \frac{\sigma_j(i)}{\lambda_i^{1/2}},$$

hence knowledge of  $\{\sigma_i\}$  and  $\{\sigma_i^+\}$  yields knowledge of the eigendecomposition of the underlying graph  $G$  in  $O(n^2)$  time ( $O(n)$  to determine all the eigenvalues and  $O(n^2)$  to determine the eigenvectors). The same argument holds *mutatis mutandis* for the normalized Laplacian.

**LEMMA 5.8.** *If a V-description of  $\mathcal{S}^+$  (resp.,  $\hat{\mathcal{S}}^+$ ) can be generated from a V-description of  $\mathcal{S}$  (resp.,  $\hat{\mathcal{S}}$ ) or vice versa in time  $O(g(n))$ , then LAPLACIAN EIGENDECOMPOSITION can be solved in time  $O(g(n) + n^2)$  for arbitrary weighted graphs. Consequently  $g(n) = \Omega(n^\tau)$ .*

An alternate way of seeing that constructing the inverse simplex from its dual is computationally challenging is to recall from Section 3.4 that  $\mathcal{S}_{\{i\}^c}$  is contained in the hyperplane  $\{\mathbf{x} \in \mathbb{R}^{n-1} : \langle \mathbf{x}, \sigma_i^+ \rangle = -1/n\}$  (Lemma 3.10) and that that  $\sigma_i^+$  is perpendicular to  $\mathcal{S}_{\{i\}^c}$  (Lemma 3.5). Hence, computing the inverse simplex would imply that we had computed normal vectors to  $n$  hyperplanes, the typical procedure for which typically involves computing an  $n \times n$  determinant and requires  $O(n^3)$  time.

We now consider transitioning between different descriptions of  $\mathcal{S}$  and  $\mathcal{S}^+$ . Let us recall that the H-description of  $\mathcal{S}$  and  $\mathcal{S}^+$  yield immediate insight into the vertices of its inverse as  $\mathcal{S} = \cap_i \{\mathbf{x} : \langle \mathbf{x}, \sigma_i^+ \rangle \geq -1/n\}$  and  $\mathcal{S}^+ = \cap_i \{\mathbf{x} : \langle \mathbf{x}, \sigma_i \rangle \geq -1/n\}$  (Equations (3.8) and (3.9)). Consequently, given a H-description of one of these simplices, the vertices of its inverse are recoverable in quadratic time. This yields the following result.

**LEMMA 5.9.** *Suppose that in time  $t(n)$  we can compute an H-description of  $\mathcal{S}$  (resp.,  $\mathcal{S}^+$ ) given its V-description. Then a V-description of  $\mathcal{S}^+$  (resp.,  $\mathcal{S}$ ) is recoverable in time  $t(n) + O(n^2)$ , implying by Lemma 5.8 that  $t(n) = \Omega(n^\tau)$ .*



We also note that a consequence of the relationship between the vertices of  $\mathcal{S}$  and the H-description of  $\mathcal{S}^+$  that given V-description of  $\mathcal{S}$  or  $\mathcal{S}^+$ , we have immediate access to the H-description of its inverse.

A similar result for going from between the H-description of the combinatorial simplices. The argument runs as usual: Given an H-description of  $\mathcal{S}$ , suppose we can generate an H-description of  $\mathcal{S}^+$  in time  $t(n)$ . We can obtain the vertices  $\{\sigma_i^+\}$  from the H-description of  $\mathcal{S}$ , and the vertices  $\{\sigma_i\}$  from the H-description of  $\mathcal{S}^+$ . Using these, we can then obtain the eigendecomposition of  $G$  in time  $O(n^2)$ . That is, we can solve LAPLACIAN EIGENDECOMPOSITION in time  $t(n) + O(n^2)$  yielding that  $t(n) = \Omega(n^\tau)$ .

LEMMA 5.10. *Generating an H-description of  $\mathcal{S}_G$  given an H-description of  $\mathcal{S}_G^+$ , and vice versa, requires time  $\Omega(n^\tau)$ .*

**Between  $G$  and  $\mathcal{S}$  or  $\widehat{\mathcal{S}}$ .** Similar kinds of results hold in these cases. Assume that we obtain the simplex  $\mathcal{S}_G$  from  $G$ . Notice that

$$\sum_{i=1}^{n-1} \sigma_i(j)^2 = \lambda_j \sum_{i=1}^{n-1} \varphi_j(i) = \lambda_j \left(1 - \frac{1}{n}\right),$$

so

$$\lambda_j = \frac{\sum_{i=1}^{n-1} \sigma_i(j)}{1 - 1/n},$$

which can be computed in  $O(n)$  time. Then, as above, knowledge of the eigenvalues furnishes knowledge of the eigenvectors in  $O(n^2)$  time. Running almost identical arguments for  $\mathcal{S}^+$ ,  $\widehat{\mathcal{S}}$ , or  $\widehat{\mathcal{S}}^+$  yields an almost equivalent result as in the previous section.

LEMMA 5.11. *If either the combinatorial or normalized simplex or their inverses can be generated from a graph  $G$  in  $O(g(n))$  time, then LAPLACIAN EIGENDECOMPOSITION can be solved in time  $O(g(n) + n^2)$  for arbitrary weighted graphs. Consequently  $g(n) = \Omega(n^\tau)$ .*

The information encoded in the dot products between vertices allow us to make queries regarding the edge weights, but each query takes  $O(n)$  time since we must compute a dot product between two vectors of length  $n - 1$ . Hence, re-constructing the graph or its Laplacian takes  $O(n^3)$  if we wish do it precisely.

Let us now consider transitioning between  $G$  and the H-description of a simplex. The following lemma summarizes the consequences of this relationship.

LEMMA 5.12. *Given a graph  $G$  suppose an H-description of  $\mathcal{S}$  (resp.,  $\mathcal{S}^+$ ) can be generated in time  $g(n)$ . Then a V-description of  $\mathcal{S}^+$  (resp.,  $\mathcal{S}$ ) can be obtained in time  $O(g(n) + n^2)$  starting from  $G$ . Consequently, by Lemma 5.11,  $g(n) = \Omega(n^\tau)$ .*

**Between different descriptions of the simplices.** Here we investigate the interplay between the various different descriptions of the simplices.

The following is an immediate consequence of Lemma 3.23.

**COROLLARY 5.1.** *If  $\mathcal{T}$  is a centred simplex in H-description, we can obtain a V-description of  $\mathcal{T}^D$  in quadratic time. In particular, given an H-description of the combinatorial simplex  $\mathcal{S}_G$  (resp., inverse combinatorial simplex  $\mathcal{S}_G^+$ ) of a graph  $G$ , a V-description of  $\mathcal{S}_G^+$  (resp.,  $\mathcal{S}_G$ ) is obtainable in quadratic time.*

Due to the fact that  $\widehat{\mathcal{S}}_G^+$  is not the dual of  $\widehat{\mathcal{S}}_G$  Lemma 3.23 is less useful here.

**LEMMA 5.13.** *Generating an V-description of the simplex  $\mathcal{S}$  given its H-description requires time  $\Omega(n^\tau)$  for any  $\mathcal{S} \in \{\mathcal{S}_G, \mathcal{S}_G^+\}$ .*

*Proof.* Consider  $\mathcal{S}_G$ ; the argument is similar for  $\mathcal{S}_G^+$ . Suppose obtaining the H-description takes time  $t(n)$ . Due to the properties of the hyperplane representations, this yields access to both sets of vertices in time  $t(n) + O(n^2)$ . Using the arithmetic in the previous section, this implies that we can obtain the eigenvalues and eigenvectors of  $G$  in time  $O(n^2)$ , i.e., we can solve LAPLACIAN EIGENDECOMPOSITION in time  $t(n) + O(n^2)$  implying that  $t(n) = \Omega(n^\tau)$ .  $\square$

**Verification.** We now turn to discussing the complexity of verifying whether a given simplex is the simplex of graph. In time  $O(n^{2.3727})$  we can compute  $\Sigma^t \Sigma$ . We can check whether this is equal to  $\mathbf{L}_G$  for some  $G$  by verifying whether (i)  $\Sigma^t \Sigma \mathbf{1} = \mathbf{0}$ , (ii)  $(\Sigma^t \Sigma)(i, i) > 0$  for all  $i$  and (iii)  $(\Sigma^t \Sigma)(i, j) \leq 0$  for all  $i \neq j$ . These three steps require time  $O(n^3)$ . We can check whether  $\Sigma^t \Sigma$  is equal to  $\widehat{\mathbf{L}}_G$  for some  $G$  by first ensuring, similarly to above, that (iii) holds and that  $(\Sigma^t \Sigma)(i, i) = 1$  for all  $i$ . Then we compute the kernel of  $\Sigma^t \Sigma$  in cubic time by means of Gaussian elimination [KS99] to obtain a vector  $\mathbf{v}$  equal to  $\sqrt{w_G}$  (if indeed  $\Sigma^t \Sigma = \widehat{\mathbf{L}}_G$ ) up to scaling. To determine whether  $\mathbf{v}$  does represent valid weightings of the vertices, we check whether  $(\Sigma^t \Sigma)(i, j)\mathbf{v}(j)$  is constant for all  $i$ . In this case  $\Sigma^t \Sigma$  is equal to the normalized Laplacian of some graph. This can also be done in cubic time. We therefore see that we can verify whether a given simplex is the combinatorial or normalized simplex of a graph in cubic time. It's not clear whether it can be done faster, however.

Finally, we note that in cubic time we can check whether all the angles  $\theta_{ij}$  between the faces  $\mathcal{T}_{\{i\}^c}$  and  $\mathcal{T}_{\{j\}^c}$  are non-obtuse, in which case  $\mathcal{T}$  is the inverse simplex of some graph.

## §5.4. Approximations

Here we are concerned with approximations of various sorts. We begin with an eye towards the problem of dimensionality. Specifically, Theorem 3.1 yields simplices of dimension  $n - 1$  for a graph on  $n$  vertices. In many application areas, graphs may have thousands to millions of vertices. Working in a Euclidean space of this size can be unwieldy. Our first two sections, therefore,

attempt dimensionality reduction. The first considers the problem of reducing the dimensionality of the simplex itself. The second considers low rank approximations of the Laplacian which are shown to yield polytopes on  $n$  vertices. We see that, depending on the rank of the approximation and the eigenvalues of the Laplacian, certain properties of this polytope approximate those of the simplex. This provides some theoretical justification for the recent work of Torres *et al.* [TCER19].

#### 5.4.1. Dimensionality Reduction: $S^+$

The idea is to map each vertex to a point in  $\mathbb{R}^d$ , for  $d \ll n$ , while maintaining the general form of the simplex. By this we mean that we'd like the distance between the new points to remain approximately as they were. If possible, we'd also like to new, lower dimensional object (note that it won't be a simplex because there will be  $n$  points in  $\mathbb{R}^d$ ) to retain some of the properties which relate it to the underlying graph. In particular, we'd like the gram matrix of the new points to approximate the gram matrix of the original set of points. As it turns out, a mapping meeting both of these criteria exists and is computable in polynomial time. It will rely on the Johnson-Lindenstrauss (JL) Lemma [JL84, DG03].

**THEOREM 5.2 (Johnson-Lindenstrauss).** *Let  $\mathcal{X} \subseteq \mathbb{R}^k$  be a set of  $n$  points, for some  $k \in \mathbb{N}$ . For any  $\epsilon > 0$  and  $d \geq 8 \log(n)\epsilon^{-2}$  there exists a map  $g_\epsilon : \mathbb{R}^k \rightarrow \mathbb{R}^d$  such that*

$$(1 - \epsilon)\|\mathbf{u} - \mathbf{v}\|_2^2 \leq \|g_\epsilon(\mathbf{u}) - g_\epsilon(\mathbf{v})\|_2^2 \leq (1 + \epsilon)\|\mathbf{u} - \mathbf{v}\|_2^2,$$

for all  $\mathbf{u}, \mathbf{v} \in \mathcal{X}$ .

