THE THREE GAP THEOREM AND THE SPACE OF LATTICES

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Abstract. The three gap theorem (or Steinhaus conjecture) asserts that there are at most three distinct gap lengths in the fractional parts of the sequence $\alpha, 2\alpha, \ldots, N\alpha$, for any integer N and real number α. This statement was proved in the 1950s independently by various authors. Here we present a different approach using the space of two-dimensional Euclidean lattices.

Imagine we divide a cake by cutting a first wedge at an angle α, then an identical second, third, and so on as illustrated in Figure 1 (left), until the remaining piece is either of the same size as the previous, or smaller. We now have a cake comprising wedges of at most two distinct sizes: the size of the original and that of the left-over wedge. Suppose we continue cutting but insist that after each cut we rotate the knife by the same angle α as before, see Figure 1 (right). How many different sizes of cake wedges are there after N cuts? The celebrated "three gap theorem" states that for each N there will be at most three! This surprising fact was understood by number theorists in the late 1950s [6, 7, 8, 9]. Various new proofs have appeared since then, with connections to continued fractions [5, 10], Riemannian geometry [1] and elementary topology [4, App. A], as well as higher-dimensional generalisations [2, 3, 11]. Our aim here is to provide a simple proof of the three gap phenomenon by exploiting the geometry of the space of two-dimensional Euclidean lattices.

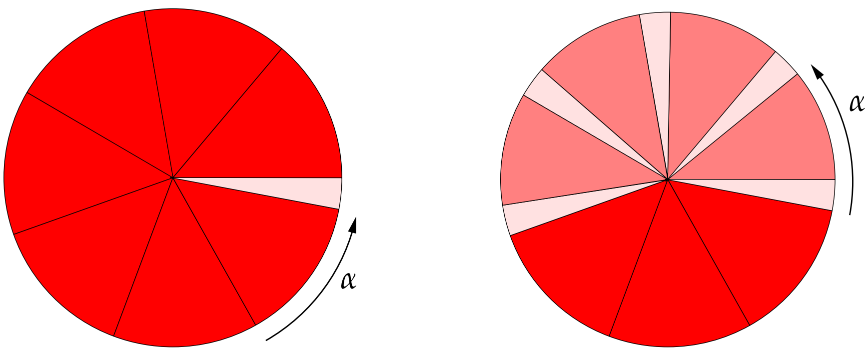

Figure 1. For each given N, there are at most three different wedge sizes.

The standard example of a Euclidean lattice in $\mathbb{R}^2$ is the square lattice $\mathbb{Z}^2$. We can generate any other Euclidean lattice $\mathcal{L}$ in $\mathbb{R}^2$ by applying a linear transformation to $\mathbb{Z}^2$. Writing points in $\mathbb{R}^2$ as row vectors $\boldsymbol{x} = (x_1, x_2)$, we have explicitly

$$\mathcal{L} = \mathbb{Z}^2 M = \{(m, n)M \mid (m, n) \in \mathbb{Z}^2\}, \tag{1}$$

Date: 14 December 2016/21 June 2017.
2010 *Mathematics Subject Classification.* 11H06; 11J71, 52C05.
To appear in the American Mathematical Monthly.

where M is a 2×2 matrix with real coefficients. If

$$M = \begin{pmatrix} a & b \\ c & d \end{pmatrix}, \qquad \det M = ad - bc \neq 0, \tag{2}$$

then a basis of the lattice $\mathcal{L} = \mathbb{Z}^2 M$ is given by the linearly independent vectors

$$\boldsymbol{b}_1 = \boldsymbol{e}_1 M = (a, b), \qquad \boldsymbol{b}_2 = \boldsymbol{e}_2 M = (c, d), \tag{3}$$

where $\boldsymbol{e}_1 = (1, 0)$, $\boldsymbol{e}_2 = (0, 1)$ is the standard basis of $\mathbb{Z}^2$. All other bases of $\mathcal{L}$ with the same orientation can be obtained by replacing M by γM provided $\gamma \in \Gamma = \mathrm{SL}(2, \mathbb{Z})$, the group of matrices with integer coefficients and unit determinant. In the following we restrict our attention to lattices $\mathcal{L} = \mathbb{Z}^2 M$ whose basis vectors span a parallelogram of unit area. This means that $\det M = \pm 1$, and by reversing the orientation of a basis vector where necessary (this will not change the lattice), we can assume in fact that $\det M = 1$. Let us therefore denote by $G = \mathrm{SL}(2, \mathbb{R})$ the group of real matrices with unit determinant. The "modular group" $\Gamma = \mathrm{SL}(2, \mathbb{Z})$ is a discrete subgroup of G, and the space of lattices can in this way be identified with the coset space $\Gamma \backslash G = \{\Gamma g \mid g \in G\}$.

