# The Farthest Point Map on the Regular Octahedron 

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## 1 Introduction

### 1.1 Background

A classic recreational problem in mathematics poses the following kind of question: Given a point on the surface of box, what is the farthest point away in the intrinsic sense? The intrinsic sense means that distances between points on the surface are measured in terms of lengths of paths on the surface of the box and not in terms of the ambient 3-dimensional Euclidean distance. The solution to this problem usually involves unfolding the surface and pressing it into the plane, so that the shortest paths can be studied in terms of ordinary planar geometry. In this paper we will study the same kind of question for the surface of the regular octahedron.

We begin with some generalities. Let $\left(X, d_{X}\right)$ be a compact metric space. The farthest point map, or farpoint map for short, associates to each point $p \in X$ the set $\mathcal{F}_{p} \subset X$ of points $q \in X$ which maximize the distance function $q \rightarrow d_{X}(p, q)$. From a dynamics point of view, it is nicer to have a map which carries points to points rather than points to subsets. Let $X^{\prime} \subset X$ be the set of points $p \in X$ such that $\mathcal{F}_{p}$ is just a single point. When $p \in X^{\prime}$ we let $F(p)$ be the unique member of $\mathcal{F}_{p}$. This gives us a map $F: X^{\prime} \rightarrow X$. To get a dynamical system, we define $X^{(1)}=X^{\prime}$. Inductively we let $X^{(n+1)}$ be the set of those points $p \in X^{\prime}$ such that $F(p) \in X^{(n)}$. The full orbit is well

[^0]defined on
\[

$$
\begin{equation*}
X^{(\infty)}=\bigcap_{n=1}^{\infty} X^{(n)} \tag{1}
\end{equation*}
$$

\]

In nice cases, $X^{(\infty)}$ is large enough to still be interesting.
I learned about the farpoint map on the regular octahedron from Peter Doyle, whose undergraduate student Annie Laurie Muahs-Pugh studied it in her Dartmouth College undergraduate thesis. At some point I wrote a graphical user interface, called Spider's Embrace [S1], which revealed essentially all the structure. In the intervening years, my PhD student Zili Wang wrote a thesis and a subsequent paper $[\mathbf{W}]$ which took Spider's Embrace as inspiration. She generalized some of the results to the case of centrally symmetric octahedra having all equal cone angles. I thought it would be good to rigorously prove the things I discovered using Spider's Embrace.

This paper has some overlap with other papers on the farpoint map. J. Rouyer's paper [R1] uses methods similar to the one in this paper to give an explicit computation of the farthest point map on the regular tetrahedron. The papers $[\mathbf{R 2}],[\mathbf{R 3}]$ study the farthest point map for general convex polyhedra, and (as we point out later in the paper) contain more general versions of a few of our subsidiary lemmas. The papers $[\mathbf{V 1}],[\mathbf{V 2}],[\mathbf{V Z}]$, and $[\mathbf{Z}]$ study the map on general convex surfaces. One focus has been on Steinhaus's conjecture concerning the ubiquity of points $p$ such that $F_{p}$ is a single point.

### 1.2 Statement of Results

Henceforth $X$ denotes the regular octahedron equipped with its intrinsic surface metric. Rather than think about the map $F$, it is nicer to think about the composition

$$
\begin{equation*}
f=F A=A F \tag{2}
\end{equation*}
$$

where $A: X \rightarrow X$ is the antipodal map. As our notation suggests, $A$ and $F$ commute. At first it might appear that in fact $A=F$, so that $f$ is the identity map, but this is not the case. Note that $f^{2}=F^{2}$, so we are not really changing the problem much by studying $f$ instead of $F$.

The map $f$ commutes with every isometry of $X$, so it suffices to describe the action of $f$ on a fundamental domain for the action of the isometry group. One sixth of a face of $X$ serves as such a fundamental domain. After
suitably scaling the metric and taking local coordinates, we can take for a fundamental domain the triangle $T$ having vertices

$$
\begin{equation*}
0, \quad 1, \quad\left(\frac{1}{4}, \frac{\sqrt{3}}{4}\right) \tag{3}
\end{equation*}
$$

Figure 1.1 shows a picture of $T$ and an auxiliary curve $J$. Figure 1.2 below shows how $T$ sits inside the (orange) face of $X$ containing it.


Figure 1.1: The domain $T$ and the curve $J$.
The curve $J$ is the graph of the function

$$
\begin{equation*}
y=\frac{1}{\sqrt{3}}\left(1-x-((2+x)(5-2 x)(1-4 x))^{1 / 3}\right) \tag{4}
\end{equation*}
$$

on the interval $[r, 1 / 4)$. Here $r \approx .239123$ is the real root of $x^{3}-x^{2}-4 x+1$. We do not consider the top endpoint to be belong to $J$.

Theorem 1.1 (Main) If $p=(x+i y) \in T-J$ then $\mathcal{F}_{p}$ is a single point. If $p \in T-J$ lies to the left of $J$, then

$$
\begin{equation*}
f(p)=\left(\frac{-x y-\sqrt{3} x+\sqrt{3} y^{2}-y}{\sqrt{3} x+y-2 \sqrt{3}}, y\right)=\left(\frac{A_{y} x+B_{y}}{C_{y} x+D_{y}}, y\right) . \tag{5}
\end{equation*}
$$

if $p \in T-J$ lies to the right of $J$, then

$$
\begin{equation*}
f(p)=\left(\frac{-x y+2 \sqrt{3} x+\sqrt{3} y^{2}-y}{\sqrt{3} x+y+\sqrt{3}}, y\right)=\left(\frac{D_{y} x-B_{y}}{-C_{y} x+A_{y}}, y\right) . \tag{6}
\end{equation*}
$$

If $p$ is the top vertex of $T$ then $f(p)=p$. If $p \in J$ then $A\left(\mathcal{F}_{p}\right)$ is the union of the two points given by the formulas above.

Figure 1.2 shows a geometric interpretation of the Main Theorem. The blue triangle is the fundamental domain $T$ and the orange triangle corresponds to the face of $X$ containing $T$. The grey triangle is a reflected copy of the orange one. The map in Equation 5 maps the blue point to the white point (on the same horizontal line) and the map in Equation 6 maps the white point to the blue point. In particular, the two branches of $f$ in $T$, when analytically continued to have a common domain, are inverses.


