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## A SIMPLE PROOF OF A THEOREM OF THUE ON THE MAXIMAL DENSITY OF CIRCLE PACKINGS IN $E^2$

by Wu-Yi HSIANG

### INTRODUCTION

The classical circle packing problem is to find out how densely a large number of identical circles can be packed together. In the limiting case of infinite expanse, one seeks the *maximal density* that can be achieved by all possible circle packings of the whole Euclidean plane  $E^2$ . A simple basic fact in circle packing is that a circle can be surrounded by *six kissing circles* in a unique, tight arrangement. Intuitively, this is clearly the *tightest local circle packing* and it is also easy to see that this type of tight local packing can, in fact, be infinitely repeated to fill the whole plane. Therefore, it is rather natural to expect that the above regular, hexagonal type of circle packing will be the *densest* possible circle packing. A proof of the above expected *maximality* of the density of the hexagonal circle packing was first given by Thue in 1910 [Thu]. In this short note, we shall give another proof of the above interesting basic fact of plane geometry which is simple, elementary and short.

### LOCAL CELL AND LOCAL DENSITY

To each given circle  $\Gamma_0$  in a given packing  $\mathcal{P}$ , it is quite natural to associate a surrounding region which consists of those points that are as close to its center as to the center of any other. We shall call it the *local cell* of  $\Gamma_0$  in  $\mathcal{P}$  and denote it by  $C(\Gamma_0, \mathcal{P})$ . The *local density* of  $\mathcal{P}$  at  $\Gamma_0$  is defined to be the ratio between the areas of the circle and its surrounding local cell. For example, the local cell of any circle in the above hexagonal regular packing is always a *circumscribing regular hexagon*. Therefore, it is easy to see that the local density of the above packing at any circle is equal to  $\pi/\sqrt{12} = 0.906899682\dots$ . Observe that the (*global*) *density* of a packing  $\mathcal{P}$  is clearly just a weighted average of the local densities of its individual circles,

a universal upper bound of the local density is automatically also an upper bound of the global density. Therefore, the proof of Thue's theorem on the *maximality of the global density* of the hexagonal regular circle packing can be reduced to the proof of the *maximality of the local density* of the local hexagonal circle surrounding, namely

**THEOREM.** *The optimal universal upper bound for the local density of circle packing in  $E^2$  is equal to  $\pi/\sqrt{12}$  and it can be realized as the local density when and only when the local cell is a circumscribing regular hexagon.*

*Proof.* Let  $\Gamma_0$  be an arbitrary circle in a given circle packing  $\mathcal{P}$ ,  $N(\Gamma_0)$  be the set of neighboring circles whose local cells have common edges with the local cell of  $\Gamma_0$  and  $\hat{N}(\Gamma_0)$  be the subset of  $N(\Gamma_0)$  whose centers are within a distance of 2.30 times the radii. We shall call  $N(\Gamma_0)$  the set of *neighbors* of  $\Gamma_0$  and  $\hat{N}(\Gamma_0)$  the set of *close neighbors* of  $\Gamma_0$ .

Choose the center of  $\Gamma_0$  to be the origin and the common radii to be the unit of length. Let  $O_j$  be the center of  $\Gamma_j \in \hat{N}(\Gamma_0)$  and set  $A_j$  to be the intersection point of  $\overline{OO_j}$  and  $\Gamma_0$ . In case that both  $\overline{OO_j}$  and  $\overline{OO_{j+1}}$  reach the upper limit of 2.30,  $\overline{A_j A_{j+1}}$  is larger than or equal to  $2/2.30$  and hence the angular separation  $\theta_j = \widehat{A_j A_{j+1}}$  is at least

$$(1) \quad 2 \operatorname{Arcsin} \left( \frac{1}{2.30} \right) = 0.89959372 > \frac{2\pi}{7}.$$

Since the base angles of the isosceles triangle  $\Delta OO_j O_{j+1}$  is considerably smaller than  $\pi/2$ , namely,  $\operatorname{Arccos} \left( \frac{1}{2.30} \right) = 1.120999466$ , the angular separation,

$\widehat{A_j A_{j+1}}$ , will always be greater than the above  $2 \operatorname{Arcsin} \left( \frac{1}{2.30} \right)$  if one

or both center distances are less than 2.30. Therefore, there can be at most six *close neighbors*.