In order to translate the three gap problem into the setting of lattices, let us measure all angles in units of 360°. That is, angles are parametrized by the coset space $\mathbb{R}/\mathbb{Z} = \{x + \mathbb{Z} \mid x \in \mathbb{R}\}$ (the set of reals taken modulo one), which we can think of as the unit interval $[0, 1]$ with the endpoints 0 and 1 identified. Fix $\alpha \in \mathbb{R}/\mathbb{Z}$, and let $\xi_k = \{k\alpha\}$ be the fractional part of $k\alpha$. The quantity ξ_k represents the angular position of the kth cut. The angles of the resulting cake wedges after N cuts are precisely the gaps between the elements of the sequence $(\xi_k)_{k=1}^N$ on $\mathbb{R}/\mathbb{Z}$. These gaps are, in other words, the lengths of the intervals that $\mathbb{R}/\mathbb{Z}$ is partitioned into by $(\xi_k)_{k=1}^N$.

The gap between ξ_k and its *next* neighbor on $\mathbb{R}/\mathbb{Z}$ (this is not necessarily the *nearest* neighbor, as the gap to the element preceding ξ_k may be the smaller one) is given by

$$s_{k,N} = \min\{(\ell - k)\alpha + n > 0 \mid (\ell, n) \in \mathbb{Z}^2,\ 0 < \ell \leq N\}. \tag{4}$$

The substitution $m = \ell - k$ yields

$$s_{k,N} = \min\{m\alpha + n > 0 \mid (m, n) \in \mathbb{Z}^2,\ -k < m \leq N - k\}. \tag{5}$$

We rewrite (5) as

$$s_{k,N} = \min\{y > 0 \mid (x, y) \in \mathbb{Z}^2 A_1,\ -k < x \leq N - k\}, \tag{6}$$

with the matrix

$$A_1 = \begin{pmatrix} 1 & \alpha \\ 0 & 1 \end{pmatrix}. \tag{7}$$

The lattice $\mathbb{Z}^2 A_1$ and $s_{k,N}$ are illustrated in Figure 2.

Now take a general element $M \in G$ and $0 < t \leq 1$, and define the function F by

$$F(M, t) = \min\left\{ y > 0 \;\middle|\; (x, y) \in \mathbb{Z}^2 M,\ -t < x \leq 1 - t \right\}. \tag{8}$$

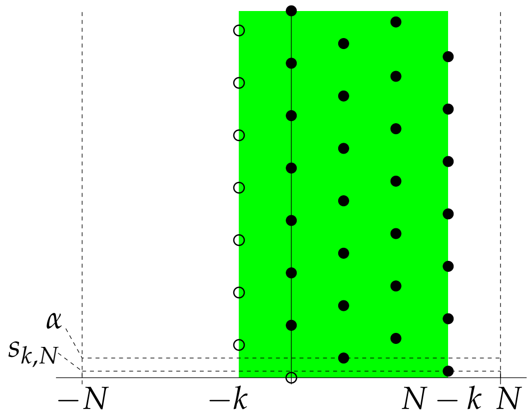

FIGURE 2. Illustration of the the expression for $s_{k,N}$ in (6) (here $N = 4$, $k = 1$).

To see the connection of F with the gap $s_{k,N}$, define

$$A_N = \begin{pmatrix} 1 & \alpha \\ 0 & 1 \end{pmatrix} \begin{pmatrix} N^{-1} & 0 \\ 0 & N \end{pmatrix} \in G, \tag{9}$$

and note that, by rescaling the set in (6), we have

$$s_{k,N} = \frac{1}{N} \min \left\{ y > 0 \;\middle|\; (x,y) \in \mathbb{Z}^2 A_N,\ -\frac{k}{N} < x \leq 1 - \frac{k}{N} \right\}. \tag{10}$$

Thus,

$$s_{k,N} = \frac{1}{N} F\left(A_N, \frac{k}{N} \right). \tag{11}$$

We first check F is well-defined as a function on the space of lattices $\Gamma\backslash G$ (Proposition 1), and then establish that the function $t \mapsto F(M,t)$ only takes at most three values for every fixed $M \in G$ (Proposition 2). The latter implies the three gap theorem via (11).