Figure 1.2 Geometric view of the maps.
Let $\partial_{\infty} T$ denote the union of the two non-horizontal sides of $T$. Let $L_{\infty}(f)$ denote the $\omega$-limit set. A point $p$ belongs to $L_{\infty}(f)$ is there is some point $q$ such that $\lim _{n \rightarrow \infty} f^{n}(q)=p$. We can use our result above to find $L_{\infty}(f)$ precisely. The restriction of $f$ to each maximal horizontal line segment $\lambda$ of $T-J$ is a linear fractional transformation having a unique fixed point in $\lambda$. The fixed point, namely $\lambda \cap \partial_{\infty} T$, is attracting. This fact, together with the rest of the Main Theorem, gives us the following corollary.

Corollary 1.2 The following is true.

1. $X^{\prime} \cap T=X^{(\infty)} \cap T=T-J$.
2. Let $p \in T-J$. Then $f(p)=p$ if and only if $p \in \partial_{\infty}(T)$.
3. $L_{\infty}(f) \cap T=\partial_{\infty} T$.

Figure 1.3 shows the intersection of $L_{\infty}(f)$ with one face of $X$.


Figure 1.3: $L_{\infty}(f)$ in one face.
Figure 1.4 shows the image of the set $J$ under 10 iterates of the dynamics. This picture illustrates how the dynamics moves points near $J$ out to the boundary of $T$. Let $J_{\ell}$ and $J_{r}$ be two copies of $J$ which, so to speak, lie infinitesimally to the left and the right of $J$. We iterate the left branch of $f$ on $J_{\ell}$ and the right branch on $J_{r}$. We have shaded in the regions between $f^{k}\left(J_{\ell}\right)$ and $f^{k}\left(J_{r}\right)$ for $k=1, \ldots, 10$.


Figure 1.4: Iterates of $J$ under the dynamics.
In $\S 2$ we prove the Main Theorem modulo some details we take care of in $\S 3$ and $\S 4$.

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## 2 The Proof in Broad Strokes

### 2.1 The Octahedral Plan

As in the introduction, $X$ denotes the regular octahedron equipped with its intrinsic metric. $X$ is locally Euclidean except for 6 cone points, each having cone angle $4 \pi / 3$. As a polyhedron, $X$ has 8 faces, each an equilateral triangle. Let $T$ be the fundamental domain discussed in the introduction. The blue triangle in Figure 2.1 is $T$. The black vertex of $T$, which we call the sharp vertex, corresponds to a cone point of $X$. Let $\Delta_{0}$ denote the face of $X$ that contains $T$. We identify $\Delta_{0}$ with the triangle in the plane whose vertices are the cube roots of unity. The face $\Delta_{0}$ is the one labeled 0 in Figure 2.1.

The face $\Delta$ is also a tile of a planar tiling $\mathcal{T}$ consisting of equilateral triangles which we call tiles. By convention, the faces of $X$ and the tiles of $\mathcal{T}$ are closed. Let $P$ be the union of tiles shown in Figure 2.1. We call $P$ the octahedral plan. There is a (unique) continuous locally isometric surjective map

$$
\begin{equation*}
\Psi: P \rightarrow X \tag{7}
\end{equation*}
$$

which is the identity on $\Delta_{0}$. We picture $X$ as sitting on $\Delta_{0}$, and $\Psi$ wraps $P$ around $X$ as if we were wrapping a gift. We have numbered the tiles of $P$ to indicate their images under $\Psi$. We say that a $j$-tile is a tile that is labeled $j$. The map $\Psi$ carries the 7 -tiles to the face of $X$ antipodal to $\Delta_{0}$. Let $A_{k}$ be the 7-tile also labeled $(k)$. Finally, we mention that the blue circle, centered on the sharp vertex, has radius 3 .


Figure 2.1: The octahedral plan $P$.

The 6 cone points of $X$ are grouped into 3 pairs of antipodal points. We use 3 colors to color these pairs: black, white, and grey. The vertices of the octahedral plan are colored according to this scheme. Thus, $\Psi$ maps all the white vertices to the union of the two white cone points of $X$, and likewise for the other colors. The next result is contained in [R3, Corollary 13]. We give a self-contained proof.

Lemma 2.1 If $p$ is a cone point then $\mathcal{F}_{p}$ is just the antipodal point.
Proof: It suffices to prove this when $p$ is the sharp vertex of $T$. Let $p^{\prime}$ be the antipodal point. Rolling $X$ out onto the equilateral tiling along a shortest geodesic segment connecting $p$ to $p^{\prime}$, we see that the image of $p^{\prime}$ is another black vertex of the planar tiling. The closest black vertices to $p$ lie on (the blue circle) $\partial D$, where $D$ is the disk of radius 3 centered at $p$. Hence $d_{X}\left(p, p^{\prime}\right)=3$. Looking at Figure 2.1, we see that $D^{o}$ contains all points of a $j$-tile, except perhaps the black vertex, for each $j=0, \ldots, 7$. Hence $\Psi\left(D^{o}\right)=X-p^{\prime}$. Hence, $d_{X}\left(p, q^{*}\right)<3$ for all $q^{*} \in X-p^{\prime}$.

We prove the following result in $\S 3$.
Lemma 2.2 (Octahedral Plan) If $p \in \Delta_{0}$ and $q^{*} \in X$, then we have $d_{X}\left(p, q^{*}\right)=|p-q|$ for some $q \in \Psi^{-1}\left(q^{*}\right)$. If $q^{*} \in \mathcal{F}_{p}$, the point $q$ lies in a 7-tile of $P$.

The Octahedral Plan Lemma combines with the properties of $\Psi$ to give the following more precise result: As long as $\Psi^{-1}\left(q^{*}\right)$ contains a point in a 7 -tile, we have

$$
\begin{equation*}
\Psi^{-1}\left(q^{*}\right)=\left\{q_{0}, \ldots, q_{5}\right\}, \quad \forall j q_{j} \in A_{j}, \quad d_{X}\left(p, q^{*}\right)=\min _{k}\left|p-q_{k}\right| \tag{8}
\end{equation*}
$$

### 2.2 The Hexagon

Let $T^{o}$ be the interior of the fundamental domain $T$. There are (unique) isometries $I_{j}$ for $j=0, \ldots, 5$ such that:

- $I_{j}$ preserves the white-black-grey vertex coloring.
- $I_{j}\left(A_{j}\right)=A_{0}$.
- $\Psi \circ I_{j}=\Psi$ on $A_{j}$ and $\Psi=\Psi \circ I_{j}^{-1}$ on $A_{0}$.