Now, let us suppose we have the vertices  $\{\sigma_i^+\}$  of the inverse simplex. Let  $\mathcal{X} = \{\sigma_i^+\} \cup \{\mathbf{0}\}$ . Apply the JL Lemma to  $\mathcal{X}$  to obtain  $n + 1$  points in  $\mathbb{R}^d$ , for  $d = O(\log(n)/\epsilon^2)$ . Let  $f$  be the mapping, e.g.,  $\sigma_i^+$  is sent to  $f(\sigma_i^+)$ . By JL, have

$$(1 - \epsilon)\|\mathbf{x} - \mathbf{y}\|_2^2 \leq \|f(\mathbf{x}) - f(\mathbf{y})\|_2^2 \leq (1 + \epsilon)\|\mathbf{x} - \mathbf{y}\|_2^2,$$

for all  $\mathbf{x}, \mathbf{y} \in \{\sigma_1^+, \dots, \sigma_n^+, \mathbf{0}\}$ . Apply a linear transformation to the points so that  $f(\mathbf{0})$  coincides with the origin  $\mathbf{0} \in \mathbb{R}^d$ . Note that this does not affect the distances between the points themselves, and does not damage the approximation. Update  $f$  to reflect this transformation. For all  $i, j$ , let  $\epsilon_{i,j}$  denote the true error of the mapping, i.e.,

$$\left\|f(\sigma_i^+) - f(\sigma_j^+)\right\|_2^2 = (1 + \epsilon_{i,j})\left\|\sigma_i^+ - \sigma_j^+\right\|_2^2,$$

where  $|\epsilon_{i,j}| \leq \epsilon$ . Define  $\epsilon_{i,\mathbf{0}}$  similarly. Then,

$$\|f(\sigma_i^+)\|_2^2 = \|f(\sigma_i^+) - f(\mathbf{0})\|_2^2 = (1 + \epsilon_{i,\mathbf{0}})\|\sigma_i^+\|_2^2 = (1 + \epsilon_{i,\mathbf{0}})\mathbf{L}_G^+(i, i),$$

hence,

$$\begin{aligned}\|f(\boldsymbol{\sigma}_i^+) - f(\boldsymbol{\sigma}_j^+)\|_2^2 &= \langle f(\boldsymbol{\sigma}_i^+) - f(\boldsymbol{\sigma}_j^+), f(\boldsymbol{\sigma}_i^+) - f(\boldsymbol{\sigma}_j^+) \rangle \\ &= \|f(\boldsymbol{\sigma}_i^+)\|_2^2 + \|f(\boldsymbol{\sigma}_j^+)\|_2^2 - 2\langle f(\boldsymbol{\sigma}_i^+), f(\boldsymbol{\sigma}_j^+) \rangle,\end{aligned}$$

implying that

$$\begin{aligned}\langle f(\boldsymbol{\sigma}_i^+), f(\boldsymbol{\sigma}_j^+) \rangle &= -\frac{1}{2} \left( (1 + \epsilon_{i,j}) \|\boldsymbol{\sigma}_i^+ - \boldsymbol{\sigma}_j^+\|_2^2 - (1 + \epsilon_{i,o}) \mathbf{L}_G^+(i, i) - (1 + \epsilon_{j,o}) \mathbf{L}_G^+(j, j) \right) \\ &= -\frac{1}{2} ((1 + \epsilon_{i,j}) r(i, j) - (1 + \epsilon_{i,o}) \mathbf{L}_G^+(i, i) - (1 + \epsilon_{j,o}) \mathbf{L}_G^+(j, j)) \\ &= -\frac{1}{2} ((1 + \epsilon_{i,j}) (\mathbf{L}_G^+(i, i) - \mathbf{L}_G^+(j, j) - 2\mathbf{L}_G^+(i, j)) \\ &\quad - (1 + \epsilon_{i,o}) \mathbf{L}_G^+(i, i) - (1 + \epsilon_{j,o}) \mathbf{L}_G^+(j, j)) \\ &= (1 + \epsilon_{i,j}) \mathbf{L}_G^+(i, j) + \varepsilon(i, j),\end{aligned}$$

where

$$\varepsilon(i, j) \stackrel{\text{def}}{=} \frac{1}{2} (\epsilon_{i,o} - \epsilon_{i,j}) \mathbf{L}_G^+(i, i) + (\epsilon_{j,o} - \epsilon_{i,j}) \mathbf{L}_G^+(i, j),$$

is an error term dictated by  $\epsilon_{i,j}$ ,  $\epsilon_{i,o}$  and  $\epsilon_{j,o}$ . Setting  $M = \max_i \mathbf{L}_G^+(i, i)$  we can bound the error term via repeated applications of the triangle inequality:

$$\begin{aligned}|\varepsilon(i, j)| &\leq \frac{1}{2} \left( |(\epsilon_{i,o} - \epsilon_{i,j}) \mathbf{L}_G^+(i, i)| + |(\epsilon_{j,o} - \epsilon_{i,j}) \mathbf{L}_G^+(i, j)| \right) \\ &\leq \frac{1}{2} \left( [|\epsilon_{i,j}| + |\epsilon_{i,o}|] \mathbf{L}_G^+(i, i) + [|\epsilon_{i,j}| + |\epsilon_{j,o}|] \mathbf{L}_G^+(j, j) \right) \\ &\leq \frac{1}{2} (2\epsilon \mathbf{L}_G^+(i, i) + 2\epsilon \mathbf{L}_G^+(j, j)) \leq \epsilon M,\end{aligned}$$

since  $|\epsilon_{i,j}|, |\epsilon_{i,o}|, |\epsilon_{j,o}| \leq |\epsilon|$ . Setting  $f(\boldsymbol{\Sigma}^+) = (f(\boldsymbol{\sigma}_1^+), \dots, f(\boldsymbol{\sigma}_n^+)) \in \mathbb{R}^{d \times n}$ , this approximation implies that

$$\mathbf{L}_G^+ - O(\epsilon M) \mathbf{I} \leq f(\boldsymbol{\Sigma}^+)^t f(\boldsymbol{\Sigma}^+) \leq \mathbf{L}_G^+ + O(\epsilon M) \mathbf{I}.$$

In other words, we can approximately recover the Gram matrix  $\mathbf{L}_G^+ = \boldsymbol{\Sigma}^+ \boldsymbol{\Sigma}^+$  using the lower dimensional matrix  $f(\boldsymbol{\Sigma}^+)$ .

The JL mapping maintains other approximate information of the graph. For example, it is well-known that the effective resistance between two vertices is related to the probability that this edge is in a random spanning tree as

$$r^{\text{eff}}(i, j) = \frac{1}{w(i, j)} \Pr_{T \sim \mu} [(i, j) \in T],$$

where  $\mu$  is the uniform distribution over all spanning trees [BP93]. Hence,

$$\left\| f(\sigma_i^+) - f(\sigma_j^+) \right\|_2^2 \in \frac{1}{w(i, j)} [(1 - \epsilon), (1 + \epsilon)] \Pr_{T \sim \mu} [(i, j) \in T].$$

#### 5.4.2. Dimensionality Reduction: $L_G$

In Section 5.4.1, we asked how to reduce the dimension of the simplex while (approximately) maintaining several of its properties. However, we might instead reduce the dimensionality of the Laplacian. This section explores this prospect.

Let us suppose the we have obtained a low rank— $k$ , say—approximation of  $L_G$ , written  $L_k$ . We might then ask several questions:

1. Is  $L_k$  still a gram matrix? That is, can  $L_k$  be written  $\tilde{\Sigma}^t \tilde{\Sigma}$  where  $\tilde{\Sigma}$  is the vertex matrix of some set of points,  $P = \{p_1, \dots, p_\ell\}$ ? If so, what is the relationship between  $\Sigma$  and  $\tilde{\Sigma}$ , where  $\Sigma = \Sigma(\mathcal{S}_G)$  is the usual vertex matrix of the combinatorial simplex of  $G$ ? If  $L_k$  has rank  $k$  then  $P$  spans a subspace of dimension  $k$  and  $\text{conv}(P)$  forms a polytope in that space. What is the relationship between the geometry of  $\text{conv}(P)$  and  $\mathcal{S}_G$ ?
2. Is  $L_k$  useful in helping estimate properties of the simplex  $\mathcal{S}_G$ ? For example, if one could bound the difference in the quadratic products of  $L_G$  and  $L_k$ , this would imply (via the results in Section 3.4) that we could estimate many of the properties of  $\mathcal{S}_G$ .

Of course, we have chosen to work with  $L_G$  and  $\mathcal{S}_G$  for convenience; we could have asked the same questions of  $\hat{L}_G$  and  $\hat{\mathcal{S}}_G$ .

We begin by considering the natural rank- $k$  approximation to  $L_G$ :

$$L_k \stackrel{\text{def}}{=} \sum_{i=1}^k \lambda_k \varphi_k \varphi_k^t,$$

where we recall that we've ordered the eigenvalues as  $\lambda_1 \geq \lambda_2 \geq \dots \lambda_{n-1} > \lambda_n = 0$ . Clearly  $L_k$  has rank  $k$ . It is, moreover, a symmetric PSD matrix. Section 3.1 thus yields the polytope  $\mathcal{P}_k \stackrel{\text{def}}{=} \mathcal{P}_{L_k}$  associated with  $L_k$ . More explicitly, if  $\Lambda_k = \text{diag}(\lambda_1, \dots, \lambda_k)$  is the diagonal matrix containing the first  $k$  eigenvalues (meaning those associated with  $\lambda_1, \dots, \lambda_k$ ) and  $\Phi_k = (\varphi_1 \dots \varphi_k)$ , then  $L_k$  is the Gram matrix of the vertices described by the matrix  $\Sigma_k = \Lambda_k^{1/2} \Phi_k^t = (\sigma_1^{(k)}, \dots, \sigma_n^{(k)})$  where  $\sigma_i^{(k)} = (\varphi_1(i) \lambda_1^{1/2}, \dots, \varphi_k(i) \lambda_k^{1/2})$ . Let us emphasize that we are using the subscript  $(k)$  to signify that these vertices are those belonging to  $\mathcal{P}_k$ .

To summarize, the rank  $k$  approximation to  $L_G$ ,  $L_k$  yields an  $n$ -vertex polytope  $\mathcal{P}_k \subseteq \mathbb{R}^k$ . Naturally, one would hope that  $\mathcal{P}_k$  “approximates” various features of  $\mathcal{S}_G$ , as it is precisely  $\mathcal{S}_G$  projected onto a particular  $k$ -dimensional subspace. The next few results demonstrate that this is true under certain assumptions placed on the distribution of the eigenvalues.

The first property worth noticing is that  $\mathcal{P}_k$  remains centred at the origin. Indeed,  $\mathbf{c}(\mathcal{P}_k) = \frac{1}{n} \mathbf{\Sigma}_k \mathbf{1} = \frac{1}{n} \mathbf{\Lambda}_k^{1/2} \mathbf{\Phi}_k^t \mathbf{1} = \mathbf{0}_k$ . Next, we might wonder whether the lengths of the centroids to different faces are similar in  $\mathcal{S}_G$  and  $\mathcal{P}_k$ . Fix  $U \subseteq [n]$  and compute

$$\begin{aligned} \left| \|\mathbf{c}(\mathcal{S}_G[U])\|_2^2 - \|\mathbf{c}(\mathcal{P}_k[U])\|_2^2 \right| &= \frac{1}{|U|^2} \left| \chi_U^t \mathbf{\Sigma}^t \mathbf{\Sigma} \chi_U - \chi_U^t \mathbf{\Sigma}_k^t \mathbf{\Sigma}_k \chi_U \right| \\ &= \frac{1}{|U|^2} \left| \chi_U^t (\mathbf{L}_G - \mathbf{L}_k) \chi_U \right| \\ &= \frac{1}{|U|^2} \left| \chi_U^t \left( \sum_{i \in [n-1]} \lambda_i \varphi_i \varphi_i^t - \sum_{i \in [k]} \lambda_i \varphi_i \varphi_i^t \right) \chi_U \right| \\ &\leq \frac{1}{|U|^2} \sum_{i=k+1}^{n-1} |\lambda_i \chi_U^t \varphi_i \varphi_i^t \chi_U| = \frac{1}{|U|^2} \sum_{i=k+1}^{n-1} \langle \chi_U, \varphi_i \rangle^2, \end{aligned}$$

where, by Cauchy-Schwarz,  $\langle \chi_U, \varphi_i \rangle^2 \leq \|\chi_U\|_2^2 \|\varphi_i\|_2^2 = |U|^2$ , hence

$$\left| \|\mathbf{c}(\mathcal{S}_G[U])\|_2^2 - \|\mathbf{c}(\mathcal{P}_k[U])\|_2^2 \right| \leq \sum_{i=k+1}^{n-1} \lambda_i \leq \lambda_{k+1} (n - (k+1)). \quad (5.1)$$

Thus, if  $\lambda_k$  is sufficiently small as a function of  $n$  and  $k$ , the lengths of the centroids are approximately equal. We summarize with the following Lemma.

