

CALIFORNIA STATE UNIVERSITY, NORTHRIDGE

PROTEIN FOLDING: PLANAR CONFIGURATION SPACES OF DISC
ARRANGEMENTS AND HINGED POLYGONS

A thesis submitted in partial fulfillment of the requirements for the degree of
Master of Science in Applied Mathematics

by

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ABSTRACT

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Chapter 1

Realizability Problems for Weighted Trees

In this chapter our goal is to prove Theorem ?? which states: “It is NP-Hard to decide whether a given tree with positive vertex weights is the contact graph of a disk arrangements with specified radii.” This chapter’s approach to proving Theorem ?? introduces an ordered weighted tree T and perturbed ordered weight tree T_ϵ , the Hausdorff distance, and then prove the following lemma:

Lemma 1. *for ever $\epsilon > 0$, there exists an ordered weighted tree T_ϵ such that every realization of T_ϵ as an ordered disk contact graph where the radii of the disks equal the vertex weights.*

Using Lemma 1, we prove Theorem ?? by extending the modified auxiliary construction in Chapter ??.

We first cover the preliminary concepts of Hausdorff distance and the ordered weighted tree families of T and T_ϵ . We then continue with the proof of Lemma 1 and Theorem ??.

1.1 Hausdorff Distance

Let A and B be sets in the plane. The *directed Hausdorff distance* is:

$$d(A, B) = \sup_{a \in A} \inf_{b \in B} \|a - b\| \quad (1.1)$$

$d(A, B)$ finds the furthest point $a \in A$ from any point in B . *Hausdorff distance* is

$$D(A, B) = \max \{d(A, B), d(B, A)\} \quad (1.2)$$

In Figure 1.1, we have two sets X and Y and illustrate $d(X, Y)$ and $d(Y, X)$. From this, it is possible to calculate the Hausdorff distance between X and Y .

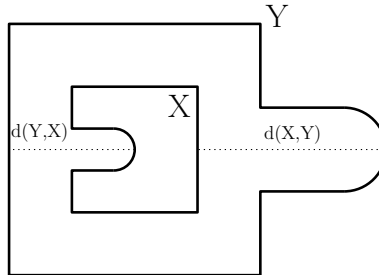


Figure 1.1: An illustrative example of $d(X, Y)$ and $d(Y, X)$ where X is the inner curve, and Y is the outer curve.

ϵ -approximation The weighted graph, G , is an ϵ -approximation of a polygon P if the Hausdorff distance between every realization of G as a contact graph of disks and a congruent copy of P is at most epsilon. A weighted graph G is said to be a $O(f(x))$ -approximation of a polygon P if there is a positive constant M such that for all sufficiently large values of x the Hausdorff distance between every realization such realization of G as a contact graph of disks and a congruent copy of P is at $M \cdot |f(x)|$. A weighted graph G is said to be a *stable* if it has the property that for every two such realizations of G , the distance between the centers of the corresponding disks is at most ϵ after a suitable rigid transformation.

An example of an ϵ -approximation

Problem 1 (Approximating Polygonal Shapes with Contact Graphs). For every $\varepsilon > 0$ and polygon P , there exists a contact graph $G = (V, E)$ such that the Hausdorff distance $d(P, G) < \varepsilon$

1.2 Weight Trees T_k

In this section we describe a particular family of unit weight trees and corresponding contact graphs disk arrangements called *snowflakes*. Note that we regard snowflakes with unit weight as a weight of $\frac{1}{2}$. For $i \in \mathbb{N}$, the construction of the snowflake tree, T_i , is as follows:

- Let v_0 be a dvertex that has six paths attached to it: p_1, p_2, \dots, p_6 . Each path has i vertices.
- For every other path p_1, p_3 , and p_5 :
 - Each vertex on that path has two paths attached, one path on each side of p_k .
 - The number of vertices that lie on a path attached to the j^{th} vertex of p_k is $i - j$.