Referring to the points in Equation 8, these properties imply that

$$
\begin{equation*}
I_{j}\left(q_{j}\right)=I_{k}\left(q_{k}\right), \quad \forall j, k \in\{0, \ldots ., 5\} . \tag{9}
\end{equation*}
$$

For a proof, use the fact that $\Psi: A_{0} \rightarrow X$ is injective.
The map $I_{0}$ is the identity. If $k \equiv j+3 \bmod 6$ then $I_{j} I_{k}^{-1}$ is a translation. Otherwise $I_{j} I_{k}^{-1}$ is a 120 degree rotation about a vertex $v_{j k}$. These are the big colored vertices in Figure 2.4 below. We let $T_{j}=I_{j}(T)$. The blue triangles in Figures 2.2 are $T_{0}, \ldots, T_{5}$. Given $p \in T$ (not the sharp vertex) we define

$$
\begin{equation*}
p_{j}=I_{j}(p) \in T_{j}, \quad j=0, \ldots, 5 \tag{10}
\end{equation*}
$$

Let $H_{p}$ be the (solid) hexagon with vertices $p_{0}, \ldots, p_{5}$.


Figure 2.2: The hexagon $H_{p}$ and the triangle $A_{0}$.
Lemma $2.3 H_{p}$ is convex, and all its inner angles are less than $\pi$.
Proof: Given the placement of the blue triangles, it is clear that the inner angle of $H_{p}$ is less than $\pi$ at $p_{j}$ for $j=1,2,3,4,5$. Consider the case $j=0$. Clockwise rotation by 120 degrees about $v_{01}$ maps $p_{1}$ to $p_{0}$. Clockwise rotation by 120 degrees about $v_{05}$ maps $p_{0}$ to $p_{5}$. Considering the three cases when $p_{0}$ is a vertex of $T_{0}$, for these are the extreme cases for the estimate at hand, we see that $\overline{p_{0} p_{1}}$ has slope in $[-\sqrt{3}, 0)$ and $\overline{p_{0} p_{5}}$ has slope in $[-\infty,-\sqrt{3}$ ). (One can also see this by a direct and easy calculation.) This shows that the inner angle at $p_{0}$ is less than $\pi$.

### 2.3 The Voronoi Decomposition

Given $q \in H_{p}$ let

$$
\begin{equation*}
\mu_{p}(q)=\min _{k \in\{0, \ldots, 5\}}\left|q-p_{k}\right| . \tag{11}
\end{equation*}
$$

We say that a minimal index for $q$ is an index $j$ such that $\mu_{p}(q)=\left|q-p_{j}\right|$. The $j$ th Voronoi cell $C_{j}$ is the set of points $q \in H_{p}$ having $j$ as one of their minimal indices. That is, $\mu_{p}(q)=\left|q-p_{j}\right|$. The list $C_{0}, \ldots, C_{5}$ is the Voronoi decomposition of $H_{p}$. The Voronoi cells are convex polygons. Each Voronoi cell has two edges in $\partial H_{p}$, and its remaining edges are contained in the union of bisectors defined by pairs of vertices of $H_{p}$. See Figures 2.3 and 2.4.


Figure 2.3: $H_{p}$ and its Voronoi decomposition.
Remark: I produced Figure 2.3 in Mathematica, using the same formulas I use in $\S 4$ to do the calculations in the paper. The picture corresponds to the parameters $a=b=1 / 2$. I mention this as a sanity check that I have correctly typed the formulas in to Mathematica. Figure 2.4 and 2.5 are produced by my Java program.

Given distinct indices $i, j, k$, let $(i j k)$ as the unique point equidistant from vertices $p_{i}, p_{j}, p_{k}$. Lemma 2.3 guarantees that this point is well-defined and various continuously with $p \in T$. Relatedly, we say that an essential vertex is a point belonging to at least 3 Voronoi cells. In Figure 2.3 there are 4 distinct essential vertices, namely: (012), (025), (235), (345). In §4 we prove:

Lemma 2.4 (Structural Stability) For all $p \in T$ the essential vertices are (012), (025), (235), (345). When $p \in T^{o}$ these 4 triples are distinct.

In the boundary case the 4 triples are never (completely) distinct. See Figure 2.5 below for an example. If $(012)=(235)$ we write (0235), etc.

Let $T^{\prime}$ denote the edge of $T$ that lies in the edges of the equilateral tiling. This is the long non-horizontal side. See Figure 2.4. Also, Figure 2.5 shows why we need to exclude $T^{\prime}$ in our next result.

Lemma 2.5 If $p \in T-T^{\prime}$ then (012), (025), (235), (345) lie in $A_{0}^{o}$.
Proof: Our proof refers to Figure 2.4 below. In figure 2.4, $b_{j k}$ is the bisector for the points $\left(p_{j}, p_{k}\right)$. The point $v_{j k}$ fixed by $I_{j} I_{k}^{-1}$ is the circled point labeled $j k$. (Our coloring convention is that the yellow points play no role in the proof, and that the red and green points play special roles in the proof.) The segments $e_{01}, e_{23}, e_{45}$ are the edges of $A_{0}$. We get our bounds by considering the action of the map $I_{j} I_{k}^{-1}$, which is usually a 120 degree rotation, on the vertices of $T_{k}$. Let $\overleftrightarrow{e}$ denote the line extending the edge $e$. We say that a line $\ell$ lies between two lines $\mu_{1}$ and $\mu_{2}$ if $\ell$ contains the crossing point $\mu_{1} \cap \mu_{2}$ and if $\ell$ lies in the acute cone determined by $\mu_{1}$ and $\mu_{2}$.

We have $v_{45} \in b_{45}$, and $b_{45}$ lies between $\overleftrightarrow{v_{45} v_{34}}$ and $\overleftrightarrow{v_{45} v_{12}}$, and $v_{34} \notin b_{45}$. Hence $b_{45}$ intersects both edges $e_{23}$ and $e_{45}$, and not at the vertex $v_{34}$. At the same time, $v_{34} \in b_{34}$, and $b_{34}$ lies strictly between $\overleftrightarrow{e_{23}}$ and $\overleftrightarrow{e_{45}}$. Hence $(345)=b_{45} \cap b_{34} \in A_{0}^{o}$. The proof for (012) is the same, with indices $0,1,2$ in place of $5,4,3$.

