COUNTING UNBRANCHED SUBGRAPHS (revised).

by David Ruelle*.

Abstract. Given an arbitrary finite graph, the polynomial $Q(z) = \sum_{F\in\mathcal{U}} z^{\mathrm{card}F}$ *associates a weight* $z^{\mathrm{card}F}$ *to each unbranched subgraph* F *of length* $\mathrm{card}F$. *We show that all the zeros of* Q *have negative real part.*

A graph (V,E,v) consists of a finite set V of vertices, a finite set E of edges, and a map v of E to the two-element subsets of V. If $a\in E$ and $v(a)=\{j,k\}$, we say that the edge a joins the vertices j, k. [We impose that $j\neq k$, but allow different edges to join the same two vertices. We assume that each vertex j is in $v(a)$ for some $a\in E$].

For our purposes a *subgraph* of (V,E,v) will be a graph (V,F,ϕ) where $F\subset E$ and $\phi=v|F$. We shall now fix (V,E,v), and say that F is a subgraph of E if $F\subset E$ (this defines (V,F,ϕ) uniquely). We define the subset $\mathcal{U}$ of *unbranched* subgraphs of E by

$$\mathcal{U}=\{F\subset E:(\forall j)\,\mathrm{card}\{a\in F:v(a)\ni j\}\leq 2\}$$

1. Proposition.

The polynomial

$$Q_{\mathcal{U}}(z)=\sum_{F\in\mathcal{U}} z^{\mathrm{card}F}$$

has all its zeros in $\{z:\mathrm{Re}z\leq -2/n(n-1)^2\}$ *where* $n\geq 2$ *is the largest number of edges ending in any vertex* j.

The proof is given in Section 5 below. This result is related to a well-known theorem of Heilman and Lieb [2] on counting dimer subgraphs (for which $\mathrm{card}\{a\in F:v(a)\ni j\}\leq 1$).

Let us consider an edge a as a closed line segment containing the endpoints $j,k\in v(a)$. Also identify a subgraph $F\subset E$ with the union of its edges. Then F is the union of its connected components, and if $F\in\mathcal{U}$, these are homeomorphic to a line segment or to a circle. We call $b(F)$ the number of components homeomorphic to a line segment, therefore

$$2b(F)=\mathrm{card}\{j\in V:v(a)\ni j\ \text{ for exactly one }\ a\in F\}$$

Let us define

$$Q_{\mathcal{U}}(z,t)=\sum_{F\in\mathcal{U}} z^{\mathrm{card}F}t^{b(F)}.$$

We see that

$$Q_{\mathcal{U}}(z,1)=Q_{\mathcal{U}}(z).$$

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2. Proposition.

If t is real $\geq 2-2/n$, then $Q_{\mathcal{U}}(z,t)$ has all its zeros (with respect to z) on the negative real axis.

The proof is given in Section 6 below. For $t \geq 2$, this is a special case a theorem of Wagner [6] as pointed out by the referee (take $Q_v(y) = 1 + sy + y^2/2$ for each vertex v in Theorem 3.2 of [6]).

We shall use the following two lemmas.

3. Lemma.

Let A, B be closed subsets of the complex plane $\mathbf{C}$, which do not contain 0. Suppose that the complex polynomial

$$\alpha + \beta z_1 + \gamma z_2 + \delta z_1 z_2$$

can vanish only when $z_1 \in A$ or $z_2 \in B$. Then

$$\alpha + \delta z$$

can vanish only when $z \in -AB$.

This is the key step in an extension (see Ruelle [5]) of the Lee-Yang circle theorem [3]. Note that in applications of the lemma, the coefficients α, β, γ, δ are usually polynomials in variables z_j (different from z_1, z_2, z).

4. Lemma.

Let $Q(z)$ be a polynomial of degree n with complex coefficients and $P(z_1, \ldots, z_n)$ the only polynomial which is symmetric in its arguments, of degree 1 in each, and such that

$$P(z, \ldots, z) = Q(z).$$

If the roots of Q are all contained in a closed circular region M, and $z_1 \notin M, \ldots, z_n \notin M$, then $P(z_1, \ldots, z_n) \neq 0$).

This is Grace's theorem, see Polya and Szegö [4] V, Exercise 145.