*Case 1:* Suppose that all the neighbors are close neighbors, namely,  $N(\Gamma_0) = \hat{N}(\Gamma_0)$ . Let  $\{\theta_j; 1 \leq j \leq n\}$  be the angular separations between the adjacent  $A$ 's and  $T\{A_j\}$  be the circumscribing  $n$ -gon bounded by the  $n$  tangent lines at the  $A$ 's. Then, it is easy to see that  $T\{A_j\}$  is always a subset of the local cell  $C(\Gamma_0, \mathcal{P})$  and the area of  $T\{A_j\}$  is given by

$$(2) \quad \sum_{j=1}^n \tan \frac{\theta_j}{2}, \quad \sum \frac{\theta_j}{2} = \pi, \quad \frac{\pi}{7} < \frac{\theta_j}{2} < \frac{\pi}{2}.$$

Now, it follows easily from the convexity of the function  $\tan x$  that

$$(3) \quad \sum_{j=1}^n \tan \frac{\theta_j}{2} \geq n \tan \frac{\pi}{n}, \quad n \leq 6.$$

Therefore the area of  $C(\Gamma_0, \mathcal{P})$  is at least equal to  $6 \tan \frac{\pi}{6} = 2\sqrt{3}$  and it is equal to  $2\sqrt{3}$  when and only when  $C(\Gamma_0, \mathcal{P})$  is itself a circumscribing regular hexagon.

*Case 2:* Suppose that  $N(\Gamma_0) \neq \hat{N}(\Gamma_0)$ , namely, there is at least one neighboring circle with center distance exceeding 2.30. Let  $\Gamma'$  be such a neighbor of  $\Gamma_0$ .

Let us first consider the most critical situation that  $\Gamma'$  touches two close neighbors, say  $\Gamma_1$  and  $\Gamma_2$ , which are actually *touching* neighbors of  $\Gamma_0$ . Then the geometry of the above four touching circles is represented as in Figure 1 where

$$(4) \quad \overline{OV} = \sec \frac{\theta_1}{2}, \quad \overline{OH} = 2 \cos \frac{\theta_1}{2}, \quad \overline{HB}_1 = \cot \frac{\theta_1}{2} \overline{VH}$$

and the intersection of  $C(\Gamma_0, \mathcal{P})$  and the angular region of  $\theta_1 = \angle A_1OA_2$  is the pentagon  $OA_1B_1B_2A_2$ . Since it is assumed that  $\overline{OV} > \overline{OH} > 1.15$ , it follows from (4) that  $\theta_1$  lies between  $\pi/2$  and  $2 \operatorname{Arccos} 0.575 = 1.916384358$ .

Moreover, the area of the quadrilateral  $OA_1VA_2$  is equal to  $\tan \frac{\theta_1}{2}$  and the area of  $\triangle VB_2B_1$  is equal to  $\overline{VH} \cdot \overline{HB}_1$  and it follows from (4) that

$$(5) \quad \begin{aligned} \overline{VH} \cdot \overline{HB}_1 &= \cot \frac{\theta_1}{2} \overline{VH}^2 = \cot \frac{\theta_1}{2} \left( \sec \frac{\theta_1}{2} - 2 \cos \frac{\theta_1}{2} \right)^2 \\ &= \frac{\left( 2 \cos^2 \frac{\theta_1}{2} - 1 \right)^2}{\cos \frac{\theta_1}{2} \sin \frac{\theta_1}{2}} = 2 \frac{\cos^2 \theta_1}{\sin \theta_1}. \end{aligned}$$