Since $v_{35},(345),(235)$ are collinear, and $v_{02},(012),(025)$ are collinear, and $v_{35}, v_{34}, v_{12}, v_{02}$ are collinear, and (012), (345) $\in A_{0}^{o}$ we see that (235) and (025) lie to the left of $\overleftrightarrow{e_{23}}$. The altitude of $A_{0}$ through $v_{34}$ is parallel to $b_{25}$ and either equals $b_{25}$ (in an extreme case) or lies to the left of it. Hence (025) and (235) lie to the right of $\overleftrightarrow{e_{45}}$. Since $v_{05} \in b_{05}$ lies to the right of $b_{25}$ and has non-negative slope, (025) lies above $\overleftrightarrow{e_{01}}$. Since $v_{23} \in b_{23}$ lies to the left of $b_{25}$ and has non-positive slope, we see that (235) lies above $\overleftrightarrow{e_{01}}$.


Figure 2.4: $H_{p}$ and its Voronoi decomposition.
Lemma 2.5 combines with the Structural Stability Lemma to show that the essential vertices lie in $A_{0}$ even when $p \in \partial T$. The only case not covered by what we have already done is when $p \in T^{\prime}$. When $p \in T^{\prime}$, reflection in $e_{23}$ swaps $p_{0}, p_{5}$ with $p_{2}, p_{3}$. This gives us $(345)=v_{34}$ and $(012)=v_{12}$ and $(025)=(235) \in e_{23}^{o} \subset b_{02}=b_{35}$. We get $(0235) \in e_{23}^{o}$ because we are excluding the sharp point. See Figure 2.5. We also note that $(025)=(235)$ when $p$ lies in the short non-horizontal edge of $A_{0}$. In this case, reflection in the horizontal line through $v_{05}$ swaps $p_{0}, p_{2}$ with $p_{5}, p_{3}$.


Figure 2.5: $H_{p}$ and its Voronoi decomposition.
Lemma 2.6 Let $q \in A_{0}$. If $q$ is not an essential vertex then there is some $r \in A_{0}$ such that $\mu_{p}(q)<\mu_{p}(r)$.

Proof: If $q$ is disjoint from all cells but at most 2, we have at least one direction where we can vary $q$ so as to increase $\mu_{p}$. If $q \in A_{0}^{o}$ we are done. If $q \in \partial A_{0}$ and lies in only one cell, then $q$ cannot be a vertex of $A_{0}$, so we can vary $q$ in at least one direction along the edge of $\partial A_{0}$ so as to increase $\mu_{p}$. This leaves the case when $q \in \partial A_{0}$ lies $C_{i} \cap C_{j}$. Since all essential vertices lie in $A_{0}$, the bisector $b_{i j}$ starts out on $\partial H_{p}$, enters $A_{0}$, then encounters an essential vertex $\beta$ before exiting $A_{0}$. After $b_{i j}$ hits $\beta$ it is disjoint from $C_{i}$ and $C_{k}$. Therefore, $q$ lies between $b_{i j} \cap \partial H_{p}$ and $\beta$. But then we push $q$ along $b$ towards $\beta$ to increase $\mu_{p}$, and this keeps us in $A_{0}$.

### 2.4 Setting up a Vertex Competition

The reader can compare our next result with [R2, Lemma 3]. The result there, though stated in different language, is essentially equivalent.

Lemma 2.7 (Vertex) If $q^{*} \in \mathcal{F}_{p}$, then $q^{*}=\Psi(q)$ where $q \in A_{0}$ is such that $\mu_{p}(q) \geq \mu_{q}(r)$ for all $r \in A_{0}$. In particular, $q$ is an essential vertex.

Proof: Let $q_{0}, \ldots, q_{5}$ be as in Equation 8, Let $q=q_{0}$. By Equations 8 and [9, we have

$$
q=I_{0}\left(q_{0}\right)=\ldots=I_{5}\left(q_{5}\right) \in A_{0}, \quad \Psi(q)=q^{*}
$$

Since $I_{j}$ is an isometry, $\left|p-q_{k}\right|=\left|p_{k}-q\right|$ for all $k$. Hence

$$
\begin{equation*}
d_{X}\left(p, q^{*}\right)=\min _{k}\left|q_{k}-p\right|=\min _{k}\left|q-p_{k}\right|=\mu_{p}(q) \tag{12}
\end{equation*}
$$

For any $r \in A_{0}$ we set $r^{*}=\Psi(r)$. Then Equation 8 applies to $r^{*}$ just as to $q^{*}$. Hence, Equation 12 holds as well. This gives

$$
\mu_{p}(r)=d_{X}\left(p, r^{*}\right) \leq d_{X}\left(p, q^{*}\right)=\mu_{p}(q)
$$

In short $\mu_{p}(q) \geq \mu_{p}(r)$ for all $r \in A_{0}$. By Lemma [2.6, the point $q$ is an essential vertex.

Lemma 2.8 $\mathcal{F}_{p} \subset\{\Psi((025), \Psi((235))\}$.
Proof: Our argument refers to Figure 2.4. The Structural Stability Lemma and the Vertex Lemma imply that

$$
\mathcal{F}_{p} \subset\{\Psi((012)), \Psi((025), \Psi((235)), \Psi((345))\}
$$

The line $\overleftrightarrow{p_{0} p_{2}}$ lies entirely beneath $A_{0}$ and in particular beneath the segment of $b_{02}$ connecting (012) to (025). Also, $\overleftrightarrow{p_{0} p_{2}}$ and $b_{02}$ are perpendicular. Therefore, as we move from $\zeta=(012)$ to $\zeta=(025)$ along $b_{02}$ we increase the function $\left|\zeta-p_{0}\right|=\left|\zeta-p_{2}\right|$. This shows that $\mu_{p}((012))<\mu_{p}((025))$ whenever $(012) \neq(025)$. The Vertex Lemma now eliminates (012) when it does not equal (025).

