

THE NON-DEGENERACY OF HARMONIC STRUCTURES ON PLANAR SIERPINSKI GASKETS

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This paper is dedicated to Professor Weiyi Su on the occasion of her 80th birthday

ABSTRACT. We present a direct and short proof of the non-degeneracy of the harmonic structures on the level- n Sierpinski gaskets for any $n \geq 2$, which was conjectured by Hino in [H1,H2] and confirmed to be true by Tsoungkas [T] very recently using Tutte's spring theorem.

1. INTRODUCTION

The theory of analysis on fractals, analogous to that on manifolds, has been being well developed. The pioneering work, developed by Kigami [K1,K2], is the analytic construction of the Laplacians, for a class of finitely ramified fractals, named *p.c.f. self-similar sets*, including the *Sierpinski gasket* as a typical example, where Laplacians are defined as renormalized limits of graph Laplacians, playing the role of differential operators of second order on manifolds.

The harmonic functions on fractal domains may have some different nature from the classical ones as a consequence of the finitely ramified topology of the fractals. For example, the Hexagasket and the Vicsek set [S2] consume *degenerate harmonic structures* so that nonconstant harmonic functions vanishing locally on small cells exist. It seems that such phenomenon always happens on those fractals containing *nonjunction* inner vertices.

Recently, Tsoungkas [T] gives a proof on the non-degeneracy of harmonic structures on the *level- n Sierpinski Gasket* \mathcal{SG}_n , $n \geq 2$, based on certain geometric graph theory, in which Tutte's spring theorem plays the key role, which was conjectured and numerically checked for the standard case for $n \leq 50$ by Hino [H1,H2].

Theorem 1.1. *For $n \geq 2$, each harmonic structure of \mathcal{SG}_n is non-degenerate.*

In this note, we aim to provide an elementary proof for this theorem using only the basic facts of the discrete Laplacians on finite sets.

For convenience, we list some basic concepts and facts on the *Laplacians on finite sets* below. Readers can find any unexplained details in the book [K3].

Definition 1.2. *Let V be a finite set. A symmetric linear operator (matrix) $H : l(V) \rightarrow l(V)$ is called a Laplacian on V if it satisfies*

- (1) H is non-positive definite,
- (2) $Hu = 0$ if and only if u is a constant on V ,
- (3) $H_{pq} \geq 0$ for all $p \neq q$.

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Denote $\mathcal{LA}(V)$ the set of Laplacians on V .

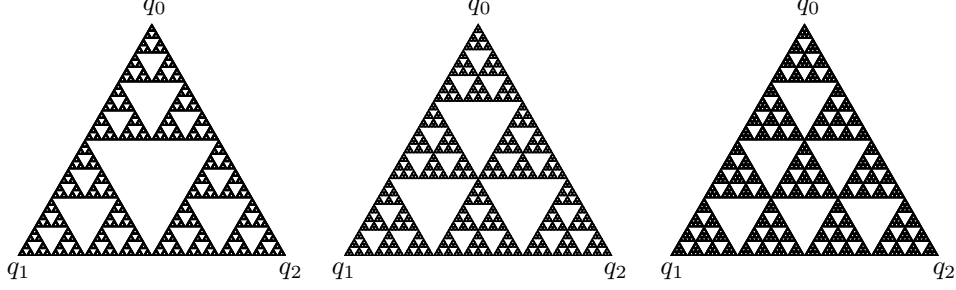


FIGURE 1.1. $\mathcal{SG}_2, \mathcal{SG}_3, \mathcal{SG}_4$.

Recall that \mathcal{SG}_n is the unique nonempty compact subset of \mathbb{R}^2 satisfying $\mathcal{SG}_n = \bigcup_{i=0}^{\frac{n^2+n-2}{2}} F_i \mathcal{SG}_n$ with F_i 's being contraction mappings defined as $F_i(z) = n^{-1}z + d_{n,i}$ with suitable $d_{n,i} \in \mathbb{R}^2$. See Figure 1.1. The set V_0 consisting of the three vertices q_0, q_1, q_2 of the smallest triangle containing \mathcal{SG}_n is called the *boundary*. In this note, we mainly discuss the Laplacians on $V_1 = \bigcup_{i=0}^{\frac{n^2+n-2}{2}} V_0$.