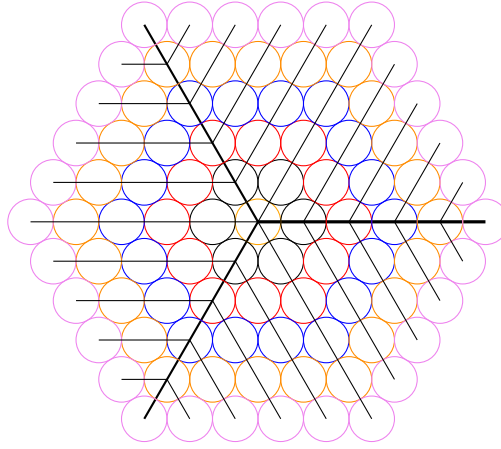


Figure 1.2: The same contact graph as in figure 1.3 overlaid with the a perfectly weighted snowflake tree.

A *perfectly weighted snowflake tree* is a snowflake tree with all vertices having weight $\frac{1}{2}$. A *perturbed snowflake tree* is a snowflake tree with all vertices having weight of 1 with the exception of v_0 ; in a perturbed snowflake tree, v_0 will have a weight of $\frac{1}{2} + \gamma$. For our analysis, all realizations of any snowflake, perfect or perturbed, shall have v_0 fixed at origin.

Perfectly Weighted Snowflake Tree. Consider the graph of the triangular lattice with unit distant edges:

$$\begin{aligned} V &= \left\{ a \cdot (1, 0) + b \cdot \left(\frac{1}{2}, \frac{\sqrt{3}}{2} \right) : a, b \in \mathbb{Z} \right\} \\ E &= \{ \{u, v\} : \|u - v\| = 1 \text{ and } u, v \in V \} \end{aligned}$$

The following graph, $G = (V, E)$ is said to be the *unit distance graph* of the triangular lattice. We can show that no two distinct edges of this graph are non-crossing. First suppose that there were two distinct edges that crossed, $\{u_1, v_1\}$ and $\{u_2, v_2\}$. With respect to u_1 , there are 6 possible edges corresponding to it, with each edge $\frac{\pi}{3}$ radians away from the next. Neither edge crosses another; and so we have a contradiction that there are no edge crossings with $\{u_1, v_1\}$.

The perfectly weighted snowflake tree that is a subgraph over the *unit distance graph*, $G = (V, E)$, of the triangular lattice. To show this, for any S_i , fix $v_0 = 0 \cdot (1, 0) + 0 \cdot \left(\frac{1}{2}, \frac{\sqrt{3}}{2} \right) = (0, 0) \in V$ at origin. Next

consider the six paths attached from origin. Fix each consecutive path $\frac{\pi}{3}$ radians away from the next such that the following points lie on the corresponding paths: $(1, 0) \in p_1$, $\left(\frac{1}{2}, \frac{\sqrt{3}}{2}\right) \in p_2$, $\left(-\frac{1}{2}, \frac{\sqrt{3}}{2}\right) \in p_3$, $(-1, 0) \in p_4$, $\left(-\frac{1}{2}, -\frac{\sqrt{3}}{2}\right) \in p_5$, $\left(\frac{1}{2}, -\frac{\sqrt{3}}{2}\right) \in p_6$. For S_i , there are i vertices on each path.

We define the six paths from origin as follows:

$$\begin{aligned} p_1 &= \{a \cdot (1, 0) = \vec{v} \mid a \in \mathbb{R}^+\} \\ p_2 &= \left\{a \cdot \left(\frac{1}{2}, \frac{\sqrt{3}}{2}\right) = \vec{v} \mid a \in \mathbb{R}^+\right\} \\ p_3 &= \left\{-a \cdot (1, 0) + a \cdot \left(\frac{1}{2}, \frac{\sqrt{3}}{2}\right) = a \cdot \left(-\frac{1}{2}, \frac{\sqrt{3}}{2}\right) = \vec{v} \mid a \in \mathbb{R}^+\right\} \\ p_4 &= \{a \cdot (-1, 0) = \vec{v} \mid a \in \mathbb{R}^+\} \\ p_5 &= \left\{a \cdot \left(-\frac{1}{2}, -\frac{\sqrt{3}}{2}\right) = \vec{v} \mid a \in \mathbb{R}^+\right\} \\ p_6 &= \left\{a \cdot (1, 0) - a \cdot \left(\frac{1}{2}, \frac{\sqrt{3}}{2}\right) = a \cdot \left(\frac{1}{2}, -\frac{\sqrt{3}}{2}\right) \mid a \in \mathbb{R}^+\right\} \end{aligned}$$