Since $p$ is not the sharp vertex, the same argument, with the indices $5,4,3,2$ in place of $0,1,2,3$, shows that $\mu_{p}((345))<\mu_{p}((235))$ whenever $(345) \neq(235)$. The Vertex Lemma now eliminates (345) when it does not equal (235).

### 2.5 The Vertex Competition

Let

$$
\begin{equation*}
G(p)=\left|p_{2}-(025)\right|^{2}-\left|p_{2}-(235)\right|^{2} \tag{13}
\end{equation*}
$$

In 84.2 , we show that

- $G(p)>0$ if $p \in T-\partial_{\infty}(T)$ lies to the left of $J$.
- $G(p)<0$ if $p \in T-\partial_{\infty}(T)$ lies to the right of $J$.
- $G(p)=0$ on $J \cup \partial_{\infty} T$.

By the Vertex Lemma and Lemma 2.8,

- $\mathcal{F}_{p}=\{\Psi((025))\}$ when $p \in T-\partial_{\infty} T$ lies to the left of $J$ and
- $\mathcal{F}_{p}=\{\Psi((235))\}$ when $p \in T-\partial_{\infty} T$ lies to the right of $J$.
- $\mathcal{F}_{p}=\left\{\Psi((025), \Psi((235))\}\right.$ when $p \in J \cup \partial_{\infty} T$.

The last case needs more analysis. When $p \in \partial_{\infty}(T)$ we have $(025)=(235)$, as already discussed. When $p \in J$, the points (025) and (235) are distinct. The Structural Stability Lemma shows this for points of $J \cap T^{o}$. For the bottom endpoint of $J$, see the remark at the end of $\$ 4.1$.

It only remains to get the formulas from the Main Theorem. Recall that $f=F A=A F$ where $A$ is the antipodal map and $F(p)$ is defined to be the member of $\mathcal{F}_{p}$ when $\mathcal{F}_{p}$ is a single point. Define

$$
\begin{equation*}
\alpha_{0}(z)=\exp ^{-2 \pi i / 3}(2-i \sqrt{3}-\bar{z}) \tag{14}
\end{equation*}
$$

The map $\alpha_{0}$ has the propery that $\alpha_{0}\left(A_{0}\right)=\Delta_{0}$, in a way that preserves the vertex coloring in Figure 2.1. Hence

$$
\Psi \circ \alpha_{0}=A \circ \Psi
$$

So, when $F(p)=\Psi((025))$, we get $f(p)=\alpha_{0}((025))$. This is exactly the map given in Equation 55. When $F(p)=\Psi((235))$, we get $f(p)=\alpha_{0}((235))$. This is exactly the map given in Equation 5. Finally, when $p \in \partial_{\infty}(T)$, either formula gives $f(p)=p$. This establishes all parts of the Main Theorem.

## 3 The Octahedral Plan Lemma

### 3.1 General Points

In this section we prove the first statement of the Octahedral Plan Lemma.
Lemma 3.1 If $p \in \Delta_{0}$ and $q^{*} \in X$ then we have $d_{X}\left(p, q^{*}\right)=|p-q|$ for some $q \in \Psi^{-1}\left(q^{*}\right)$.

Proof: To avoid trivialities we assume that $q^{*} \neq p$.
Let $\alpha^{*}$ be a length-minimizing geodesic segment connecting $p$ to $q^{*}$. Since $X$ has positive curvature at its cone points, $\alpha^{*}$ contains no cone points in its interior. We can therefore uniquely develop $X$ out onto the equilateral tiling $\mathcal{T}$, along $\alpha^{*}$, to get a segment $\alpha \subset \boldsymbol{R}^{2}$. The segments $\alpha$ and $\alpha^{*}$ have the same length. Since the octahedral plan $P$ is star shaped with respect to $p$, we have $\Psi(q)=q^{*}$ provided that $q \in P$. We will suppose $q \notin P$ and get a contradicton.

By symmetry it suffices to consider the case when $\alpha$ crosses the two blue edges in Figure 3.1. If $\alpha$ exits $P$ then it exits through one of the red edges. So, by passing to a sub-arc of $\alpha^{*}$, which is also a distance minimizer, we can assume without loss of generality that $q$ lies in either the yellow tile or one of the green tiles.


Figure 3.1: Filling in around the octahedral plan
We treat all three cases in the same way. See Figure 3.2. In each case we have placed a purple equilateral triangle $\tau$ about a certain vertex $v$ in the tiling. Rotation by 120 degrees about $v$ is a color-preserving automorphism of the tiling which preserves $\tau$. The points $q$ and $r$ are both vertices of $\tau$ and $r$ lies in the octahedral plan. Let $r^{*}=\Psi(r)$.


Figure 3.2: The three cases
We claim that $q^{*}=r^{*}$. Let $\zeta_{q}$ and $\zeta_{r}$ respectively be the faces of $X$ containing $q^{*}$ and $r^{*}$. Given the color-preserving nature of the rotation carrying $q$ to $r$ it suffices to prove that $\zeta_{q}=\zeta_{r}$. In the first case, $\zeta_{q}$ and $\zeta_{r}$ share the vertex $\Psi(v)$ and are separated by 2 edges from the face $\Psi\left(B_{1}\right)$. Hence $\zeta_{q}=\zeta_{r}$. The second case has the same proof, with $B_{2}$ replacing $B_{1}$. In the third case, both $\zeta_{q}$ and $\zeta_{r}$ are the face antipodal to $\Psi\left(B_{1}\right)$, and hence coincide. This proves our claim.

In each case, all points of $\Delta_{0}$ except perhaps the sharp vertex lie on the same side of the (red colored) bisector $(r, q)$ as does $r$. Hence $|p-r|<|p-q|$. We get strict inequality because $q \notin P$. Given that $\Psi(\overline{p r})$ has the same endpoints as $\alpha^{*}$ and is shorter, we have a contradiction.

### 3.2 Points in the Farthest Point Set

This section is devoted to the proof of the second statement of the Octahedral Plan Lemma.