Let $D \in \mathcal{LA}(V_0)$, and \mathcal{E}_0 be its associated Dirichlet form

$$\mathcal{E}_0(u, v) = \sum_{p, q \in V_0} D_{pq}(u(p) - u(q))(v(p) - v(q)), \quad u, v \in l(V_0).$$

For $\mathbf{r} = (r_0, r_1, \dots, r_{\frac{n^2+n-2}{2}})$ with $r_i > 0$, denote by \mathcal{E}_1 the induced Dirichlet form on V_1 with

$$\mathcal{E}_1(u, v) = \sum_{i=0}^{\frac{n^2+n-2}{2}} r_i^{-1} \mathcal{E}_0(u \circ F_i, v \circ F_i), \quad u, v \in l(V_1).$$

We call the pair (D, \mathbf{r}) a *harmonic structure* if the restriction of \mathcal{E}_1 on V_0 equals \mathcal{E}_0 . Once the pair (D, \mathbf{r}) is a harmonic structure, it could naturally induce a self-similar Dirichlet form on the fractal \mathcal{SG}_n , see [K3]. The Laplacian on V_1 associated with \mathcal{E}_1 , denoted by H_1 , can be expressed as

$$H_1 = \sum_{i=0}^{\frac{n^2+n-2}{2}} r_i^{-1} R_i^t D R_i,$$

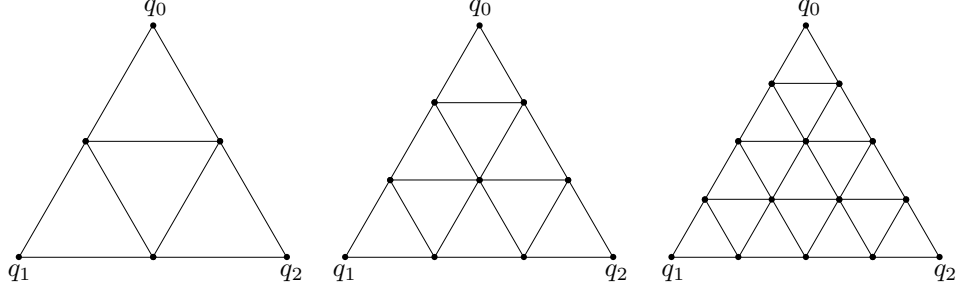
where $R_i : l(V_1) \rightarrow l(V_0)$ is defined by $R_i v = v \circ F_i$.

By Theorem 3.2.11 in [K3], it is easy to check that $(H_1)_{pq} > 0$ if and only if $p, q \in F_i V_0$ for some $0 \leq i \leq \frac{n^2+n-2}{2}$ due to the topology of \mathcal{SG}_n . We always denote $p \sim q$ if $(H_1)_{pq} > 0$. The edge relation ' \sim ' together with the vertex set V_1 gives the *level-1 graph approximation* G_1 of \mathcal{SG}_n . See Figure 1.2 for $n = 2, 3, 4$ cases.

Let h be a harmonic function on \mathcal{SG}_n and $v = h|_{V_1} \in l(V_1)$, then

$$(1.1) \quad (H_1 v)|_{V_1 \setminus V_0} = 0.$$

Conversely, for any v satisfying (1.1), it has a unique extension h so that h is harmonic on \mathcal{SG}_n . Thus we only need to study the solutions of (1.1). The following discrete *maximum principle* is important. See Proposition 2.1.7 in [K3].


 FIGURE 1.2. The level-1 graph approximation G_1 of $\mathcal{SG}_2, \mathcal{SG}_3, \mathcal{SG}_4$.

Proposition 1.3.(Maximum Principle) *Let V be a finite set and $H \in \mathcal{LA}(V)$. Let U be a proper subset of V . For $p \in V \setminus U$, write*

$$U_p = \{q \in U : \text{There exist } p_1, p_2, \dots, p_m \in V \setminus U \text{ with } p_1 = p \\ H_{p_i p_{i+1}} > 0 \text{ for } i = 1, 2, \dots, m-1 \text{ and } H_{p_m q} > 0\}.$$

Then if $(Hv)|_{V \setminus U} = 0$, then for any $p \in V \setminus U$,

$$\min_{q \in U_p} v(q) \leq v(p) \leq \max_{q \in U_p} v(q).$$

Moreover, $v(p) = \max_{q \in U_p} v(q)$ (or $v(p) = \min_{q \in U_p} v(q)$) if and only if v is constant on U_p .