LEMMA 5.14. *If  $\lambda_{k+1} = o((n-k)^{-1})$ , then  $\left| \|\mathbf{c}(\mathcal{S}_G[U])\|_2^2 - \|\mathbf{c}(\mathcal{P}_k[U])\|_2^2 \right| = o(1)$ .*

*Proof.* Assume  $\lambda_k = o((n-k)^{-1})$  and apply Equation (5.1). \(\square\)

Remark 5.3. The above result should seem intuitively plausible. How well  $\mathbf{L}_k$  approximates  $\mathbf{L}_G$  relies precisely on the size of  $\lambda_k$ . We should thus expect the same to be true of  $\mathcal{P}_k$  and  $\mathcal{S}_G$ .

Next, we investigate the relative distances between the vertex vectors.

$$\begin{aligned} \left| \|\sigma_i - \sigma_j\|_2^2 - \|\sigma_i^{(k)} - \sigma_j^{(k)}\|_2^2 \right| &= \left| \sum_{\ell \in [n-1]} (\sigma_i(\ell) - \sigma_j(\ell))^2 - \sum_{\ell \in [k]} (\sigma_i(\ell) - \sigma_j(\ell))^2 \right| \\ &= \left| \sum_{\ell \in [n-1]} \lambda_\ell (\varphi_\ell(i) - \varphi_\ell(j))^2 - \sum_{\ell \in [k]} \lambda_\ell (\varphi_\ell(i) - \varphi_\ell(j))^2 \right| \\ &= \left| \sum_{\ell=k+1}^{n-1} \lambda_\ell (\varphi_\ell(i) - \varphi_\ell(j))^2 \right| \\ &\leq \lambda_{k+1} \sum_{\ell=k+1}^{n-1} |\varphi_\ell(i) - \varphi_\ell(j)|^2. \end{aligned}$$

The goal is thus to bound the final summation in terms of some function of  $n$  or  $k$ , so that we may provide sufficient conditions on  $\lambda_{k+1}$  in order for  $\left\| \boldsymbol{\sigma}_i^{(k)} - \boldsymbol{\sigma}_j^{(k)} \right\|_2^2$  to approximate  $\left\| \boldsymbol{\sigma}_i - \boldsymbol{\sigma}_j \right\|_2^2$ . We proceed as follows.

$$\begin{aligned}
 \sum_{\ell=k+1}^{n-1} |\boldsymbol{\varphi}_\ell(i) - \boldsymbol{\varphi}_\ell(j)|^2 &= \left| \sum_{\ell=k+1}^{n-1} |\boldsymbol{\varphi}_\ell(i) - \boldsymbol{\varphi}_\ell(j)|^2 \right| \\
 &= \left| \sum_{\ell=k+1}^{n-1} \boldsymbol{\varphi}_\ell(i)^2 + \boldsymbol{\varphi}_\ell(j)^2 - 2\boldsymbol{\varphi}_\ell(i)\boldsymbol{\varphi}_\ell(j) \right| \\
 &\leq \sum_{\ell=k+1}^{n-1} \boldsymbol{\varphi}_\ell(i)^2 + \sum_{\ell=k+1}^{n-1} \boldsymbol{\varphi}_\ell(j)^2 + 2 \left| \sum_{\ell=k+1}^{n-1} \boldsymbol{\varphi}_\ell(i)\boldsymbol{\varphi}_\ell(j) \right| \\
 &\leq \sum_{\ell=k+1}^{n-1} \boldsymbol{\varphi}_\ell(i)^2 + \sum_{\ell=k+1}^{n-1} \boldsymbol{\varphi}_\ell(j)^2 + 2 \left( \sum_{\ell=k+1}^{n-1} \boldsymbol{\varphi}_\ell(i)^2 \sum_{m=k+1}^{n-1} \boldsymbol{\varphi}_m(j)^2 \right)^{1/2} \\
 &\leq \sum_{\ell \in [n]} \boldsymbol{\varphi}_\ell(i)^2 + \sum_{\ell \in [n]} \boldsymbol{\varphi}_\ell(j)^2 + 2 \left( \sum_{\ell \in [n]} \boldsymbol{\varphi}_\ell(i)^2 \sum_{m=k+1}^{n-1} \boldsymbol{\varphi}_m(j)^2 \right)^{1/2}.
 \end{aligned}$$

Now, recall that due to double orthogonality of the eigenvector matrix we have  $\sum_{\ell=1}^n \boldsymbol{\varphi}_\ell(i)\boldsymbol{\varphi}_\ell(j) = \delta_{ij}$ . The above quantity is therefore equal to 6. Consequently, combining the previous few equations yields

$$\left\| \boldsymbol{\sigma}_i - \boldsymbol{\sigma}_j \right\|_2^2 - \left\| \boldsymbol{\sigma}_i^{(k)} - \boldsymbol{\sigma}_j^{(k)} \right\|_2^2 \leq 6\lambda_{k+1} = O(\lambda_{k+1}).$$

LEMMA 5.15. *If  $\lambda_{k+1} = o(1)$  then  $\left\| \boldsymbol{\sigma}_i - \boldsymbol{\sigma}_j \right\|_2^2 - \left\| \boldsymbol{\sigma}_i^{(k)} - \boldsymbol{\sigma}_j^{(k)} \right\|_2^2 = o(1)$ .*

Summarizing, we see that under assumptions on the sizes of the eigenvalues (which relates directly to how good of an approximation  $\mathbf{L}_k$  is to  $\mathbf{L}_G$ ), the features of the polytope  $\mathcal{P}_k$  will approximate those of  $\mathcal{S}_G$ . As we stated previously, this could help explain in part the success of the experiments run by Torres *et al.* [TCER19]. In their work, they assume they are given  $\mathcal{P}_k$  and attempt to reconstruct certain graph features, most notably its connectivity. Since the connectivity of a graph is related to the centroids of  $\mathcal{S}_G$  (Section 3.4), if  $k$  is sufficiently small then the centroids  $\mathcal{P}_k$  will recover this connectivity.

### 5.4.3. Distance Matrix of $\mathcal{S}_G^+$

We end with a brief section which demonstrates that we can leverage several results from the literature on Laplacian optimization to approximate the distance matrix of  $\mathcal{S}_G^+$ . An elegant result of Spielman and Srivastava [SS11] allows to build a matrix which approximately represents the effective resistances.

THEOREM 5.3 ([SS11]). *For any  $\epsilon > 0$  and graph  $G = (V, E, w)$ , there exists an algorithm which*

computes a matrix  $\tilde{\mathbf{R}} \in \mathbb{R}^{O(\log(n)\epsilon^{-2}) \times n}$  such that

$$(1 - \epsilon)r(i, j) \leq \left\| \tilde{\mathbf{R}}(\mathbf{x}_i - \mathbf{x}_j) \right\|_2^2 \leq (1 + \epsilon)r(i, j).$$

The algorithm runs in time  $\tilde{O}(|E| \log(r)/\epsilon^2)$ , where

$$r = \frac{\max_{i,j} w(i, j)}{\min_{i,j} w(i, j)}.$$

Therefore, given a graph  $G = (V, E, w)$ , we use the algorithm of Theorem 5.3 to compute all the approximate distances  $\left\| \boldsymbol{\sigma}_i^+ - \boldsymbol{\sigma}_j^+ \right\|_2^2 = r^{\text{eff}}(i, j)$  in time

$$\tilde{O}(|E| \log(r)/\epsilon^2) + O(|E| \log(n)/\epsilon^2) = \tilde{O}(|E|/\epsilon^2),$$

assuming  $r = O(1)$ . Note that we can compute a single effective resistance in time  $O(\log n/\epsilon^2)$ , since it involves simply computing the  $\ell_2$  norm the vector  $\tilde{\mathbf{R}}(\mathbf{x}_i - \mathbf{x}_j)$  which is simply the difference of two columns of  $\tilde{\mathbf{R}}$ .



## Conclusion

*One has to belong to the intelligentsia to believe things like that: no ordinary man could be such a fool.*

— George Orwell, Notes on Nationalism

*One must imagine Sisyphus happy.*

— Albert Camus, The Myth of Sisyphus.

This dissertation has expounded and expanded upon the graph-simplex correspondence, which associates with each connected, weighted graph  $G$  four simplices:  $\mathcal{S}_G$ ,  $\mathcal{S}_G^+$  (the combinatorial simplices),  $\widehat{\mathcal{S}}_G$ , and  $\widehat{\mathcal{S}}_G^+$  (the normalized simplices). Presenting and building on the previous work of Fiedler [Fie93, Fie11] and Devriendt and Van Mieghem [DVM18], we have seen the synthesis of the geometry of these simplices with properties of the graph. In particular, we have seen that

1. The geometry of  $\mathcal{S}_G$  is closely related to the connectivity of  $G$ , the geometry of  $\mathcal{S}_G^+$  is related to the effective resistance of  $G$ , while its volume is inversely proportional to the total weight of spanning trees in  $G$ ;
2. Matrix equations can be used to relate the graph to the simplex, thus yielding new insights into both objects.

We also explored the algorithmic underpinnings of the correspondence, and established that

3. transitioning between various objects in the correspondence (exactly) typically takes cubic time;
4. the correspondence can be used to help classify the computational complexity of geometric problems; and
5. There exist low dimensional approximations to the simplices which approximately maintain their Gram matrix relations, and low rank approximations to the Laplacian which yield low dimensional polytopes which approximate the geometry of  $\mathcal{S}_G$  and  $\mathcal{S}_G^+$ .

The main goal, however, was not to achieve any particular results but rather to demonstrate the utility of the graph-simplex correspondence as a tool with which to analyze graphs. We hope we have succeeded in our role as evangelist and convinced the reader to include the correspondence in their mathematical toolkit. We end by listing several possible directions for future work.

### §6.1. Open Problems and Future Directions

We believe there are several exciting avenues for further research.

- In Section 5.2 we gave several examples of how various graph theoretic problems translate to the simplex and vice versa, and examined what implications this had for computational complexity. Due to time and space constraints we were unable to fully explore this area; and it seems likely that we have left many results untapped. For example, we mostly explored how specific NP-complete graph problems translated to NP-complete polyhedral problems. It could be fruitful to explore the converse. More importantly for possible applications, problems which are easy (meaning, solvable in polynomial time) in one domain may have analogues in the other, which would result in new polynomial time algorithms.
- While we gave implicit conditions on the dual of  $\widehat{\mathcal{S}}_G$  and  $\widehat{\mathcal{S}}_G^+$ , we were unable to give their explicit equations. It would be desirable to discover what these are.
- In Section 5.4.3 it was noted that the distance matrix of  $\mathcal{S}_G^+$  can be approximated. It would be interesting to explore whether it's possible to use this to generate an approximate embedding of  $\mathcal{S}_G^+$ . The connection between  $\mathcal{S}_G^+$  and the resistive polytope (Section 4.5) might be of use here.
- Section 4.2 deals mostly with block equations concerning the normalized simplex  $\mathcal{S}_G$  and Laplacian  $L_G$ . It could be fruitful to explore whether similar equations hold for the other simplices.