Therefore, the area of the pentagon  $OA_1B_1B_2A_2$  is given by

$$(6) \quad \hat{A}(\theta_1) = \tan \frac{\theta_1}{2} - 2 \frac{\cos^2 \theta_1}{\sin \theta_1}, \quad \frac{\pi}{2} < \theta_1 < 1.916384358.$$

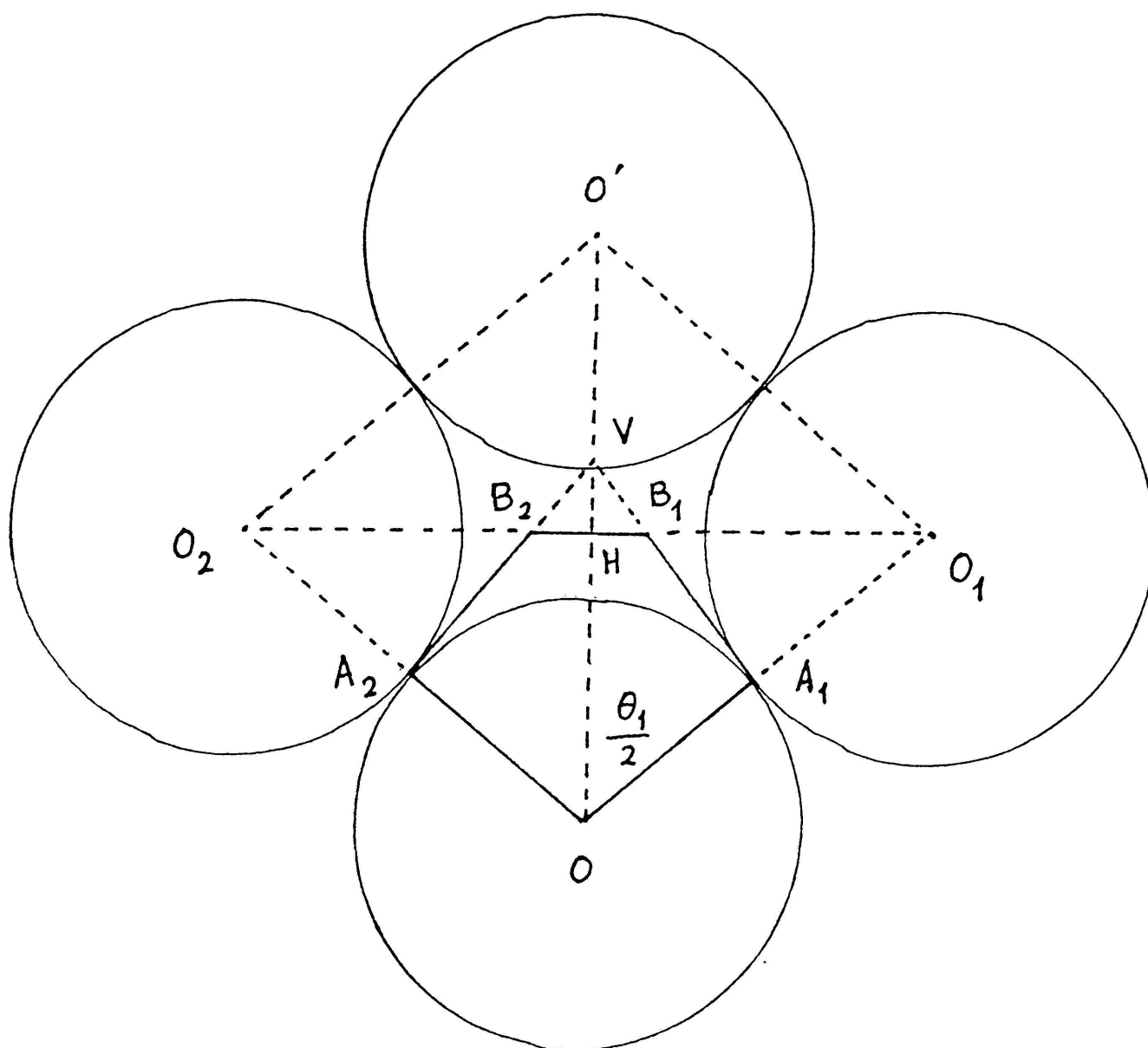


FIGURE 1

Set

$$(7) \quad \psi(\theta) = \tan \frac{\theta}{2} - \frac{\theta}{2} - 2 \frac{\cos^2 \theta}{\sin \theta}, \quad \frac{\pi}{2} < \theta < 1.917.$$

Then

$$\begin{aligned} \psi'(\theta) &= \frac{1}{2} \tan^2 \frac{\theta}{2} + 2 \frac{\cos \theta}{\sin^2 \theta} (1 + \sin^2 \theta) \\ (8) \quad &= \frac{1}{2 \sin^2 \theta} \{ (1 - \cos \theta)^2 + 4 \cos \theta (2 - \cos^2 \theta) \} \\ &= \frac{1}{2 \sin^2 \theta} \{ 1 + 6u + u^2 - 4u^3 \} \end{aligned}$$

where  $u$  lies between  $\cos(1.917)$  and 0. From (8), it is easy to show that  $\psi'(\theta)$  has exactly one root  $\theta_0$  in the above range of  $[\pi/2, 1.917]$ , namely,  $\psi'(\theta) > 0$  (resp.  $< 0$ ) for  $\frac{\pi}{2} \leq \theta < \theta_0$  (resp.  $\theta_0 < \theta < 1.917$ ). Therefore

$$(9) \quad \psi(\theta) = \hat{A}(\theta) - \frac{\theta}{2} \geq \min \left\{ \psi\left(\frac{\pi}{2}\right), \psi(1.917) \right\} = \psi\left(\frac{\pi}{2}\right) \\ = 1 - \pi/4 = 0.214601836 .$$