5. Proof of Proposition 1.

If $a \in E$, and $v(a) = \{j,k\}$, we introduce complex variables z_{aj}, z_{ak}. For each $j \in V$, let p_j be the polynomial in $Z^{(j)} = (z_{aj})_{v(a)\ni j}$ such that

$$p_j(Z^{(j)}) = 1 + \sum_a z_{aj} + \sum_{a\neq b} z_{aj} z_{bj}$$

(where we assume $v(a) \ni j$, $v(b) \ni j$). Putting all z_{aj} equal to z, we obtain a polynomial

$$q_j(z) = 1 + n_j z + \frac{n_j(n_j-1)}{2} z^2$$

where $n_j > 0$ is the number of edges ending in j. Define $\zeta_\pm^{(j)} = -1$ when $n_j = 1$ or 2, and

$$\zeta_\pm^{(j)} = \frac{-n_j \pm \sqrt{2n_j - n_j^2}}{n_j(n_j - 1)}$$

if $n_j \geq 2$. The zeros of q_j, considered as a polynomial of degree n_j are $\zeta_\pm^{(j)}$, and ∞ if $n_j > 2$. They are therefore contained in the closed circular regions (half-planes)

$$H_{\theta+}^{(j)} = \{z : \mathrm{Re}[e^{-i\theta}(z - \zeta_+^{(j)})] \leq 0\}$$

$$H_{\theta-}^{(j)} = \{z : \mathrm{Re}[e^{i\theta}(z - \zeta_-^{(j)})] \leq 0\}$$

for $0 \leq \theta < \pi/4$. By Lemma 4, we have thus $p_j(Z^{(j)}) \neq 0$ if $z_{aj} \notin H_{\theta\pm}^{(j)}$ for all $a \in E$ such that $j \in v(a)$.

If a polynomial is separately of first order in two variables z_1, z_2, *i.e.*, it is of the form

$$\alpha + \beta z_1 + \gamma z_2 + \delta z_1 z_2$$

the *Asano contraction* [1] consists in replacing it by the first order polynomial

$$\alpha + \delta z$$

in one variable z, as in Lemma 3. As already noted, the coefficients α, β, γ, δ may depend on variables z_i different from z_1, z_2, z. Let now $Z = (z_a)_{a \in E}$ and

$$P_\mathcal{U}(Z) = \sum_{F \in \mathcal{U}} \prod_{a \in F} z_a.$$

If we take the product $\prod_{j \in V} p_j(Z^{(j)})$ and perform the Asano contraction

$$\alpha + \beta z_{aj} + \gamma z_{ak} + \delta z_{aj} z_{ak} \qquad \longrightarrow \qquad \alpha + \delta z_a$$

for all $a \in E$ we obtain $P_\mathcal{U}(Z)$. Using Lemma 3 iteratively, once for each edge $a \in E$, we see thus that $P_\mathcal{U}(Z)$ has no zeros when for each $a \in E$

$$z_a \in \mathbf{C} \setminus (-H_{\theta\pm}^{(j)} H_{\theta\pm}^{(k)})$$

where $v(a) = \{j, k\}$ and

$$H_{\theta\pm}^{(j)} H_{\theta\pm}^{(k)} = \{uv : u \in H_{\theta\pm}^{(j)}, v \in H_{\theta\pm}^{(k)}\}.$$

We have

$$\mathbf{C} \setminus (-H_{\theta\pm}^{(j)} H_{\theta\pm}^{(k)}) \supset \mathbf{C} \setminus (-H_{\theta\pm} H_{\theta\pm})$$

where $H_{\theta\pm}$ is the largest $H_{\theta\pm}^{(j)}$ (obtained by replacing n_j by $n = \max_j n_j$). Note that $\mathbf{C} \setminus (-H_{\theta\pm} H_{\theta\pm})$ is the interior of a parabola passing through $-\zeta_\pm^2$ and with axis passing through 0 and making an angle $\pm 2\theta$ with the positive real axis. When $\pm\theta$ varies between $-\pi/4$ and $\pi/4$, the parabola sweeps the region $\mathrm{Re} z > -\mathrm{Re}\zeta_\pm^2 = -2/n(n-1)^2$. Since $Q_{\mathcal{U}}(z)$ is obtained from $P_{\mathcal{U}}(Z)$ by putting all z_a equal to z, this proves Proposition 1. □

6. Proof of Proposition 2.

We proceed as for Proposition 1, defining here

$$p_j(Z^{(j)}) = 1 + s\sum_a z_{aj} + \sum_{a\neq b} z_{aj} z_{bj}$$

$$q_j(z,t) = 1 + n_j s z + \frac{n_j(n_j-1)}{2} z^2$$

If $s \geq \sqrt{2 - 2/n_j}$, the roots of q_j are real negative, and the same type of argument used for theorem 1 shows that all the zeros of $Q_{\mathcal{U}}(z, s^2)$ are real and negative. □

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