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## Omitted Proofs

### §A.1. Chapter 2

*Proof of Observation 2.1.* We begin by proving uniqueness. Suppose  $\{\mathbf{u}_i\}$  and  $\{\mathbf{w}_i\}$  are both biorthogonal bases of  $\{\mathbf{v}_i\}$ . We will show that  $\mathbf{u}_i = \mathbf{w}_i$  for all  $i$ . Fix  $i \in [n]$ . By independence,  $\text{span}(\mathbf{v}_1, \dots, \mathbf{v}_{i-1}, \mathbf{v}_{i+1}, \dots, \mathbf{v}_n)$  is a hyperplane—that is,

$$\dim \text{span}(\mathbf{v}_1, \dots, \mathbf{v}_{i-1}, \mathbf{v}_{i+1}, \dots, \mathbf{v}_n)^\perp = 1.$$

(Recall that we are working in  $\mathbb{R}^n$  and with bases thereof.) Both  $\mathbf{u}_i$  and  $\mathbf{w}_i$  are orthogonal to this hyperplane (since they are orthogonal to  $\mathbf{v}_j$  for all  $j \neq i$ ), thus are either parallel or anti-parallel. Therefore, there exists some  $\alpha \in \mathbb{R}$  such that  $\mathbf{v}_i = \alpha \mathbf{w}_i$ . By definition,  $\langle \mathbf{v}_i, \mathbf{u}_i \rangle = \langle \mathbf{v}_i, \mathbf{w}_i \rangle = 1$ , hence  $\langle \mathbf{v}_i, \alpha \mathbf{w}_i \rangle = \langle \mathbf{v}_i, \mathbf{w}_i \rangle$  implying that  $\alpha = 1$ . This demonstrates that  $\mathbf{u}_i = \mathbf{w}_i$  for all  $i$ .

Next we demonstrate that  $\mathbf{Q}^t = \mathbf{M}^{-1}$  where  $\mathbf{Q} = (\mathbf{u}_1, \dots, \mathbf{u}_n)$  and  $\mathbf{M} = (\mathbf{v}_1, \dots, \mathbf{v}_n)$ . By the orthogonality relationships of dual bases, we have

$$\mathbf{Q}^t \mathbf{M} = \begin{pmatrix} \mathbf{u}_1^t \\ \vdots \\ \mathbf{u}_n^t \end{pmatrix} \begin{pmatrix} \mathbf{v}_1 & \dots & \mathbf{v}_n \end{pmatrix} = \begin{pmatrix} \langle \mathbf{u}_1, \mathbf{v}_1 \rangle & \dots & \langle \mathbf{u}_1, \mathbf{v}_n \rangle \\ \vdots & \ddots & \vdots \\ \langle \mathbf{u}_n, \mathbf{v}_1 \rangle & \dots & \langle \mathbf{u}_n, \mathbf{v}_n \rangle \end{pmatrix} = \mathbf{I}_n.$$

Observing that  $\mathbf{M}^{-1}$  exists by independence of  $\{\mathbf{v}_1, \dots, \mathbf{v}_n\}$  we apply it to both sides of the above to obtain  $\mathbf{Q}^t = \mathbf{M}^{-1}$ . □

*Proof of Lemma 2.2.* It suffices to show that  $\dim \ker \mathbf{Q} = \dim \ker \mathbf{Q}^t \mathbf{Q}$ , by rank-nullity. Clearly  $\ker \mathbf{Q} \subseteq \ker \mathbf{Q}^t \mathbf{Q}$  since  $\mathbf{Q} \mathbf{f} = \mathbf{0}$  implies  $\mathbf{Q}^t \mathbf{Q} \mathbf{f} = \mathbf{0}$ . Conversely, if  $\mathbf{Q}^t \mathbf{Q} \mathbf{f} = \mathbf{0}$  then  $0 = \mathbf{f}^t \mathbf{Q}^t \mathbf{Q} \mathbf{f} = \|\mathbf{Q} \mathbf{f}\|_2^2$ , implying that  $\mathbf{Q} \mathbf{f} = \mathbf{0}$ . □

*Proof of Lemma 2.5.* Put  $\mathbf{Q} = \sum_{i=1}^k \lambda_i^{-1} \boldsymbol{\varphi}_i \boldsymbol{\varphi}_i^t$ . Since the pseudoinverse is unique, it suffices to show that  $\mathbf{Q}$  satisfies the condition of Definition 2.1. Since the eigenvectors are orthonormal by assumption,  $\boldsymbol{\varphi}_i^t \boldsymbol{\varphi}_j = \delta_{i,j}$  for all  $i, j$ . Hence,

$$\mathbf{M} \mathbf{Q} = \sum_{i=1}^k \lambda_i \boldsymbol{\varphi}_i \boldsymbol{\varphi}_i^t \sum_{j=1}^k \lambda_j^{-1} \boldsymbol{\varphi}_j \boldsymbol{\varphi}_j^t = \sum_{i,j=1}^k \lambda_i \lambda_j^{-1} \boldsymbol{\varphi}_i \boldsymbol{\varphi}_i^t \boldsymbol{\varphi}_j \boldsymbol{\varphi}_j^t$$



$$= \sum_{i=1}^k \lambda_i \lambda_i^{-1} \varphi_i \varphi_i^t \varphi_i \varphi_i^t = \sum_{i=1}^k \varphi_i \varphi_i^t = \mathbf{Q}M.$$

Performing a similar computation then demonstrates that

$$M\mathbf{Q}M = \sum_{i=1}^k \varphi_i \varphi_i^t \sum_{j=1}^k \lambda_j \varphi_j \varphi_j^t = \sum_{i,j=1}^k \lambda_i \varphi_i \varphi_i^t \varphi_j \varphi_j^t = \sum_{i=1}^k \lambda_i \varphi_i \varphi_i^t = M,$$

and similarly,  $\mathbf{Q}M\mathbf{Q} = \mathbf{Q}$ . Moreover,  $\varphi_i \varphi_i^t(k, \ell) = \varphi_i(k) \varphi_i(\ell) = \varphi_i(\ell) \varphi_i(k) = (\varphi_i \varphi_i^t)^t(k, \ell)$  implying that  $\varphi_i \varphi_i^t = (\varphi_i \varphi_i^t)^t$ , so

$$(\mathbf{Q}M)^t = (M\mathbf{Q})^t = \left( \sum_{i=1}^k \varphi_i \varphi_i^t \right)^t = \sum_{i=1}^k (\varphi_i \varphi_i^t)^t = \sum_{i=1}^k \varphi_i \varphi_i^t = M\mathbf{Q} = \mathbf{Q}M,$$

so both required conditions hold, and we conclude that  $\mathbf{Q} = M^+$ .  $\square$

*Proof of Lemma 2.7.* By definition

$$\mathbf{R}_G(i, j) = \chi_i^t \mathbf{L}_G^+ \chi_i + \chi_j^t \mathbf{L}_G^+ \chi_j - 2\chi_i^t \mathbf{L}_G^+ \chi_j = \mathbf{L}_G^+(i, i) + \mathbf{L}_G^+(j, j) - 2\mathbf{L}_G^+(i, j),$$

whence

$$\mathbf{R}_G = \mathbf{1}\mathbf{u}^t + \mathbf{u}\mathbf{1}^t - 2\mathbf{L}_G^+,$$

(where we recall that  $\mathbf{u} = \text{diag}(\mathbf{L}_G^+(i, i))$ ). From here we see that  $\mathbf{x}^t \mathbf{R}_G \mathbf{x} = -2\mathbf{x}^t \mathbf{L}_G^+ \mathbf{x}$  for any  $\mathbf{x} \in \text{span}(\mathbf{1})^\perp$ . Therefore,

$$\begin{aligned} \mathbf{L}_G^+(i, j) &= \chi_i^t \mathbf{L}_G^+ \chi_j \\ &= \left( \chi_i - \frac{1}{n} \mathbf{1} \right)^t \mathbf{L}_G^+ \left( \chi_j - \frac{1}{n} \mathbf{1} \right) \\ &= -\frac{1}{2} \left( \chi_i - \frac{1}{n} \mathbf{1} \right)^t \mathbf{R}_G \left( \chi_j - \frac{1}{n} \mathbf{1} \right) \\ &= \frac{1}{2n} \left( \sum_{k \in [n]} r^{\text{eff}}(i, k) + r^{\text{eff}}(j, k) \right) - \frac{1}{2} r^{\text{eff}}(i, j) - \frac{R_G}{n^2}. \end{aligned} \quad \square$$

*Proof of Lemma 2.6.* Focus for the moment on the combinatorial Laplacian  $\mathbf{L}_G$ , with eigenvalues  $\lambda_1 \geq \lambda_2 \geq \dots \geq \lambda_n$  and corresponding orthonormal eigenfunctions  $\varphi_1, \dots, \varphi_n$ . It is a straightforward consequence of Equation (??) is that all eigenvalues of  $\mathbf{L}_G$  are non-negative. Let  $\lambda$  be an eigenvalue with (unit) eigenvector  $\varphi$ . Then,

$$\lambda = \lambda \langle \varphi, \varphi \rangle = \langle \lambda \varphi, \varphi \rangle = \langle \mathbf{L}_G \varphi, \varphi \rangle = \langle \mathbf{B}_G^t \mathbf{B}_G \varphi, \varphi \rangle = \langle \mathbf{B}_G \varphi, \mathbf{B}_G \varphi \rangle = \|\mathbf{B}_G \varphi\|_2^2 \geq 0.$$

Now, suppose  $\mathbf{L}_G \varphi = \mathbf{0}$ . Then  $\varphi^t \mathbf{L}_G \varphi = \mathcal{L}(\varphi) = 0$ , which implies that  $\varphi(i) = \varphi(j)$  for all  $i, j \in V_\ell$ .

We can immediately see that any vector in  $\text{span}(\mathbf{1})$  satisfies this condition. On the other hand, consider a non-zero vector  $\boldsymbol{\varphi}$  which is orthogonal to  $\mathbf{1}$ . Then

$$0 = \sum_{i=1}^k \langle \boldsymbol{\varphi}, \boldsymbol{\chi}_{V_i} \rangle = \langle \boldsymbol{\varphi}, \mathbf{1} \rangle = \sum_{i=1}^k \varphi(i),$$

implying that there exists  $\ell \in [k]$  such that  $\varphi(i) \neq \varphi(j)$  for some  $i, j \in V_\ell$ . Hence,  $\mathcal{L}(\boldsymbol{\varphi}) > 0$  and so  $\mathbf{L}\boldsymbol{\varphi} \neq \mathbf{0}$ . Therefore, there are no other linearly independent eigenfunctions corresponding to the zero eigenvalue. We have thus shown that 0 is an eigenvalue of  $\mathbf{L}$  with multiplicity one, and  $\ker(\mathbf{L}) = \text{span}(\mathbf{1})$ .