2. MAIN RESULT

Call a finite sequence of vertices $\{p_1, p_2, \dots, p_m\} \subset V_1$ a *chain* if $p_i \sim p_{i+1}$ for $1 \leq i < m$ and $p_i \neq p_j$ for $i \neq j$. Before proving Theorem 1.1, we list some lemmas.

Lemma 2.1. *Let $v \in \mathcal{L}(V_1)$ satisfying (1.1), and assume v is not a constant. If $p \in V_1 \setminus V_0$ is a vertex with a neighbor $q \sim p$ such that $v(q) \neq v(p)$, then there exists a chain $\{p_1, p_2, \dots, p_m\}$ with $p_1 = p$ and $p_m \in V_0$ satisfying*

$$v(p_1) < v(p_2) < \dots < v(p_m).$$

Similarly, there is another chain satisfying $v(p_1) > v(p_2) > \dots > v(p_m)$.

Proof. Let $p_1 = p$. There must exist some $q \sim p_1$ such that $v(p_1) < v(q)$, since by (1.1),

$$(H_1 v)(p_1) = \sum_{p' \sim p_1} (H_1)_{p_1 p'} (v(p') - v(p_1)) = 0.$$

Set this q as p_2 . If $p_2 \in V_0$, then we have already find the chain. Otherwise, repeat the above procedure until we find a $p_m \in V_0$. The process will stop after finite times of operations, since V_1 is a finite set. \square

Lemma 2.2. *Let A be a proper subset of $V_1 \setminus V_0$ with at least two vertices. Write $\partial A = \{p \in A \mid \text{There exists } q \in V_1 \setminus (A \cup V_0) \text{ such that } (H_1)_{pq} > 0\}$. Then $\#\partial A \geq 2$.*

Proof. If $\partial A = A$, then we immediately get the lemma. Otherwise, it is easy to see that $A \setminus \partial A$ and $V_1 \setminus (A \cup V_0)$ are disconnected with each other, which also leads to $\#\partial A \geq 2$ as $(V_1 \setminus V_0, \sim)$ is 2-connected. Here we call a graph *2-connected* if it could not be disconnected by removing 1 vertex. \square

Proof of Theorem 1.1. Let v be the restriction of a nonconstant harmonic function h on V_1 . For $c \in \mathbb{R}$, define

$$E(v, c) = \{p \in V_1 : v(p) = c\}.$$

We only need to show that $F_i V_0 \not\subset E(v, c)$ for any $0 \leq i \leq \frac{n^2+n-2}{2}$ and any $c \in \mathbb{R}$.

Assume $F_{i_1} V_0 \subset E(v, c)$ for some i_1 and c . We may find another i_2 such that $F_{i_2} V_0 \subset E(v, c)$ and $F_{i_2} V_0 \cap F_{i_1} V_0 \neq \emptyset$. Also, another i_k such that $F_{i_k} V_0 \subset E(v, c)$ and $F_{i_k} V_0 \cap (\bigcup_{l=1}^{k-1} F_{i_l} V_0) \neq \emptyset$. Repeat the procedure until we can not find another such i , and set A to be the union of these $F_{i_k} V_0$'s. As a consequence of Lemma 2.2, there should be at least two vertices, denoted by $a_1, a_2 \in A \setminus V_0$, such that for each a_i , there exists a neighbor $p \sim a_i$ with $v(p) \neq c$.