We use the octahedral plan labeling as in Figure 2.1. Suppose $q^{*} \in \mathcal{F}_{p}$. Let $q$ be as in Lemma 3.1. We suppose that $q$ does not lie in a 7 -tile and we derive a contradiction. If $q$ avoids all $k$-tiles for $k>3$ then we can choose $s \in \overrightarrow{p q}$ such that $|p-s|>|p-q|$ and $\Psi^{-1}\left(s^{*}\right)=\{s\}$, where $s^{*}=\Psi(s)$. But then we have a contradiction:

$$
d_{X}\left(p, q^{*}\right)=|p-q|<|p-s|=d_{X}\left(p, s^{*}\right) .
$$

The last equality is Lemma 3.1.


Figure 3.3: Pushing out $q_{j}$ towards $r_{j}$.
For the remaining cases, we can assume by symmetry that $q$ lies in a 5 -tile and avoids all 7 -tiles. Our argument refers to Figure 3.3. We have $q \in \Psi^{-1}\left(q^{*}\right)=\left\{q_{0}, q_{1}\right\}$ where $q_{j}$ lies in the 5 -tile sharing an edge $e_{j}$ with $A_{j}$. Let $r_{j}=e_{j} \cap \overleftrightarrow{v_{0} q_{j}}$ (or else the midpoint of $e_{j}$ when $v_{0}=q_{0}=q_{1}$.) Let $B_{j}$ be the bisector defined by $\left(q_{j}, r_{j}\right)$. The tile $\Delta_{0}$ lies on the same side of $B_{j}$ as does $q_{j}$. Therefore $\left|p-r_{j}\right|>\left|p-q_{j}\right|$. Rotation by 120 degrees clockwise about $v_{0} \operatorname{maps}\left(q_{0}, r_{0}, e_{0}\right)$ to $\left(q_{1}, r_{1}, e_{1}\right)$.

By continuity and symmetry, there exists points $s_{j} \in \overline{q_{j} r_{j}}$ which avoid the 7-tiles and satisfy $\left|p-s_{j}\right|>\left|p-q_{j}\right|$ and $s^{*}=\Psi\left(s_{0}\right)=\Psi\left(s_{1}\right)$. But then $\Psi^{-1}(s)=\left\{s_{0}, s_{1}\right\}$ and we have a contradiction:

$$
d_{X}\left(p, q^{*}\right)=\min \left(\left|p-q_{0}\right|,\left|p-q_{1}\right|\right)<\min \left(\left|p-s_{1}\right|,\left|p-s_{2}\right|\right)=d_{X}\left(p, s^{*}\right)
$$

The last equality is Lemma 3.1.

## 4 The Calculations

### 4.1 Structural Stability

We will be considering functions on $T$, the fundamental domain. It will be more convenient to deal with functions on the unit square $[0,1]^{2}$. So, we explain a convenient map from $[0,1]^{2}$ to $T$. We define

$$
\begin{equation*}
(x, y)=\phi(a, b)=\left(a+\frac{1}{4}(1-a) b, \frac{\sqrt{3}}{4}(1-a) b\right) \tag{15}
\end{equation*}
$$

Here $\phi$ is a surjective polynomial map from $[0,1]^{2}$ to $T$ which maps $(0,1)^{2}$ onto $T^{o}$. We get $\phi$ by composing the map $(a, b) \rightarrow(a, a b)$ with an affine map from the triangle with vertices $(0,0),(1,0),(1,1)$ to $T$.

We first prove the Structural Stability Lemma for $p \in T^{o}$. The combinatorics of the Voronoi decomposition can change only if one of the edges of the cell decomposition collapses to a point. The only edges for which this can happen are those joining consecutive points on the list (012), (025), (235), (345). Such an edge collapses if and only if one of the quadruples (0125), (0235), (2345) is such that the corresponding vertices are equidistant from a single point - i.e. co-circular. We rule this out.

As is well known, 4 distinct points $z_{1}, z_{2}, z_{3}, z_{4} \in \boldsymbol{C}$ are co-circular only if

$$
\begin{equation*}
\chi\left(z_{1}, z_{2}, z_{3}, z_{4}\right)=\operatorname{Im}\left(\left(z_{1}-z_{2}\right)\left(z_{3}-z_{4}\right) \overline{\left(z_{1}-z_{3}\right)\left(z_{2}-z_{4}\right)}\right)=0 \tag{16}
\end{equation*}
$$

This function is the imaginary part of the cross ratio. (It also vanishes when the points are collinear.) Thus, it suffices to prove that the 3 functions

$$
\begin{equation*}
T_{i j k \ell}=\frac{16}{27 \sqrt{3}} \chi\left(p_{i}, p_{j}, p_{k}, p_{\ell}\right) \circ \phi \tag{17}
\end{equation*}
$$

corresponding to the quads above never vanish on $(0,1)^{2}$. The factor out in front is included to make the formulas below nicer. Now we give formulas for the vertices of $H_{p}$. Let

$$
\begin{equation*}
Z\left(k_{1}, \ell_{1}, k_{2}, \ell_{2} ; p\right)=w\left(k_{1}, \ell_{1}\right) p+w\left(k_{2}, \ell_{2}\right), \quad w(k, \ell)=\frac{k+\ell \sqrt{3} i}{2} \tag{18}
\end{equation*}
$$

We have $p=p_{0}=x+i y$, and then a careful inspection of Figure 2.2 gives us

1. $p_{1}=Z(-1,+1,+3,-1 ; p)$.
2. $p_{2}=Z(-1,-1,+9,+1 ; p)$.
3. $p_{3}=Z(+2,+0,+9,+3 ; p)$.
4. $p_{4}=Z(-1,+1,+3,+5 ; p)$.
5. $p_{5}=Z(-1,-1,+0,+4 ; p)$.

We plug this in to Equation 17 and factor using Mathematica [Wo]:

$$
\begin{equation*}
T_{0125}=(a-1) b \nu_{1}, \quad T_{2345}=(1-a) b \nu_{2}, \quad T_{0235}=24 a(a-1)(b-1) \tag{19}
\end{equation*}
$$

Here, $\nu_{1}$ and $\nu_{2}$ are positive on $[0,1]^{2}$ :

$$
\begin{aligned}
& \nu_{1}=\left(8-4 a^{2}-b^{2}\right)+\left(8 a-4 a b-a^{2} b^{2}\right)+\left(2 b+2 a^{2} b+2 a b^{2}\right) \\
& \nu_{2}=\left(16 a-2 a b-2 a^{2} b-2 a b^{2}\right)+\left(4+a^{2} b^{2}+4 a^{2}+4 b+b^{2}\right)
\end{aligned}
$$

Hence our 3 functions in Equation 19 are positive on $(0,1)^{2}$. This completes the proof when $p \in T^{o}$.