A similar analysis holds for the normalized Laplacian. Using the same argument but replacing  $\mathbf{B}$  with  $\widehat{\mathbf{B}}$  demonstrates that its eigenvalues are non-negative. Its kernel can be determined as follows. For any eigenfunction  $\boldsymbol{\varphi}$  of  $\mathbf{L}$  corresponding to the zero eigenvalue, observe that

$$\widehat{\mathbf{L}}\mathbf{W}^{1/2}\boldsymbol{\varphi} = \mathbf{W}^{-1/2}\mathbf{L}\mathbf{W}^{-1/2}\mathbf{W}^{1/2}\boldsymbol{\varphi} = \mathbf{W}^{-1/2}\mathbf{L}\boldsymbol{\varphi} = \mathbf{0},$$

so  $\mathbf{W}^{1/2}\mathbf{1}$  lies in the kernel of  $\widehat{\mathbf{L}}$ . Conversely, if  $\boldsymbol{\varphi} \in \ker(\widehat{\mathbf{L}})$ , define  $\boldsymbol{\varphi}'$  such that  $\boldsymbol{\varphi} = \mathbf{W}^{1/2}\boldsymbol{\varphi}'$  (this is possible because  $\mathbf{W}^{1/2}$  is diagonal—we simply factor out  $\sqrt{w(i)}$  from  $\varphi(i)$  to obtain  $\varphi'(i)$ ). Then

$$\mathbf{0} = \widehat{\mathbf{L}}\boldsymbol{\varphi}' = \mathbf{W}^{-1/2}\mathbf{L}\mathbf{W}^{-1/2}\mathbf{W}^{1/2}\boldsymbol{\varphi} = \mathbf{W}^{-1/2}\mathbf{L}\boldsymbol{\varphi},$$

so  $\mathbf{L}\boldsymbol{\varphi} = \mathbf{0}$  (since  $w(i) > 0$  for all  $i$ ). That is, each element in the kernel of  $\widehat{\mathbf{L}}$  takes the form  $\mathbf{W}^{1/2}\boldsymbol{\varphi}$  for  $\boldsymbol{\varphi} \in \ker(\mathbf{L})$ . We conclude that  $\ker(\widehat{\mathbf{L}}) = \text{span}(\sqrt{\mathbf{w}})$ .  $\square$

*Proof of Lemma 2.8.* Throughout the proof let  $R = R_G^{\text{tot}}$ . We need to show that

$$-\frac{1}{2} \begin{pmatrix} 0 & \mathbf{1}_n^t \\ \mathbf{1}_n & \mathbf{R} \end{pmatrix} \begin{pmatrix} \Delta^t \mathbf{L}_G \Delta + \frac{4}{n^2} R & -(\mathbf{L}_G \Delta + \frac{2}{n} \mathbf{1})^t \\ -(\mathbf{L}_G \Delta + \frac{2}{n} \mathbf{1}) & \mathbf{L}_G \end{pmatrix} = \mathbf{I}.$$

Multiplying out the left hand side, the top left-hand corner of the resulting block matrix is

$$-\frac{1}{2}(\mathbf{1}^t \mathbf{L}_G - \frac{2}{n} \mathbf{1}^t \mathbf{1}) = 1,$$

since  $\mathbf{1}^t \mathbf{L}_G = \mathbf{1}^t \mathbf{L}_G^t = \mathbf{0}$ . Likewise the top-right hand corner is  $\mathbf{0}$ . The bottom left-hand corner is

$$-\frac{1}{2} \left( \mathbf{1} \Delta^t \mathbf{L}_G \Delta + \frac{4}{n^2} R \mathbf{1} - \mathbf{R} \mathbf{L}_G \Delta - \frac{2}{n} \mathbf{R} \mathbf{1} \right), \quad (\text{A.1})$$

where, using that  $\mathbf{R} = \Delta \mathbf{1}^t + \mathbf{1} \Delta^t - 2\mathbf{L}_G^+$  and  $\mathbf{1}^t \mathbf{L}_G = \mathbf{0}$ ,

$$\mathbf{R} \mathbf{L}_G = \mathbf{1} \Delta^t \mathbf{L}_G - 2 \left( \mathbf{I} - \frac{1}{n} \mathbf{J} \right). \quad (\text{A.2})$$

Observing that  $\Delta(i) = \mathbf{L}_G^+(i, i) = \frac{1}{n}(\mathbf{R}\mathbf{1})(i) - R/n^2$  due to Lemma 2.7, write

$$\Delta = \frac{1}{n}\mathbf{R}\mathbf{1} - \frac{R}{n^2}\mathbf{1} = \frac{1}{n}\mathbf{R}\mathbf{1} - \frac{1}{2n^2}\mathbf{J}\mathbf{R}\mathbf{1},$$

(where we've used that  $R = \frac{1}{2}\mathbf{1}^t\mathbf{R}\mathbf{1}$ ). After some re-arranging, Equation (A.1) thus becomes

$$\begin{aligned} \frac{1}{n}\mathbf{R}\mathbf{1} - \frac{2}{n^2}\mathbf{R}\mathbf{1} - \left(\mathbf{I} - \frac{1}{n}\mathbf{J}\right)\Delta &= \frac{1}{n}\mathbf{R}\mathbf{1} - \frac{2}{n^2}\mathbf{R}\mathbf{1} - \left(\mathbf{I} - \frac{1}{n}\mathbf{J}\right)\left(\frac{1}{n}\mathbf{R}\mathbf{1} - \frac{1}{2n^2}\mathbf{J}\mathbf{R}\mathbf{1}\right) \\ &= \frac{1}{n}\mathbf{R}\mathbf{1} - \frac{1}{n^2}\mathbf{J}\mathbf{R}\mathbf{1} - \frac{1}{n}\mathbf{R}\mathbf{1} + \frac{1}{n^2}\mathbf{J}\mathbf{R}\mathbf{1} + \frac{1}{2n^2}\mathbf{J}\mathbf{R}\mathbf{1} - \frac{1}{2n^3}\mathbf{J}^2\mathbf{R}\mathbf{1} \\ &= \mathbf{0}, \end{aligned}$$

using that  $\mathbf{J}^2 = n\mathbf{J}$ . Finally, again using (A.2), the bottom right-hand side is

$$\frac{1}{2}\mathbf{1}\Delta^t\mathbf{L}_G + \frac{1}{n}\mathbf{1}\mathbf{1}^t - \frac{1}{2}\mathbf{R}\mathbf{L}_G = \frac{1}{n}\mathbf{J} + \left(\mathbf{I} - \frac{1}{n}\mathbf{J}\right) = \mathbf{I}.$$

This demonstrates that (A.1) holds. We now show that  $\mathbf{L}_G\mathbf{R}\mathbf{L}_G = -2\mathbf{L}_G$  and that  $\mathbf{R}\mathbf{L}_G\mathbf{R}\mathbf{x} = -2\mathbf{R}\mathbf{x}$  for all  $\mathbf{x} \in \text{span}(\mathbf{1})^\perp$ , which will complete the proof. Applying Equation (A.2) we have

$$\mathbf{L}_G\mathbf{R}\mathbf{L}_G = \mathbf{L}_G\mathbf{1}\Delta^t\mathbf{L}_G = -2\mathbf{L}_G + \frac{2}{n}\mathbf{L}_G\mathbf{1}\mathbf{1}^t = -2\mathbf{L}_G.$$

In the same way as (A.2) was derived, we see that

$$\mathbf{L}_G\mathbf{R} = \mathbf{L}_G\Delta\mathbf{1}^t - 2\left(\mathbf{I} - \frac{1}{n}\mathbf{J}\right),$$

and so

$$\mathbf{R}\mathbf{L}_G\mathbf{R} = \left(\mathbf{R}\mathbf{L}_G\Delta^t + \frac{2}{n}\mathbf{1}\right)\mathbf{1}^t - 2\mathbf{R},$$

as desired.  $\square$

*Proof of Lemma 2.9.* Suppose that  $\{\mathbf{x}_j - \mathbf{x}_i\}_{i \neq j}$  is not linearly independent, and let  $\{\beta_i\}$  (not all zero) be such that  $\sum_{i \neq j} \beta_i(\mathbf{x}_j - \mathbf{x}_i) = \mathbf{0}$ . Putting  $\beta = \sum_i \beta_i$ , we can write this as

$$\sum_{i \neq j} \frac{\beta_i}{\beta} \mathbf{x}_i - \mathbf{x}_j = \mathbf{0}.$$

But these coefficients sum to 0, i.e.,  $\sum_{i \neq j} \beta_i/\beta - 1 = 1 - 1 - 0$ , so  $\{\mathbf{x}_i\}$  are not affinely independent. Conversely, suppose that  $\sum_i \alpha_i \mathbf{x}_i = \mathbf{0}$  where  $\sum_i \alpha_i = 0$  and  $\alpha_k \neq 0$  for some  $k$ . Then,

$$\mathbf{0} = \sum_i \alpha_i \mathbf{x}_i = \sum_{i \neq j} \alpha_i \mathbf{x}_i + \alpha_j \mathbf{x}_j = \sum_{i \neq j} \alpha_i \mathbf{x}_i - \sum_{i \neq j} \alpha_i \mathbf{x}_j = \sum_{i \neq j} \alpha_i (\mathbf{x}_i - \mathbf{x}_j),$$

implying that  $\{\mathbf{x}_j - \mathbf{x}_i\}_{i \neq j}$  is not linearly independent.  $\square$

*Proof of Lemma 2.10.* By Lemma 2.9, the vectors  $\zeta_i = \mathbf{x}_i - \mathbf{x}_n$ ,  $i < n$  are linearly independent and span  $\mathbb{R}^{n-1}$ . Therefore, there exist real numbers  $\alpha_i$ ,  $i < n$  with  $\mathbf{y} - \mathbf{x}_n = \sum_{i < n} \alpha_i \zeta_i$ . Putting  $\alpha_n = 1 - \sum_{i < n} \alpha_i$ , we have  $\mathbf{y} = \sum_{i < n} \alpha_i \zeta_i + \mathbf{x}_n = \sum_{i < n} \alpha_i \mathbf{x}_i + (1 - \sum_{i < n} \alpha_i) \mathbf{x}_n = \sum_{i \in [n]} i \alpha_i \mathbf{x}_i$ . It's immediate that  $\sum_i \alpha_i = 1$ .  $\square$

*Proof of Claim 2.1.* Suppose not and let  $\{\beta_i\}$  be such that  $\sum_i \beta_i \gamma_i^* = \mathbf{0}$  with  $\sum_i \beta_i = 0$ . Then,

$$\mathbf{0} = \sum_i \beta_i \gamma_i^* = \sum_{i=1}^{n-1} \beta_i \gamma_i^* - \left( \sum_{i=1}^{n-1} \beta_i \right) \sum_{j=1}^{n-1} \gamma_j^* = \sum_{i=1}^{n-1} \left( \beta_i - \sum_{j=1}^{n-1} \beta_j \right) \gamma_i^*,$$

implying that  $\{\gamma_i^*\}_{i=1}^{n-1}$  is linearly dependent; a contradiction.  $\square$

*Proof of Observation 2.2.* Let  $\{v_i\}_{i \in [n]}$  be a set of vectors and let  $U \subsetneq [n]$  be a proper subset of  $[n]$ . If  $\{\mathbf{v}_i\}_{i \in U}$  is not affinely independent, then there exists  $\{\alpha_i\}_{i \in U}$  not all zero such that  $\sum_{i \in U} \alpha_i \mathbf{v}_i = \mathbf{0}$  and  $\sum_i \alpha_i = 0$ . Taking  $\alpha_j = 0$  for  $j \in U^c$  implies that  $\sum_{i \in [n]} \alpha_i \mathbf{v}_i = \mathbf{0}$  while maintaining that  $\sum_i \alpha_i = 0$ . Hence  $\{v_i\}_{i \in [n]}$  is not affinely independent.  $\square$

*Proof of Lemma 2.11.* We need to show that  $\langle \gamma_i, \mathbf{u}_j \rangle = \delta_{ij}$  for all  $i, j \neq k$ . For  $i \neq n$ , we have

$$\begin{aligned} \langle \gamma_i, \sigma_j - \sigma_k \rangle &= \langle \gamma_i, \sigma_j - \sigma_n + \sigma_n - \sigma_k \rangle \\ &= \langle \gamma_i, \sigma_j - \sigma_n \rangle - \langle \gamma_i, \sigma_k - \sigma_n \rangle \\ &= \delta_{ij} - \delta_{ik} = \delta_{ij}, \end{aligned}$$

since  $i \neq k$ . For  $i = n$  meanwhile,

$$\begin{aligned} \langle \gamma_n, \sigma_j - \sigma_k \rangle &= - \sum_{\ell=1}^{n-1} \langle \gamma_\ell, \sigma_j - \sigma_n + \sigma_n - \sigma_k \rangle \\ &= \sum_{\ell=1}^{n-1} \langle \gamma_\ell, \sigma_j - \sigma_n \rangle - \sum_{\ell=1}^{n-1} \langle \gamma_\ell, \sigma_k - \sigma_n \rangle = \sum_{\ell} \delta_{j\ell} - \delta_{k\ell} = 0. \end{aligned} \quad \square$$

*Proof of Lemma 2.12.* We are given that  $\langle \gamma_i^*, \gamma_j - \gamma_n \rangle = \delta_{ij}$  and  $\langle \sigma_i, \gamma_j^* - \gamma_n^* \rangle = \delta_{ij}$ . Since dual bases are unique, it suffices to show that  $\gamma_i - \gamma_n$  satisfies the relationships of  $\sigma_i$ , and indeed  $\langle \gamma_i - \gamma_n, \gamma_j^* - \gamma_n^* \rangle = \langle \gamma_i, \gamma_j^* - \gamma_n^* \rangle - \langle \gamma_n, \gamma_j^* - \gamma_n^* \rangle = \delta_{ij} - \delta_{in} = \delta_{ij}$ .  $\square$