Therefore, if there are at least two non-close neighbors, then the above estimate already implies that the area of the local cell  $C(\Gamma_0, \mathcal{P})$  must be more than  $\pi + 0.42 > 2\sqrt{3}$ .

Finally, let us consider the remaining case that there is exactly one non-close neighbor of  $\Gamma_0$ . If the number of close neighbors of  $\Gamma_0$  is less than 6, then the proof of Case 1 also applies to  $N(\Gamma_0, \mathcal{P})$  instead of  $\hat{N}(\Gamma_0, \mathcal{P})$ . If the number of close neighbors of  $\Gamma_0$  is equal to 6, then the area of  $C(\Gamma_0, \mathcal{P})$  is clearly bounded below by

$$(10) \quad \hat{A}(\theta_1) + \sum_{j=2}^6 \tan \frac{\theta_j}{2} \geq \hat{A}(\theta_1) + 5 \tan \frac{2\pi - \theta_1}{10}$$

where  $\theta_1$  may assume to be between  $\frac{\pi}{2}$  and 1.92 without loss of generality. It

follows from (9) that  $\hat{A}(\theta_1) - \frac{\theta_1}{2} > 0.2146$  and it is easy to see that

$$(11) \quad 5 \tan \frac{2\pi - \theta_1}{10} - \left( \pi - \frac{\theta_1}{2} \right) \geq 5 \tan \frac{2\pi - 1.917}{10} - (\pi - 0.9585) > 0.15$$

and hence

$$\hat{A}(\theta_1) + 5 \tan \frac{2\pi - \theta_1}{10} > \pi + 0.3646 > 2\sqrt{3} .$$

This completes the proof of the theorem and hence also the theorem of Thue that  $\pi/\sqrt{12}$  is indeed the optimal upper bound of global density of circle packings in  $E^2$ .