For S_i there exists i vertices on each path. We shall denote the i^{th} vertex on the j^{th} path as $v_{j,i}$. For each path defined above, the paths are defined as a set of vectors, $\vec{v} = a \cdot \vec{p}$ for some $a \in \mathbb{R}^+$ and $\vec{p} \in \mathbb{R}^2$. By setting $a = 1, 2, \dots, i$, we obtain points that are contained in V . For $j = 1, 3, 5$ and $l = 1, \dots, i$, there exists two paths attached to each vertex $v_{j,l}$. We borrow the term *petiole* from botany to describe the two paths attached to $v_{j,l}$. In botany, the stalk that attaches to a stem of a plant is called a petiole; petioles usually have leaves attached to their ends. For S_i , each petiole attached to the k^{th} vertex of p_j , there are $i - k$ vertices. We will need to show that each of the $i - k$ vertices on each corresponding path are also in V .

The triangular lattice is symmetric under rotation about v_0 by $\frac{\pi}{3}$ radians. For each vertex $v_{1,l}$ for $l = 1, 2, \dots, i - k$, we place two petioles from it; the first petiole $\frac{\pi}{3}$ above p_1 at $v_{1,l}$ and $\frac{-\pi}{3}$ below p_1 at $v_{1,l}$ and call these petioles $p_{1,l}^+$ and $p_{1,l}^-$ respectively. With respect to $v_{1,l}$, one unit along $p_{1,l}^+$ is a point on the triangular lattice and similarly so on $p_{1,l}^-$. Continuing the walk along these paths, unit distance-by-unit distance, we obtain the next point corresponding point on the the triangular lattice up to $i - k$ distance away from $v_{1,l}$. This shows that each of the $i - k$ vertices on $p_{1,l}^-$ and $p_{1,l}^+$ are in V . By rotating all of the paths along p_1 by $\frac{2\pi}{3}$ and $\frac{4\pi}{3}$, we obtain the the paths along p_3 and p_5 respectively, completing the construction.

In Figure 1.3, we have a set of unit radius disks arranged in a manner that outlines regular, concentric hexagons.

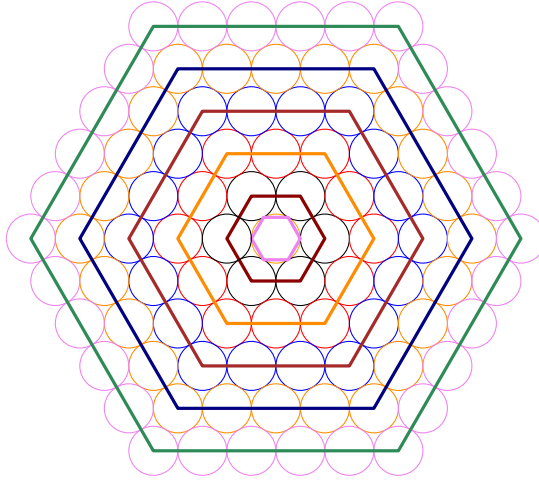


Figure 1.3: A contact graph that resembles the shape of concentric hexagons.

1.2.1 Perturbed Weighted Trees T_ε

A perturbed weighted tree T_ε is a weighted unit tree with unit weight on every vertex with the exception of the root vertex having weight $\frac{1}{2} + \varepsilon$ where $\varepsilon > 0$ can be realized as a disk touching graph (a disk arrangement).

The perturbed snowflake follows the construction of the perfect snowflake with the exception of v_0 having weight $\frac{1}{2} + \varepsilon$ where $\varepsilon > 0$. A perturbed snowflake realization has some distinct qualities from perfect snowflake realizations. The angular relationships between adjacent vertices may vary; the distance between adjacent and neighboring vertices may vary as well.

In general, the perturbation ε can modify the realization of a perfect snowflake S_i in the following ways:

Modification of S_1 .