*Proof of Lemma 2.13.* Let  $\Sigma(\mathcal{S}) = (\sigma_1, \dots, \sigma_n)$  and  $\Sigma(\mathcal{S}^*) = (\sigma_1^*, \dots, \sigma_n^*)$ . Let  $\Sigma \mathbf{x} \in \mathcal{S}_U$  and  $\Sigma^* \mathbf{y}_1, \Sigma^* \mathbf{y}_2 \in \mathcal{S}_{U^c}^*$ , where  $\mathbf{y}_1$  and  $\mathbf{y}_2$  are barycentric coordinates. Fix  $k \in U^c$ . We need to show that  $\langle \Sigma \mathbf{x}, \Sigma^* \mathbf{y}_1 - \Sigma^* \mathbf{y}_2 \rangle = 0$ . First, using  $\|\mathbf{y}_i\| = 1$ ,  $i = 1, 2$ , write

$$\Sigma^* \mathbf{y}_1 - \Sigma^* \mathbf{y}_2 = \sum_{j \in U^c} \sigma_j^* (y_1(j) - y_2(j))$$

$$\begin{aligned}
&= \sum_{j \in U^c \setminus \{k\}} \sigma_j^*(y_1(j) - y_2(j)) + \sigma_k^*(y_1(k) - y_2(k)) \\
&= \sum_{j \in U^c \setminus \{k\}} \sigma_j^*(y_1(j) - y_2(j)) - \sigma_k^* \left( \sum_{j \in U^c \setminus \{k\}} y_1(j) - y_2(j) \right) \\
&= \sum_{j \in U^c \setminus \{k\}} (\sigma_j^* - \sigma_k^*)(y_1(j) - y_2(j)).
\end{aligned}$$

Now, by definition,  $\langle \sigma^i, \sigma_j^* - \sigma_k^* \rangle = \delta_{i,j}$  for  $i, j \neq k$  so it follows that

$$\begin{aligned}
\langle \Sigma \mathbf{x}, \Sigma^*(\mathbf{y}_1 - \mathbf{y}_2) \rangle &= \sum_{i \in U} x(i) \langle \sigma_i, \Sigma^*(\mathbf{y}_1 - \mathbf{y}_2) \rangle \\
&= \sum_{i \in U} x(i) \sum_{j \in U^c \setminus \{k\}} \langle \sigma_i, \sigma_j^* - \sigma_k^* \rangle (y_1(j) - y_2(j)) \\
&= \sum_{i \in U} x(i) \sum_{j \in U^c \setminus \{k\}} \delta_{i,j} (y_1(j) - y_2(j)) = 0,
\end{aligned}$$

since  $U^c \setminus \{k\} \cap \{i\} = \emptyset$ . \(\square\)

### §A.2. Chapter 3

*Proof of Lemma 3.4.* Let us simply perform the calculation:

$$\begin{aligned}
(\mathbf{L}_{G \times H} f_{uv})(ij) &= \deg_{G \times H}((i, j)) f_{uv}(ij) - \sum_{(k, \ell) \in \partial((i, j))} f_{uv}(k\ell) \\
&= (\deg_G(i) + \deg_H(j)) \varphi_u(i) \psi_v(j) - \sum_{(k, \ell) \in \partial_{G \times H}((i, j))} \varphi_u(i) \psi_v(j) \\
&= (\deg_G(i) + \deg_H(j)) \varphi_u(i) \psi_v(j) - \sum_{k \in \partial_G(i)} \varphi_u(k) \psi_v(j) - \sum_{\ell \in \partial_H(j)} \varphi_u(i) \psi_v(\ell) \\
&= \left( \deg_G(i) \varphi_u(i) - \sum_{k \in \partial_G(i)} \varphi_u(k) \right) \psi_v(j) \\
&\quad + \left( \deg_H(j) \psi_v(j) - \sum_{\ell \in \partial_H(j)} \psi_v(\ell) \right) \varphi_u(i) \\
&= (\mathbf{L}_G \varphi_u)(i) \cdot \psi_v(j) + (\mathbf{L}_H \psi_v)(j) \cdot \varphi_u(i) \\
&= \lambda_u \varphi_u(i) \psi_v(j) + \mu_v \psi_v(j) \varphi_u(i) \\
&= (\lambda_u + \mu_v) \varphi_u(i) \psi_v(j) = (\lambda_u + \mu_v) f_{uv}(ij),
\end{aligned}$$

as desired. \(\square\)

*Proof of Lemma 3.9.* Put  $E = \{\mathbf{x} \in \mathbb{R}^{n-1} : \mathbf{x}^t \Sigma^+ + \mathbf{1}^t/n \geq \mathbf{0}^t\}$ . First we show that  $E \subseteq \mathcal{S}$ . Since  $\text{rank}(\Sigma) = n - 1$ , it follows that given any  $\mathbf{x} \in E$  (indeed, any  $\mathbf{x} \in \mathbb{R}^{n-1}$ ) we can write  $\mathbf{x} = \Sigma \mathbf{y}$  for

some  $\mathbf{y} \in \mathbb{R}^n$ . Letting  $\bar{y} = n^{-1} \sum_i y(i)$  be the mean of the vector  $\mathbf{y}$ , compute

$$\mathbf{x}^t \Sigma^+ = \mathbf{y}^t \Sigma^t \Sigma^+ = \mathbf{y}^t (\mathbf{I} - \mathbf{1}\mathbf{1}^t/n) = \mathbf{y}^t - \bar{y} \mathbf{1}^t.$$

If  $\mathbf{x} \in E$  the above implies that

$$\mathbf{y}^t - \bar{y} \mathbf{1}^t + \mathbf{1}^t/n \geq \mathbf{0}^t.$$

Moreover, since  $\Sigma \mathbf{1} = \mathbf{0}$ , we have  $\mathbf{x} = \Sigma \mathbf{y} = \Sigma(\mathbf{y} - \bar{y} \mathbf{1} + \mathbf{1}/n)$ . Noticing that

$$\langle \mathbf{y} - \bar{y} \mathbf{1} + \mathbf{1}^t/n, \mathbf{1} \rangle = n\bar{y} - n\bar{y} + 1 = 1,$$

demonstrates that the vector  $\tilde{\mathbf{y}} = \mathbf{y} - \bar{y} \mathbf{1} + \mathbf{1}^t/n$  is a barycentric coordinate for  $\mathbf{x}$ , and so  $\mathbf{x} \in \mathcal{S}$ .

Conversely, for  $\mathbf{x} \in \mathcal{S}$  let  $\mathbf{y}$  be its barycentric coordinate. Then

$$\mathbf{x}^t \Sigma^+ + \frac{\mathbf{1}^t}{n} = \mathbf{y}^t \left( \mathbf{I} - \frac{\mathbf{J}}{n} \right) + \frac{\mathbf{1}^t}{n} = \mathbf{y}^t - \frac{\mathbf{1}^t}{n} + \frac{\mathbf{1}^t}{n} = \mathbf{y}^t \geq \mathbf{0}^t,$$

hence  $\mathcal{S} \subseteq E$ . This completes the proof.  $\square$

### §A.3. Chapter 4

*Proof of Lemma 4.7.* Before proceeding to the main part of the proof, we recall the equation of the determinant of a matrix in terms of its co-factor expansion. Let  $\mathbf{Q} \in \mathbb{R}^{m \times m}$ . For any  $i, j \in [m]$ , let  $\mathbf{Q}_{-i, -j}$  denote the matrix obtained by removing row  $i$  and column  $j$  from  $\mathbf{Q}$ . The cofactor expansion along row  $i \in [n]$  is the relationship

$$\det(\mathbf{Q}) = \sum_{k=1}^m (-1)^{i+k} \mathbf{Q}(i, k) \det(\mathbf{Q}_{-i, -k}),$$

while the cofactor expansion along column  $j \in [n]$  reads

$$\det(\mathbf{Q}) = \sum_{k=1}^m (-1)^{j+k} \mathbf{Q}(k, j) \det(\mathbf{Q}_{-k, -j}).$$

We may now proceed with the argument. Let  $\mathbf{D}$  be the distance matrix of  $\mathcal{T}$ , and recall that  $\mathbf{D} = \mathbf{R}$  where  $\mathbf{R}$  is the effective resistance matrix of the graph  $G$ . Set

$$\mathbf{r} = -\left( \mathbf{L}_G \Delta + \frac{2}{n} \mathbf{1} \right), \quad \alpha = \Delta^t \mathbf{L}_G \Delta + 4R_G^{\text{tot}}/n^2.$$

Combining Lemma 4.6 and Equation (2.18), write

$$\begin{aligned}\text{vol}(\mathcal{T})^2 &= \frac{(-1)^n}{((n-1)!)^2 2^{n-1}} \det \left( -2 \begin{pmatrix} \alpha & \mathbf{r} \\ \mathbf{r} & \mathbf{L}_G \end{pmatrix}^{-1} \right) \\ &= \frac{-4}{((n-1)!)^2} \left[ \det \begin{pmatrix} \alpha & \mathbf{r} \\ \mathbf{r} & \mathbf{L}_G \end{pmatrix} \right]^{-1},\end{aligned}$$

where we've employed the basic determinant properties  $\det(\beta \mathbf{Q}) = \beta^m \det(\mathbf{Q})$  for  $\mathbf{Q} \in \mathbb{R}^{m \times m}$  and  $\det(\mathbf{Q}^{-1}) = \det(\mathbf{Q})^{-1}$  for  $\mathbf{Q}$  invertible. We are thus left with task of evaluating the above determinant. We claim it is equal to  $-4\Gamma_G$ , which will complete the proof. Put

$$\mathbf{Q} = \begin{pmatrix} \alpha & \mathbf{r} \\ \mathbf{r} & \mathbf{L}_G \end{pmatrix} \in \mathbb{R}^{n+1 \times n+1}.$$

First we carry out a cofactor expansion along the first row, which yields

$$\det(\mathbf{Q}) = \alpha \det(\mathbf{L}_G) + \sum_{j=2}^{n+1} (-1)^{1+j} r(j-1) \det(\mathbf{Q}_{-1,-j}) = \sum_{j=1}^n (-1)^j r(j) \det(\mathbf{Q}_{-1,-j+1}).$$

For each  $j$ , carrying out a cofactor expansion of the first column of  $\mathbf{Q}_{-1,-j+1}$  yields

$$\det(\mathbf{Q}_{-1,-j+1}) = \sum_{k=1}^n (-1)^{k+1} r(k) \det(\mathbf{L}_{-k,-j}),$$

hence,

$$\det(\mathbf{Q}) = - \sum_{j=1}^n \sum_{k=1}^n r(j) r(k) (-1)^j (-1)^k \det(\mathbf{L}_{-k,-j}) = - \sum_{j=1}^n \sum_{k=1}^n r(j) r(k) \Gamma_G,$$

by Theorem 2.2. It remains only to note that  $-\sum_{j,k=1}^n r(j) r(k) = -(\sum_j r(j))^2 = -\langle \mathbf{1}, \mathbf{r} \rangle^2 = -4$  by definition of  $\mathbf{r}$ .  $\square$

*Proof of Lemma 4.10.* We begin by computing the left hand side of the matrix equation. Note that for connected trees on  $n$  nodes, there are precisely  $n-1$  edges. Therefore,  $\mathbf{1}^t \mathbf{d} - 2n = \sum_i \deg(i) - 2n = 2|E| - 2n = -2$ , by the handshaking lemma. Since  $\mathbf{1}^t \mathbf{L}_T = \mathbf{0}$ , it follows that the top row of the resulting matrix is as desired. Next, let us consider the term

$$\sum_{i \sim j} \frac{1}{w(i, j)} + \mathbf{S}_T(\mathbf{d} - 2\mathbf{1}),$$

which we need to demonstrate is equal to  $\mathbf{0}$ . Consider the  $k$ -th row of the above vector,

$$\sum_{i \sim j} \frac{1}{w(i, j)} + \sum_{\ell \in [n]} \mathbf{S}_T(k, \ell)(\deg(\ell) - 2). \quad (\text{A.3})$$

