

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

We begin this chapter with the preliminary concepts to solving Problems ?? and ??, and then prove related Theorem ?. Recall the Unordered and Ordered Realizability Problem for a contact graph and corresponding theorem which state:

Problem ?? Given a planar graph with positive weighted vertices, is it a contact graph of some disk arrangement where the radii equal the vertex weights?

Problem ?? Given a planar graph with positive weighted vertices and a combinatorial embedding, is it a contact graph of some disk arrangement where the radii equal the vertex weights and the counter-clockwise order of neighbors of each disk is specified by the combinatorial embedding?

Theorem ?? 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.

The preliminary concepts for Disk Arrangements are the Unit Disk Touching Graph Recognition Problem, the Perturbed Root with Unit Disk Leaves Touching Graph Recognition Problem, and Hausdorff distance. All together the preliminary concepts will allow us to approximate the geometry of polygons and allow us to use the results of the polygonal linkages in Chapter ?.

1.1 Hausdorff Distance

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

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

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

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

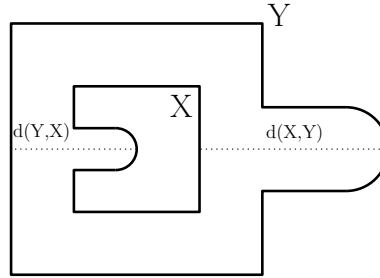


Figure 1.1: An illustrative example of $d(X, Y)$ and $d(Y, X)$ where X is the inner curve, and Y is the outer curve.

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.

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 Unit Disk Touching Graph Recognition Problem (UDTGRP)

The UDTGRP is to determine when given an instance of a weighted graph (V, E) where each vertex has unit weight can be realized as a disk touching graph (a disk arrangement).

In this section we describe a particular family of unit weight graphs and corresponding 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, S_i , is as follows:

- Let v_0 be a vertex 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 $i - j$.

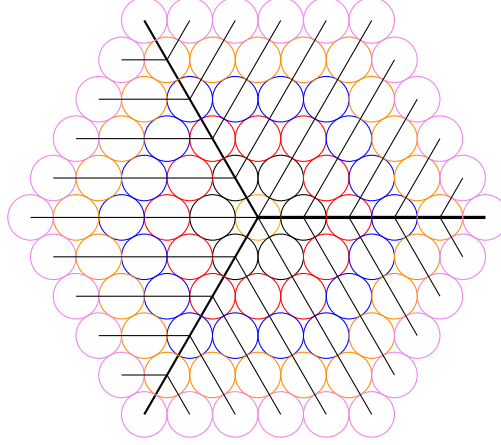


Figure 1.2: The same contact graph as in figure 1.3 overlaid with the a perfectly weighted snowflake tree.

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 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 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.

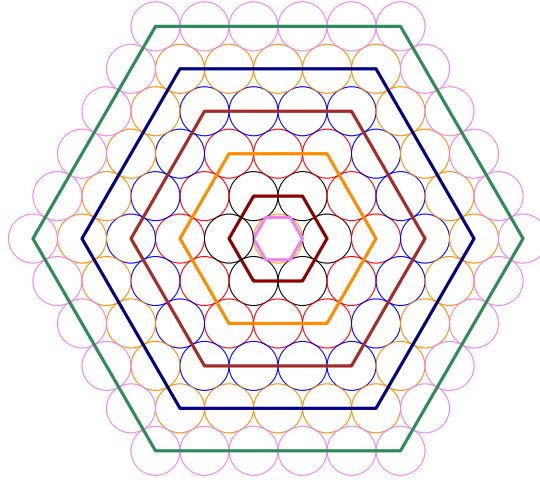


Figure 1.3: A contact graph that resembles the shape of concentric hexagons.

1.3 Perturbed Root with Unit Disk Leaves Touching Graph Recognition Problem (PRUDTGRP)

The PRUDTGRP is to determine when given an instance of a weighted tree (V, E) where each vertex has unit weight with the exception of the root vertex having weight $\frac{1}{2} + \gamma$ where $\gamma > 0$ 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 $\frac{1}{2} + \gamma$ where $\gamma > 0$. 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 γ can modify the realization of a perfect snowflake S_i in the following ways:

1. Modification of S_1 .

Given an instance of a perturbed snowflake with v_0 having weight $\frac{1}{2} + \gamma$ where $\gamma > 0$, 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, $\varepsilon(\gamma)$, 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 $i \in \mathbb{N}$.

Lemma 1. *For any realized perturbed snowflake S_i , the gaps created in subset $S_1 \subset S_i$ are small.*

2. **Modification of disk placement corresponding to vertices of p_k .** We've shown how the disks can be displaced in S_1 ; for larger snowflakes, the displacement can propagate through the remaining disks of the arrangement. The disks can along the paths p_1 through p_6 may also have displacement as well. In canonical position, the disks along paths p_1 through p_6 will form angles $\alpha_k = \frac{\pi}{3}$ and $\beta_k = \frac{2\pi}{3}$ (see Figure 1.4 for example). In noncanonical position, the disks along paths p_1 through p_6 will form angles that may vary.

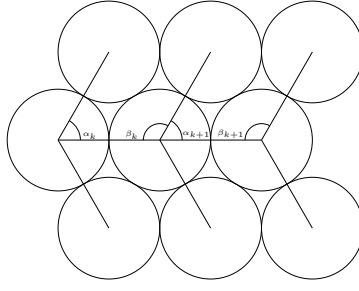


Figure 1.4: This figure shows a disk arrangement along a path p_k in canonical position. Note that perturbation in a snowflake and modify the placement of the disks in such a way that α_k and β_k or α_{k+1} and β_{k+1} may be of a noncanonical value.