Given an instance of a perturbed snowflake with v_0 having weight $\frac{1}{2} + \varepsilon$ where $\varepsilon > 0$, vertices neighboring v_0 each have a range of placement on the plane when realized as a disk arrangement. Figure ?? shows a realization of S_1 and illustrates one such example of possible gaps, ε , that could be created between adjacent disks of S_1 in a perfect snowflake.

Note that (1) the adjacent disks in a perfect snowflake may or may not be adjacent in a given perturbed snowflake of S_1 and (2) $S_1 \subseteq S_i$ for any $i \in \mathbb{N}$.

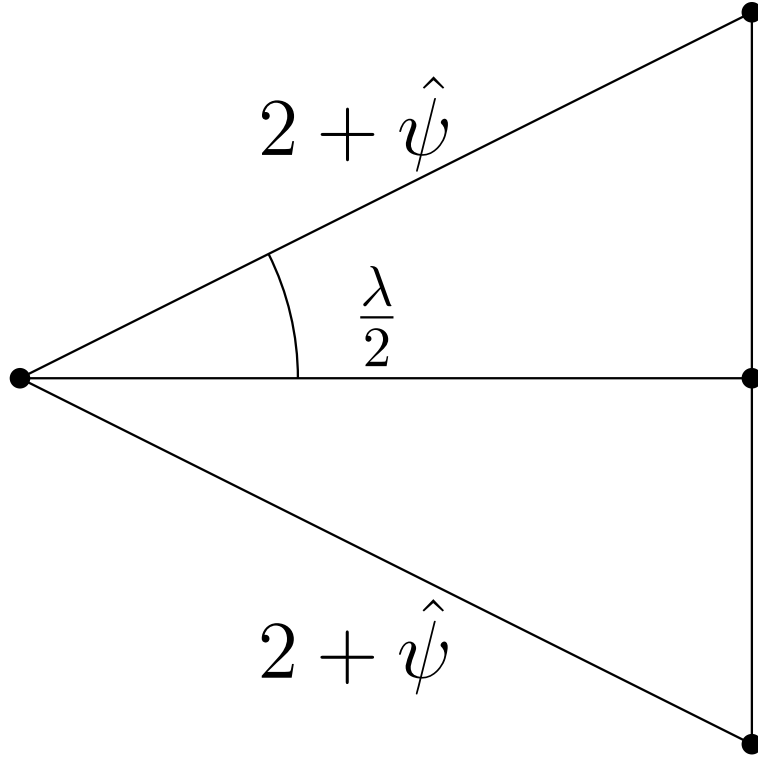


Figure 1.4

$$\begin{aligned}
 \sin\left(\frac{\pi}{6} - \chi\right) &= \frac{1}{2 + \psi} \\
 \sin\frac{\pi}{6} \cos\chi - \cos\frac{\pi}{6} \sin\chi &= \frac{1}{2 + \psi} \\
 \frac{1}{2} \cos\chi - \frac{\sqrt{3}}{2} \sin\chi &= \frac{1}{2 + \psi} \\
 &\geq \frac{1}{2 + \psi} + \frac{\sqrt{3}}{4} \chi - \frac{\sqrt{3}}{12} \chi^3 \\
 \frac{1}{2} &\geq \frac{1}{2 + \psi} + \frac{\sqrt{3}}{4} \chi
 \end{aligned}$$

$$\frac{\psi}{4} \geq \frac{\psi}{2(2 + \psi)} \geq \frac{\sqrt{3}}{4} \chi \iff \frac{\psi}{\sqrt{3}} \geq \chi$$

$$\frac{\pi}{3} - 2\chi = \lambda_{\min} \leq \lambda \leq \lambda_{\max} = \frac{\pi}{3} + 10\chi$$

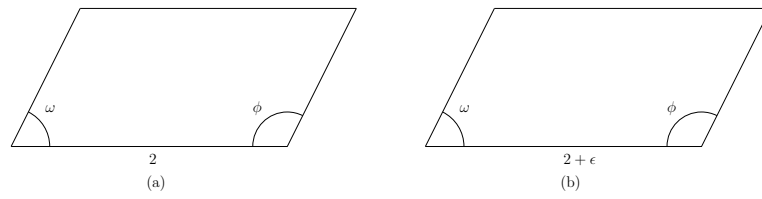


Figure 1.5

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