Denote the sum on the right by  $S$ . Fix some  $(i, j) \in E$  and let us consider how many occurrences of  $1/w(i, j)$  there are in  $S$ . Since  $T$  is a tree, we may partition  $V$  into two disjoint sets of vertices,  $V_i$  and  $V_j$  (so that  $V_i \cup V_j = V$  and  $V_i \cap V_j = \emptyset$ ) where  $i \in V_i$ ,  $j \in V_j$ , and  $T[V_i]$ ,  $T[V_j]$  are both connected trees. That is, the original graph  $T$  is a union of  $T[V_i]$ ,  $T[V_j]$  and the edge  $(i, j)$  which connects them. Now, the edge  $(i, j)$  will be on the path between two vertices if and only if one lies in  $V_i$  and the other in  $V_j$ . (Again, this is due to the fact that  $T$  is a tree—there is thus no other path between the components  $V_i$  and  $V_j$  other than via  $(i, j)$ .) Assume without loss of generality that  $k \in V_i$ . Then, by the above argument,  $1/w(i, j)$  appears only in those terms  $\mathbf{S}_T(k, \ell)$  with  $\ell \in V_j$ . Consequently, collecting and summing over all the terms  $1/w(i, j)$ , we may rewrite  $S$  as

$$\sum_{i \sim j} \frac{1}{w(i, j)} \sum_{\ell \in V_j} (\deg_T(\ell) - 2).$$

Since  $T[V_j]$  is a tree,  $\sum_{\ell \in V_j} \deg_{T[V_j]}(\ell) = 2(|V_j| - 1)$  (using the same arguments as above). Moreover,  $\deg_{T[V_j]}(\ell) = \deg_T(\ell)$  for every  $\ell \in V_j \setminus \{j\}$ , since no other vertex besides  $j$  shares an edge with any vertex in  $V_i$ . On the other hand, since  $(i, j) \in E$ ,  $\deg_{T[V_j]}(j) = \deg_T(j) - 1$ . Hence,

$$\sum_{\ell \in V_j} (\deg_T(\ell) - 2) = 2(|V_i| - 1) + 1 - 2|V_i| = -1.$$

We have thus shown that  $S = -\sum_{i \sim j} 1/w(i, j)$ , and so (A.3) is indeed 0. Finally, we consider the term  $\mathbf{1}^t \mathbf{d} - 2\mathbf{1}\mathbf{1}^t + \mathbf{S}_T \mathbf{L}_T$ , which we need to show is  $-2\mathbf{I}$ . Let us expand the  $(k, \ell)$ -th component of this matrix:

$$\begin{aligned} \deg(\ell) - 2 + \sum_{i \in [n]} \mathbf{S}_T(k, i) \mathbf{L}_T(\ell, k) &= \deg(\ell) - 2 + \mathbf{S}_T(k, \ell) \mathbf{L}_T(\ell, \ell) + \sum_{i \neq \ell} \mathbf{S}_T(k, i) \mathbf{L}_T(\ell, k) \\ &= \deg(\ell) - 2 + \mathbf{S}_T(k, \ell) w(\ell) - \sum_{i \in \delta(\ell)} \mathbf{S}_T(k, i) \\ &= \deg(\ell) - 2 + \sum_{i \in \delta(\ell)} w(i, \ell) (\mathbf{S}_T(k, \ell) - \mathbf{S}_T(k, i)). \end{aligned}$$

For  $k = \ell$ , we have  $\mathbf{S}_T(k, \ell) = 0$  and  $\mathbf{S}_T(k, i) = \mathbf{S}_T(\ell, i) = 1/w(i, \ell)$ . It follows that the above sum is  $-2$ , as desired. Now consider  $k \neq \ell$ . Fix  $i \in \delta(\ell)$  and let  $P = (k = v_1, \dots, v_r = \ell)$  be the unique path between  $k$  and  $\ell$ . First, suppose that  $i \in P$  so that  $i = v_{r-1}$ . Then  $\mathbf{S}_T(k, \ell) - \mathbf{S}_T(k, i) = \sum_{s=1}^{r-1} 1/w(v_s, v_{s+1}) - \sum_{s=1}^{r-2} 1/w(v_s, v_{s+1}) = 1/w(v_{r-1}, v_r) = 1/w(i, \ell)$ . Otherwise, if  $i \notin P$  then the unique path between  $i$  and  $k$  in  $T$  is  $P \cup \{\ell\} = (v_1, \dots, v_r, i)$ . In this case  $\mathbf{S}_T(k, \ell) - \mathbf{S}_T(k, i) = \sum_{s=1}^{r-1} 1/w(v_s, v_{s+1}) - (\sum_{s=1}^{r-1} 1/w(v_s, v_{s+1}) + 1/w(i, \ell)) = -1/w(i, \ell)$ . Finally, we note that there



can be at most one neighbour of  $\ell$  which is on the shortest path between  $k$  and  $\ell$ . Therefore,  $\sum_{i \in \delta(\ell)} w(i, \ell)(\mathcal{S}_T(k, \ell) - \mathcal{S}_T(k, i)) = 1 - (|\delta(\ell)| - 1) = 2 - \deg(\ell)$ , demonstrating that the  $(k, \ell)$ -th component is zero, completing the proof.  $\square$

*Proof of Lemma 4.11.* Let  $F^+$  be as above and let  $F^- \stackrel{\text{def}}{=} [n] \setminus F^+ = \{i : f(i) < 0\}$ . Observe that

$$\|f\|_1 = \sum_i |f(i)| = \langle \chi_{F^+} - \chi_{F^-}, f \rangle = (\chi_{F^+} - \chi_{F^-})^t f = (\chi_{F^+} - \chi_{F^-})^t (\mathbf{I} - \mathbf{J}/n) f,$$

where the last inequality follows since  $f$  is orthogonal to  $\mathbf{1}$  by assumption. Using the pseudoinverse relation (3.4), we can continue as

$$\begin{aligned} \|f\|_1 &= (\chi_{F^+} - \chi_{F^-})^t (\Sigma^+)^t \Sigma f \\ &= (\chi_{F^+} - \mathbf{1} + \chi_{F^+})^t (\Sigma^+)^t \Sigma f \\ &= 2\chi_{F^+}^t (\Sigma^+)^t \Sigma f - (\Sigma^+ \mathbf{1})^t \Sigma f \\ &= 2\langle \Sigma^+ \chi_{F^+}, \chi_{F^+}^t (\Sigma^+)^t \Sigma f \rangle && \text{since } \Sigma^+ \mathbf{1} = \mathbf{0} \\ &\leq 2\|\Sigma \chi_{F^+}\|_2 \cdot \|\Sigma^+ f\|_2 && \text{by Cauchy-Schwartz}^1 \\ &= 2(\chi_{F^+} \mathbf{L}^+ \chi_{F^+} \cdot f^t \mathbf{L} f)^{1/2}. \end{aligned}$$

Squaring both sides and recalling that  $\chi_{F^+} \mathbf{L}^+ \chi_{F^+} = w(\delta^+ F^+)$  gives the desired result.  $\square$

*Proof of Lemma 4.14.* We prove Equation (4.14) only; Equation (4.15) follows similarly. Set  $\mathbf{M} = \Sigma^+ (\Sigma^+)^t$  and  $E = \{\mathbf{x} : \mathbf{x}^t \mathbf{M} \mathbf{x} = (n-1)/n\}$ . The claim is that  $\mathcal{E}(\mathcal{S}) = E$ . First we demonstrate that the vertices of  $\mathcal{S}$  are contained in  $E$ . Noticing that  $\mathbf{J}^2 = n\mathbf{J}$ , we compute

$$\sigma_i^t \mathbf{M} \sigma_i = \chi_i^t \Sigma^t \Sigma^+ (\Sigma^+)^t \Sigma \chi_i = \chi_i^t \left( \mathbf{I} - \frac{1}{n} \mathbf{J} \right)^2 \chi_i = \chi_i^t \left( \mathbf{I} - \frac{1}{n} \mathbf{J} \right) \chi_i = 1 - \frac{1}{n},$$

so indeed the vertices  $\sigma_i$  are contained in  $E$ . Now, define the hyperplane

$$\mathcal{H} \stackrel{\text{def}}{=} \left\{ \mathbf{x} : \mathbf{x}^t \mathbf{M} \sigma_i = -\frac{1}{n} \right\}.$$

We claim that  $\mathcal{H}$  is the plane containing the points  $\{\sigma_j\}_{j \neq i}$ . Indeed, consider  $\sigma_j$  for some fixed  $j \neq i$ . Then, as above

$$\sigma_j^t \mathbf{M} \sigma_i = \chi_j^t \left( \mathbf{I} - \frac{1}{n} \mathbf{J} \right) \chi_i = -\frac{1}{n}.$$

It remains to show that  $\mathcal{H}$  is parallel to the tangent plane of  $E$  at the point  $\sigma_i$ . But this tangent plane is defined by the equation [Fie05] [Should figure out how this is actually done](#)

$$\mathbf{x}^t \mathbf{M} \sigma_i = \frac{n-1}{n},$$

which is clearly parallel to  $\mathcal{H}$ . This completes the proof.  $\square$

*Proof of Lemma 4.16.* Set  $\boldsymbol{\zeta} = \frac{1}{2}(\mathbf{L}_G \boldsymbol{\xi} + \mathbf{1}/n)$  and  $r = \boldsymbol{\xi}^t \mathbf{L}_G \boldsymbol{\xi} + 4R_G/n^2$ . Let us expand  $\mathbf{x}$  in barycentric coordinates in accordance with Lemma 2.10. Put  $\mathbf{x} = \sum_i \alpha_i \boldsymbol{\sigma}_i$  where  $\sum_i \alpha_i = \sum_i \beta_i = 1$ . Let  $\boldsymbol{\alpha} = (\alpha_1, \dots, \alpha_n)$ . The claim is that the circumscribed sphere of  $\mathcal{S}^+$  is given by the equation

$$\|\mathbf{x} - \Sigma \boldsymbol{\zeta}\|_2^2 = \frac{1}{4}r, \quad (\text{A.4})$$

and that this equation is equivalent to  $\boldsymbol{\alpha}^t \mathbf{D} \boldsymbol{\alpha} = 0$ . Note first that due to Equation 2.18,  $\langle \mathbf{1}, -2\boldsymbol{\zeta} \rangle = \langle \mathbf{1}, -\mathbf{L}_G \boldsymbol{\xi} - \frac{2}{n} \mathbf{1} \rangle = -2$ , so  $\boldsymbol{\zeta} = (\zeta_1, \dots, \zeta_{n-1})$  obeys  $\sum_i \zeta_i = 1$ . The left hand side of (A.4) then becomes

$$\begin{aligned} \langle \mathbf{x} - \Sigma \boldsymbol{\zeta}, \mathbf{x} - \Sigma \boldsymbol{\zeta} \rangle &= \sum_{i,j \in [n]} (\alpha_i - \zeta_i)(\alpha_j - \zeta_j) \langle \boldsymbol{\sigma}_i, \boldsymbol{\sigma}_j \rangle \\ &= \sum_{i,j \in [n]} (\alpha_i - \zeta_i)(\alpha_j - \zeta_j) \langle \boldsymbol{\sigma}_i - \boldsymbol{\sigma}_n, \boldsymbol{\sigma}_j - \boldsymbol{\sigma}_n \rangle, \end{aligned}$$

where the last line uses that  $\boldsymbol{\sigma}_n \sum_i (\alpha_i - \zeta_i) = \mathbf{0}$ . Observing that

$$\langle \boldsymbol{\sigma}_i - \boldsymbol{\sigma}_n, \boldsymbol{\sigma}_j - \boldsymbol{\sigma}_n \rangle = \frac{1}{2}(\|\boldsymbol{\sigma}_i - \boldsymbol{\sigma}_n\|_2^2 + \|\boldsymbol{\sigma}_j - \boldsymbol{\sigma}_n\|_2^2 - \|\boldsymbol{\sigma}_i - \boldsymbol{\sigma}_j\|_2^2),$$

we may proceed as

$$\begin{aligned} \langle \mathbf{x} - \Sigma \boldsymbol{\zeta}, \mathbf{x} - \Sigma \boldsymbol{\zeta} \rangle &= \frac{1}{2} \left( \sum_j (\alpha_j - \zeta_j) \sum_i (\alpha_i - \zeta_i) \|\boldsymbol{\sigma}_i - \boldsymbol{\sigma}_n\|_2^2 \right. \\ &\quad + \sum_i (\alpha_i - \zeta_i) \sum_j (\alpha_j - \zeta_j) \|\boldsymbol{\sigma}_j - \boldsymbol{\sigma}_n\|_2^2 \\ &\quad \left. - \sum_{i,j} (\alpha_i - \zeta_i)(\alpha_j - \zeta_j) \|\boldsymbol{\sigma}_i - \boldsymbol{\sigma}_j\|_2^2 \right) \\ &= -\frac{1}{2} \sum_{i,j} (\alpha_i - \zeta_i)(\alpha_j - \zeta_j) \|\boldsymbol{\sigma}_i - \boldsymbol{\sigma}_j\|_2^2. \end{aligned} \quad (\text{A.5})$$