For the boundary case, we just have to see that there is no $p \in \partial T$ such that the cells $C_{i_{1}}, \ldots C_{i_{k}}$ meet at a point and less than 3 of these indices come from one of the 4 triples above. If this happens, then by continuity the same thing happens when $p$ is perturbed into $T^{o}$. Hence, this does not happen. This proves the Structural Stability Lemma in the boundary case.

Remark: The case when $p$ lies in the interior of the bottom edge of $T$ corresponds to $b=0$ and $a \in(0,1)$. In this case, $T_{0235} \neq 0$. This means that (012) and (235) are distinct in this case.

### 4.2 The Vertex Competition

In this section we calculate the function $G$ from $\$ 2.5$, Using the formulas for the vertices listed above, we compute the relevant bisectors and the relevant intersections of these bisectors to arrive at formulas for the essential vertices. Here they are.

$$
\begin{gathered}
(012)=\frac{3 \sqrt{3} x^{2}-6 y x-11 \sqrt{3} x+21 y+5 y^{2} \sqrt{3}+8 \sqrt{3}}{2\left(\sqrt{3} x^{2}-3 \sqrt{3} x+3 y+y^{2} \sqrt{3}+2 \sqrt{3}\right)}+i \frac{3 x^{2}-2 \sqrt{3} y x-15 x-3 y^{2}-\sqrt{3} y+12}{2\left(\sqrt{3} x^{2}-3 \sqrt{3} x+3 y+y^{2} \sqrt{3}+2 \sqrt{3}\right)} \\
(025)=\frac{2 \sqrt{3} y^{2}+2 x y-3 y+3 x \sqrt{3}-8 \sqrt{3}}{2(y+x \sqrt{3}-2 \sqrt{3})}+i \frac{2 y^{2}-2 \sqrt{3} x y+3 \sqrt{3} y+3 x-12}{2(y+x \sqrt{3}-2 \sqrt{3})} \\
(235)=\frac{\sqrt{3} y^{2}+x y+3 y+3 x \sqrt{3}+2 \sqrt{3}}{y+x \sqrt{3}+\sqrt{3}}+i \frac{y^{2}-\sqrt{3} x y+6 x+3}{y+x \sqrt{3}+\sqrt{3}} \\
(345)=\frac{3 \sqrt{3} x^{2}+8 \sqrt{3} x-3 y+y^{2} \sqrt{3}+4 \sqrt{3}}{\sqrt{3} x^{2}+3 \sqrt{3} x-3 y+y^{2} \sqrt{3}+2 \sqrt{3}}+i \frac{6 x^{2}+2 y \sqrt{3} x+15 x+6 y^{2}-2 \sqrt{3} y+6}{\sqrt{3} x^{2}+3 \sqrt{3} x-3 y+y^{2} \sqrt{3}+2 \sqrt{3}}
\end{gathered}
$$

For $G$ we don't make the change of variables, but rather compute in terms of $p=x+i y \in T^{o}$. We have

$$
G(x+i y)=-\frac{18 H(x+i y)}{(\sqrt{3} x+y-2 \sqrt{3})^{2}(\sqrt{3} x+y+\sqrt{3})^{2}}
$$

where

$$
H(x+i y)=\left(\begin{array}{c}
3 x^{5}-6 x^{4}-9 x^{3}+15 x^{2}-3 x \\
3 \sqrt{3} x^{4}-4 \sqrt{3} x^{3}-6 \sqrt{3} x^{2}-3 \sqrt{3} x+\sqrt{3} \\
2 x^{3}-6 x^{2}+15 x-2 \\
2 \sqrt{3} x^{2}-2 \sqrt{3} \\
-x+4 \\
-\sqrt{3}
\end{array}\right) \cdot\left(\begin{array}{c}
1 \\
y \\
y^{2} \\
y^{3} \\
y^{4} \\
y^{5}
\end{array}\right)
$$

The denominator is positive on $T$, so the sign of $H$ determines the sign of the whole expression. Using Mathematica to solve the equation $H=0$ for $y$ in terms of $x$, we find that the solutions are

$$
\begin{gather*}
y=\frac{x-1}{\sqrt{3}}, \quad y=\sqrt{3} x \\
y=\frac{1}{\sqrt{3}}\left(1-x-\omega^{k}((2+x)(5-2 x)(1-4 x))^{1 / 3}\right) \tag{20}
\end{gather*}
$$

Here $\omega=\exp (2 \pi i / 3)$ and $k=0,1,2$. The first two solutions correspond to the sides of $\partial_{\infty}(T)$. This third solution intersects $T$ only when $k=0$. This is precisely the function in Equation 4 , the one which defines the curve $J$ from the Main Theorem. Finally, $G(1 / 2)=-1 / 3$, which shows that $G$ is positive to the left of $J$ and negative to the right, when restricted to $T-\partial_{\infty} T$. This establishes everything we needed to know about $G$.

## 5 References

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## Response to Referee Report 2:

I thank the referee for again going through the paper carefully and pointing out numerous places where it could be improved. The extensive criticism helped immensely. During the course of revising the paper, I considerably simplified the proof, so some of the criticisms no longer apply. I tried to get the paper down to what is really essential and I replaced algebraic calculations with geometric arguments in many cases. Let me explain the changes I made.

## Notation and Terminology:

- I made the change from triangle to face in all cases when I was dealing with a triangle that is isometric to a face of $X$. So, in particular, the equilateral triangles in the planar tiling are faces now.
- The indices are chosen, as suggested by the referee, so that they do not collide with the notation $i=\sqrt{-1}$.
- I eliminated the polynomials $F_{1}, F_{2}$ because I found a quick geometric proof for the statement I had used them for previously. I renamed $F_{3}$ as $G$, to avoid the nearness of the notation to $F_{p}$.
- Since I found so many short geometric proofs, there are only two nice polynomials. I call them $\nu_{1}$ and $\nu_{2}$.
- I changed $\Psi(015)$ to $\Psi((015))$, etc.
- I changed $A \cup B$ to $\{A, B\}$ where requested.
- I changed the hexagon $\widehat{H}_{p}$ to $H_{p}$, which is simpler.
- I call the points in $H_{p}$ which belong to at least 3 Voronoi cells the essential vertices.