Let $CH = \{p_1, p_2, \dots, p_m\} \subset A$ be a *geodesic chain* (with minimal number of edges, may not be unique) in A connecting $p_1 = a_1$ and $p_m = a_2$. See Figure 2.1 for examples of such chains. The value of v is always c along this chain. On the other hand, for each $i = 1, 2$, by using Lemma 2.1, we could connect a_i to the boundary V_0 by two different chains $CH^{S,i}$ and $CH^{L,i}$, denoted as

$$\begin{aligned} CH^{S,i} &= \{p_k^{S,i}\}_{k=1}^{m_{S,i}}, \text{ with } p_1^{S,i} = a_i \text{ and } p_{m_{S,i}}^{S,i} \in V_0, \\ CH^{L,i} &= \{p_k^{L,i}\}_{k=1}^{m_{L,i}}, \text{ with } p_1^{L,i} = a_i \text{ and } p_{m_{L,i}}^{L,i} \in V_0, \end{aligned}$$

satisfying that $p_k^{S,i} < c, \forall 2 \leq k \leq m_{S,i}$ and $p_k^{L,i} > c, \forall 2 \leq k \leq m_{L,i}$.

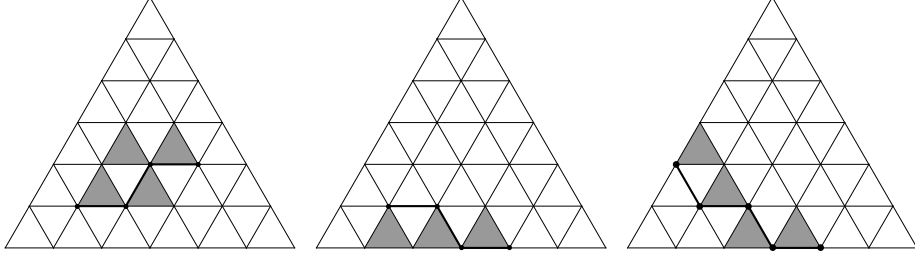


FIGURE 2.1. Examples of possible cases for CH .

Take a vertex $p \in A \setminus CH$ such that $p \sim p_{i_1}, p \sim p_{i_2}$ for two different $p_{i_1}, p_{i_2} \in CH$. Note that $v(p) = c$. It is not possible for $p \in V_0$, otherwise it will contradict to the fact that there exist five chains as shown above, since $CH^{S,i}$ and $CH^{L,j}$ never cross when $i \neq j$. Now as in Proposition 1.3, we take U to be the union of V_0 and above five chains, and V to be V_1 . Noticing that $p \in V \setminus U$, we have

$$(2.1) \quad \text{either } U_p \subset CH \cup CH^{S,1} \cup CH^{S,2} \text{ or } U_p \subset CH \cup CH^{L,1} \cup CH^{L,2}.$$

Moreover, since CH is a geodesic chain, it could not encircle a nonempty subset of $V_1 \setminus V_0$, and thus there must exist a chain in $V_1 \setminus CH$ which connects p to some $q_i \in V_0$. So we have

$$(2.2) \quad U_p \setminus CH \neq \emptyset.$$

By (2.1), (2.2) and the definition of $CH^{S,i}$ and $CH^{L,i}$, we have either $\min_{q \in U_p} v(q) < c = \max_{q \in U_p} v(q)$ or $\min_{q \in U_p} v(q) = c < \max_{q \in U_p} v(q)$. Thus we get $v(p) \neq c$ by using the maximum principle as stated in Proposition 1.3. However, this contradicts to the fact that $p \in A$. \square

As we know, harmonic functions on \mathcal{SG}_n are of 3-dimensional, and could be uniquely determined by their boundary values on V_0 . More precisely, there exist *harmonic extension matrices* A_i , $0 \leq i \leq \frac{n^2+n-2}{2}$, so that

$$h|_{F_i V_0} = A_i h|_{V_0}$$

holds for any harmonic function h on \mathcal{SG}_n . We could restate Theorem 1.1 as following.

Corollary 2.3. *All the harmonic extension matrices A_i of \mathcal{SG}_n are nondegenerate.*

Proof. Let h be a harmonic function and let $v = h|_{V_1}$. If $v|_{V_0} = c \neq 0$, then $v|_{F_i V_0} = c$. If $v|_{V_0}$ is not a constant, then by Theorem 1.1, $v|_{F_i V_0}$ is also not a constant. These show that $A_i v|_{V_0} \neq 0$ if $v|_{V_0} \neq 0$. \square

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