Recalling the block matrix equation (2.18) for hyperacute simplices, for all  $i$  we have  $\mathbf{1}(\boldsymbol{\xi}^t \mathbf{L}_G \boldsymbol{\xi} + 4R_G/n^2) - \mathbf{D}(\mathbf{L}_G \boldsymbol{\xi} + 2\mathbf{1}/n) = \mathbf{0}$ , i.e.,  $r\mathbf{1} - 2\mathbf{D} = \mathbf{0}$ . Hence

$$\langle \mathbf{D}(i, \cdot), \boldsymbol{\zeta} \rangle = \frac{r}{2}.$$

Using this, we rewrite the summation on the right hand side of (A.5) as

$$\sum_{i,j} (\alpha_i - \zeta_i)(\alpha_j - \zeta_j) \mathbf{D}(i, j) = \sum_i (\alpha_i - \zeta_i) \left( \sum_j \alpha_j \mathbf{D}(i, j) - \sum_j \alpha_j \mathbf{D}(i, j) \right)$$

$$\begin{aligned}
&= \sum_j \alpha_j \sum_i (\alpha_i - \zeta_i) \mathbf{D}(i, j) - \frac{1}{2}r \sum_i (\alpha_i - \zeta_i) \\
&= \sum_j \alpha_j \left( \sum_i \alpha_i \mathbf{D}(i, j) - \frac{1}{2}r \right) \\
&= \sum_{i,j} \alpha_i \mathbf{D}(i, j) \alpha_j - \frac{1}{2}r = \boldsymbol{\alpha}^t \mathbf{D} \boldsymbol{\alpha} - \frac{1}{2}r.
\end{aligned}$$

The equation of the sphere in (A.4) now becomes  $\frac{1}{4}r - \frac{1}{2}\boldsymbol{\alpha}^t \mathbf{D} \boldsymbol{\alpha} = \frac{1}{4}r$ , i.e.,  $\boldsymbol{\alpha}^t \mathbf{D} \boldsymbol{\alpha} = \mathbf{0}$  as was claimed. Now, to see that this sphere contains the vertices of  $\mathcal{S}^+$ ,  $\{\boldsymbol{\sigma}_i^+\}$ , we need only note that the barycentric coordinate of  $\boldsymbol{\sigma}_\ell^+$  is  $\boldsymbol{\chi}_\ell$  and that  $\boldsymbol{\chi}_\ell^t \mathbf{D} \boldsymbol{\chi}_\ell = \sum_{i,j} \boldsymbol{\chi}_\ell(i) \mathbf{D}(i, j) \boldsymbol{\chi}_\ell(j) = \mathbf{D}(\ell, \ell) = 0$ .  $\square$

## Intuition Behind Effective Resistance

Here we provide a derivation of effective resistance using the analogy of a graph as an electrical network.

Given an undirected, weighted graph  $G = (V, E, w)$ , place an arbitrary orientation the edges (say, for example,  $(i, j)$  is directed from  $i$  to  $j$  iff  $i < j$ ) and for each edge  $e$ , let  $e^- \in V$  denote the vertex at which  $e$  ends, and  $e^+$  the vertex at which it begins. Set

$$\mathbf{B}(e, i) = \begin{cases} 1 & \text{if } i = e^+, \\ -1 & \text{if } i = e^-, \\ 0 & \text{otherwise,} \end{cases} \quad (\text{B.1})$$

or, equivalently,  $\mathbf{B}(e, i) = (\chi_{(i=e^+)} - \chi_{(i=e^-)})$ . We will consider  $G$  as an electrical network. To do this, we imagine placing a resistor of resistance  $1/w(e)$  on each edge  $e$ . Edges thus carry current between the nodes and, in general, higher weighted edges will carry more current. An *electrical flow*  $\mathbf{f} : E \rightarrow \mathbb{R}_{\geq 0}$  on  $G$  assigns a current to each edge  $e$  and respects, roughly speaking, Kirchoff's current law and Ohm's law. More precisely, let  $\mathbf{e}$  be a vector describing the amount of current injected at each node. By Kirchoff's law, the amount of current passing through a vertex  $i$  must be conserved. That is,

$$\sum_{e:i=e^+} f(e) - \sum_{e:i=e^-} f(e) = e(i),$$

or, more succinctly,

$$\mathbf{B}^t \mathbf{f} = \mathbf{e}. \quad (\text{B.2})$$

Note that this property is also called *flow conservation* in the network flow literature. By Ohm's law, the amount of flow across an edge is proportional to the difference of potential at its endpoints. The constant of proportionality is the inverse of the resistance of that edge, i.e., the weight of the edge. Let  $\boldsymbol{\rho} : V \rightarrow \mathbb{R}_{\geq 0}$  describe the potential at each vertex. For  $e = (i, j)$  with  $i = e^+$ ,  $j = e^-$ ,  $\boldsymbol{\rho}$  is defined by the relationship

$$f(e) = w(e)(\rho(i) - \rho(j)) = w(e)(\mathbf{B}(e, i)\rho(i) + \mathbf{B}(e, j)\rho(j)),$$

so that

$$\mathbf{f} = \mathbf{W} \mathbf{B} \boldsymbol{\rho}. \quad (\text{B.3})$$

Combining (B.2) and (B.3) we see that  $\mathbf{e} = \mathbf{B}^t \mathbf{f} = \mathbf{B}^t \mathbf{W} \mathbf{B} \boldsymbol{\rho} = \mathbf{L}_G \boldsymbol{\rho}$ , and so  $\boldsymbol{\rho} = \mathbf{L}_G^+ \mathbf{e}$  whenever  $\langle \mathbf{e}, \mathbf{1} \rangle = \mathbf{0}$  (recall that  $\mathbf{L}_G^+$  is the inverse of  $\mathbf{L}_G$  in the space  $\text{span}(\mathbf{1})^\perp$ ).

The *effective resistance* of an edge  $e = (i, j)$  is the potential difference induced across the edge when one unit of current is injected at  $i$  and extracted at  $j$ . That is, for  $\mathbf{e} = \boldsymbol{\chi}_i - \boldsymbol{\chi}_j$ , we want to measure  $\rho(i) - \rho(j)$ . We do this by noticing that

$$\rho(i) - \rho(j) = \langle \boldsymbol{\chi}_i, \boldsymbol{\rho} \rangle - \langle \boldsymbol{\chi}_j, \boldsymbol{\rho} \rangle = \langle \boldsymbol{\chi}_i - \boldsymbol{\chi}_j, \mathbf{L}_G^+ \mathbf{e} \rangle = \mathcal{L}_G^+(\boldsymbol{\chi}_i - \boldsymbol{\chi}_j).$$

Note that here we've relied on the fact that  $\boldsymbol{\chi}_i - \boldsymbol{\chi}_j \perp \mathbf{1}$ . This gives rise to Definition 2.2.

## Figures

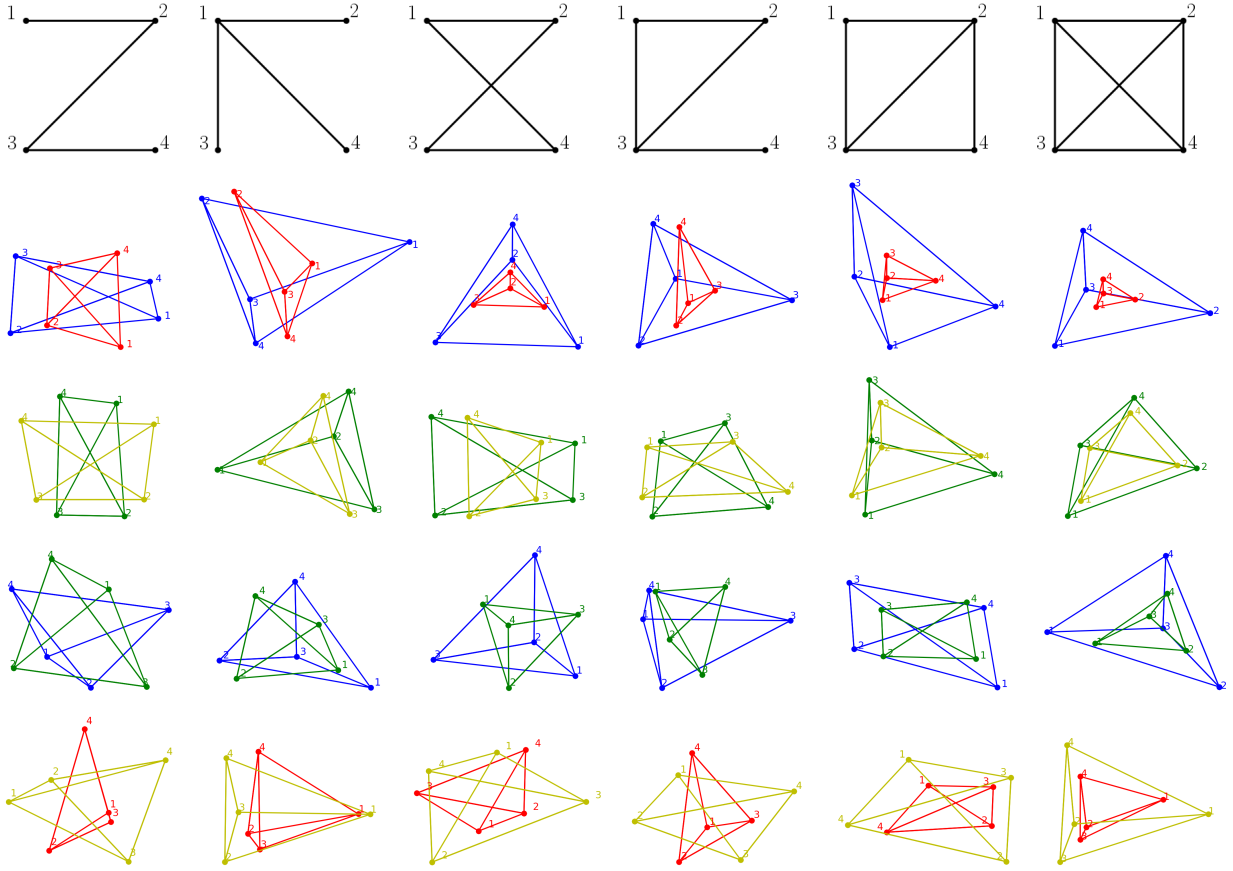


Figure C.1: The six unique unweighted graphs on four vertices, up to isomorphism, and a comparison of all of their simplicies. Below each graph in the first row are its two combinatorial simplicies ( $\mathcal{S}_G$  and  $\mathcal{S}_G^+$ ), then its two normalized simplicies ( $\widehat{\mathcal{S}}_G$  and  $\widehat{\mathcal{S}}_G^+$ ), then its combinatorial and normalized simplex ( $\mathcal{S}_G$  and  $\widehat{\mathcal{S}}_G$ ), followed in the final row by the two inverse simplicies ( $\mathcal{S}_G^+$  and  $\widehat{\mathcal{S}}_G^+$ ). The combinatorial simplex and its inverse are coloured blue and red respectively, and the normalized simplex and its inverse are in green and yellow respectively. The relative size of the the simplicies in each subfigure are to scale but the same scale is not maintained across figures.