Organization: The proof is so much shorter that Chapter 5 is gone. I now do the calculations for structural stability and the competition between vertices in Chapter 4.

## Chapter 1:

- I eliminated all mention of billiards. However, I want to protest a little bit: Polygonal billiards deals with the geometry of translation surfaces, which are examples of flat cone surfaces. This paper also deals with a flat cone surface. It is not just a shallow analogy. The whole approach of developing the space out into a planar plan is quite close to the techniques one uses in polygonal billiards. Also, people studying polygonal billiards frequently study paths on cone surfaces joining cone points - i.e., saddle connections. This seems related.
- I made it more clear which papers in the references concern convex polyhredra and which concern convex surfaces.
- I made it clear that J. Rouyer's paper [R1] gets results which are similar to the ones in my paper, and by similar methods. Also, I mentioned in the introduction that there is overlap between some of the subsidiary lemmas in my paper and some results in the other papers by J. Rouyer.
- I permuted a few of the paragraphs in $\S 1.1$ to make it read better.
- I sharpened Figure 1.4.


## Chapter 2:

- Now I give a short geometric proof that when $p$ is a cone point, $F_{p}=$ $\left\{p^{\prime}\right\}$ where $p^{\prime}$ is the antipodal point. I call this result Lemma 2.1. I mention that [R3, Cor. 13] has this exact statement but it seems worth giving a 7-line self-contained proof.
- I eliminate the statement (and later proof) that $F_{p}$ does not contain a cone point when $p$ is not a cone point. The proof I give of the Main Theorem does not need this result.
- I sharpen the statement of the Octahedral Plan lemma so that it explicitly says that when $q^{*} \in F_{p}$, the points of $\Psi^{-1}\left(q^{*}\right)$ lie in the 7 -faces of the octahedral plan, and $d_{X}\left(p, q^{*}\right)$ equals the minimum distance from $p$ to one of these points in the plan.
- I give a short geometric proof that the hexagon $H_{p}$ is strictly convex when $p$ is not the cone point. This is Lemma 2.3. This eliminates the algebraic proof.
- I give a short geometric proof that the essential vertices lie in $A_{0}^{o}$ for all $p \in T$ except when $p$ lies in the long side of $\partial_{\infty} T$. This is Lemma 2.5 .
- I prove the statement that if $q \in A_{0}$ is a point which does not maximize $\mu_{p}$ then there is another $r$, also in $A_{0}$, such that $\mu_{p}(q)<\mu_{q}(r)$. When $q \in A_{0}^{o}$ this is easy. When $q \in \partial A_{0} \mathrm{I}$ look at the combinatorial picture. This is Lemma 2.6.
- The Vertex Lemma now has a short and clean proof which I think meets all the objections raised by the referee. I have stated it so that it explicitly implies that I can use norms to select the vertices which lie in $F_{p}$. This was something that the referee questioned.
- In the new version I mention that the reader can compare the Vertex Lemma to [R2, Lemma 3], and I say this result is essentially equivalent. However, I do not give a translation between the one result and the other. (I looked at $[\mathbf{R 2}$, Lemma 3] and I could see that it was quite similar, but stated in different terms. ) I hope what I did is sufficient.
- In the final section I treat the boundary cases at the same time as the interior cases. Now I have thought much more about the boundary cases and I was able to treat them much more efficiently.


## Chapter 3:

- I eliminated the proof of the result (no longer stated or used) that when $p$ is not a cone point $F_{p}$ contains no cone points.
- I cleaned up the proof of the Octahedral Plan Lemma. It is the same proof, but it is presented more simply and it avoids excessive terminology.


## Chapter 4:

- I eliminated the algebraic proof that $H_{p}$ is a strictly convex hexagon because now I have given a short geometric proof in Chapter 2.
- My calculations only involve the polynomials $\nu_{1}$ and $\nu_{2}$. For these two polynomials I write them in a way which makes it obvious they are positive on $[0,1]^{2}$. The question about using the method of Positive

Dominance is moot, but I would like to tell the referee that before I managed to eliminate all but 2 of these polynomials (by geometric arguments) I went through and wrote each and every one of them in a way, like I do for $\nu_{1}$ and $\nu_{2}$, which made their non-vanishing obvious. I was completely converted to the referee's point of view before finding ways to eliminate these polynomials. In fact, writing out the factorizations more clearly, as suggested by the referee, helped me to find geometric proofs.

- I simplified the proof of the structural stability result, so now there are just 3 "quads" I need to consider - the ones corresponding to the edges of the Voronoi decomposition that lie in $A_{0}$. (Writing out all the factorizations, as suggested by the referee, let me see algebraically that there were 3 essential ones and 6 unimportant ones; I later found the geometric reason why.)
- I eliminated the algebraic proof that the essential vertices lie in $A_{0}^{o}$ for $p \in T^{o}$ because I have proved a sharper statement in $\S 2$ with a short geometric argument.
- I eliminated the discussions of the boundary cases at the end, because I now treat all this in the last section of $\S 2$.


## Response to Referee report 3:

This time the suggestions from the referee were very straightforward to implement, as s/he points out in the report. Here are comments on those suggestions that did not simply involve fixing typos.

- I did follow the suggestion to call the equilateral triangles in the planar tiling tiles. Now the space $X$ has faces and the tiling has tiles.
- I renamed the power set version of the farpoint map $p \rightarrow \mathcal{F}_{p}$, and then I let $F(p)$ be the member of $\mathcal{F}_{p}$ in case this set is a singleton.
- In the proof of Lemma 2.5 I added some sentences in the first paragraph explaining the notation in the figure and also explaining more precisely what it means for one line to lie between two others. The proof is the same except for this extra explanation of the terminology and notation.
- In Section 3.1 I eliminated the alternate labeling of the octahedral plan and gave more straightforward proof of Lemma 3.1. To answer the question of the referee, the purpose of the alternate labeling was to help prove the claim that $q^{*}=r^{*}$ and the purpose of the claim was to show, first of all, that $q^{*}$ and $r^{*}$ lie in the same face of $X$. That is, the claim was the first step in proving that $q^{*}=r^{*}$. The new argument that $q^{*}=r^{*}$ is more direct.


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