Our goal here is to show that the change of the angular value of α_k and β_k are small:

Lemma 2. *For any realized perturbed snowflake S_i , the angular value of α_k and β_k are small.*

3. **Modification of disk placement along corresponding to the $p_{k,j}^{\text{th}}$ vertex of S_i .** For the j^{th} disk along the k^{th} path $p_{k,j}^+$ or $p_{k,j}^-$, perturbation can displace the position of the disk on the plane and the angular relationship of the neighboring disks (see Figure 1.5 for example).

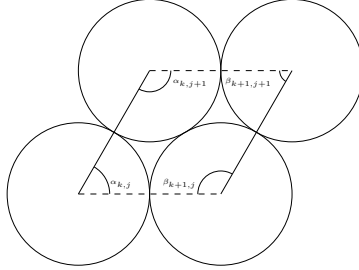


Figure 1.5: This illustration the relationship angular relationships between neighboring disks $D_{k,j}$, $D_{k+1,j}$, $D_{k+1,j+1}$, and $D_{k,j+1}$.

In this case we will show that the distances between the centers of neighboring disks are small relatively to canonical position of a perfect snowflake, i.e.

Lemma 3. *For any realized perturbed snowflake S_i , the distance between disks $D_{k,j}$, $D_{k+1,j}$, $D_{k+1,j+1}$, and $D_{k,j+1}$ are relatively small with respect to the relative distance in a perfect snowflake where $k = 1, \dots, 6$ and $j = 2, \dots, i$.*

We will show the proofs of Lemmas 1 through 3 later on.

1.4 Proofs of Lemmas 1 through 3

We now prove the Lemmas 1 through 3.

1.4.1 Proof of Lemma 1

Proof. Recall that we are to show that for any realized perturbed snowflake S_i , the gaps created in subset $S_1 \subset S_i$ are small.



Figure 1.6: A canonical disk arrangement from a perturbed snowflake with 6 unit disks around a central disk with radius $\frac{1}{2} + \gamma$.

One way to do this is to demonstrate that the sum of gaps for any realization of a contact graph of a perturbed snowflake S_1 is small. Denote the vertices around v_0 as v_1 through v_6 in a clockwise pattern about v_0 . Without loss of generality, given a realization denote $\epsilon_{k,k+1}(\gamma) \geq 0$ as the gap created between adjacent disks corresponding to v_1 through v_6 .

Consider the realization where $\epsilon_{k,k+1}(\gamma) = 0$ with the exception of $\epsilon_{1,6} > 0$. That is, every consecutive pair of disks about the central disk is in contact with each other with the exception of D_1 and D_6 . The realization provides 5 congruent triangles between the centers of D_0 and (D_1, D_2) , (D_2, D_3) , (D_3, D_4) , (D_4, D_5) , and (D_5, D_6) . Given perturbation $\gamma > 0$, the side lengths between (D_0, D_i) are $1 + \gamma$ and the side length of (D_i, D_{i+1}) is 1. Using law of cosine the angle formed between (D_0, D_i) and (D_0, D_{i+1}) is

$$2 \tan^{-1} \frac{1}{2(1 + \gamma)}.$$

The angle between (D_6, D_1) is

$$y = 2\pi - 5 \cdot \left(2 \tan^{-1} \frac{1}{2(1 + \gamma)} \right).$$

The side length of (D_6, D_1) is

$$\sqrt{-2(\gamma + 1)^2 \cos \left(-10 \arctan \left(\frac{1}{2(\gamma + 1)} \right) \right) + 2(\gamma + 1)^2}.$$

Note that as $\gamma \rightarrow 0$, the side length of (D_6, D_1) is approximately $1 + .466861$, where $\epsilon(\gamma) \approx .466861$ as $\gamma \rightarrow 0$. This establishes an upperbound on the maximal displacement about S_1 with respect to the side lengths between the centers of disks about D_0 .

The lower bound is established using the configuration found in Figure 1.6. The realization provides 6 congruent triangles between the centers of D_0 and each disk about D_0 . Without loss of generality, to find the side length of between neighboring disks about D_0 , we find need to $\epsilon(\gamma)$. The angle between (D_0, D_i) and (D_0, D_{i+1}) is $\frac{\pi}{3}$; using the law of cosine, we can determine the side length of (D_i, D_{i+1}) is

$$\sqrt{1 + 2\gamma + \gamma^2}.$$

Thus the perturbation about S_1 in and configuration is bounded and small. \square

1.4.2 Proof of Lemma 2

Proof. Recall that we are to show that for any realized perturbed snowflake S_i , the angular value of α_k and β_k are small. In canonical position, the angle between $p_{k,j}^+$ and $p_{k,j}^-$ is $\frac{\pi}{3}$. In a non-canonical position, we

define the change in angle to be $f(\varepsilon)$. About a We prove this with induction.



Figure 1.7

$$\begin{aligned}\alpha_i + \beta_i &\leq 120 + f(\varepsilon) \\ 2\pi &\leq \gamma_i + \delta_i + \frac{2\pi}{3} + f(\varepsilon) \\ 2\pi - (\gamma_i + \delta_i) &\leq \frac{2\pi}{3} + f(\varepsilon) \\ \alpha_{i+1} + \beta_{i+1} &\leq \frac{2\pi}{3} + f(\varepsilon)\end{aligned}$$

□

1.4.3 Proof of Lemma 3

Proof. Recall that we are to show that for any realized perturbed snowflake S_i , the distance between disks $D_{k,j}$, $D_{k+1,j}$, $D_{k+1,j+1}$, and $D_{k,j+1}$ are relatively small with respect to the relative distance in a perfect snowflake where $k = 1, \dots, 6$ and $j = 2, \dots, i$.



Figure 1.8

□

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