Proposition 1. *F is well-defined as a function $\Gamma\backslash G \times (0,1] \to \mathbb{R}_{>0}$.*

Proof. Let us begin by showing that

$$\left\{ y > 0 \;\middle|\; (x,y) \in \mathbb{Z}^2 M,\ -t < x \leq 1 - t \right\} \tag{12}$$

is nonempty for every $M \in G$, $t \in (0,1]$. Let

$$M = \begin{pmatrix} a & b \\ c & d \end{pmatrix}, \tag{13}$$

and assume first that $a = 0$. Then $c \neq 0$ and $b = -1/c$, and (12) becomes

$$\left\{ bm + dn > 0 \;\middle|\; (m,n) \in \mathbb{Z}^2,\ -t < cn \leq 1 - t \right\} \supset |b|\mathbb{N}, \tag{14}$$

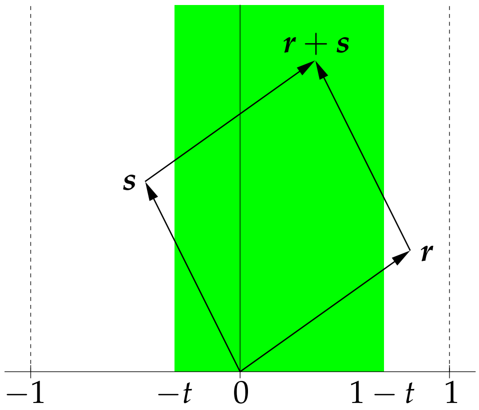

FIGURE 3. Illustration of the lattice configuration in the proof of Proposition 2.

which is nonempty. If $a \neq 0$, we have

$$M = \begin{pmatrix} a & b \\ c & d \end{pmatrix} = \begin{pmatrix} a & 0 \\ c & a^{-1} \end{pmatrix} \begin{pmatrix} 1 & ba^{-1} \\ 0 & 1 \end{pmatrix}, \tag{15}$$

and so (12) equals

$$\left\{ y + ba^{-1}x > 0 \;\middle|\; (x,y) \in \mathbb{Z}^2 \begin{pmatrix} a & 0 \\ c & a^{-1} \end{pmatrix},\ -t < x \leq 1-t \right\}. \tag{16}$$

Since $-t < x \leq 1-t$ implies $|x| \leq 1$, the set in (16) contains the set

$$\begin{aligned} &\left\{ y + ba^{-1}x \;\middle|\; (x,y) \in \mathbb{Z}^2 \begin{pmatrix} a & 0 \\ c & a^{-1} \end{pmatrix},\ -t < x \leq 1-t,\ y > |ba^{-1}| \right\} \\ &\qquad = \left\{ bm + dn \;\middle|\; (m,n) \in \mathbb{Z}^2,\ -t < am + cn \leq 1-t,\ n > |b| \right\}. \end{aligned} \tag{17}$$

If c/a is rational, there exist $(m,n) \in \mathbb{Z}^2$ with $n > |b|$ such that $am + cn = 0$. If c/a is irrational, then the set $\{am + cn \mid (m,n) \in \mathbb{Z}^2,\ n > |b|\}$ is dense in $\mathbb{R}$. Therefore, in both cases, (17) is nonempty, and the minimum of (12) exists due to the discreteness of $\mathbb{Z}^2 M$.

Finally, we note that $F(\,\cdot\,,t)$ is well-defined on $\Gamma\backslash G$ since $F(M,t) = F(\gamma M,t)$ for all $M \in G$, $\gamma \in \Gamma$. □

The following assertion implies the classical three gap theorem; recall (11).

Proposition 2. *For every given $M \in G$, the function $t \mapsto F(M,t)$ is piecewise constant and takes at most three distinct values. If there are three values, then the third is the sum of the first and second.*

Proof. Among all points of $\mathcal{L} = \mathbb{Z}^2 M$ in the region $\mathcal{A} = (-1,1) \times \mathbb{R}_{>0}$, let $\boldsymbol{r} = (r_1, r_2)$ be a point with minimal second coordinate r_2. See Figure 3. Next let $\boldsymbol{s} = (s_1, s_2)$ be a point in $\mathcal{A} \cap \mathcal{L} \setminus \mathbb{Z}\boldsymbol{r}$ with s_2 minimal. (If such a vector $\boldsymbol{s}$ does not exist, then $F(M,t) = r_2$ for all t.) Then $s_2 \geq r_2 > 0$. Let us assume $s_2 > r_2$ (the case $s_2 = r_2$ is treated at the end of the proof).

The parallelogram $\mathbf{0}, \boldsymbol{r}, \boldsymbol{s}, \boldsymbol{r}+\boldsymbol{s}$ does not contain any other lattice points: if $\boldsymbol{u}$ were such a lattice point, then $\boldsymbol{u}$ or $\boldsymbol{r}+\boldsymbol{s}-\boldsymbol{u}$ would have second coordinate smaller than s_2, contradicting the assumed minimality of s_2. This implies that $\boldsymbol{r}, \boldsymbol{s}$ form a basis of $\mathcal{L}$.

Note that r_1 and s_1 must have opposite signs, i.e. $r_1 s_1 < 0$, since otherwise $\boldsymbol{s} - \boldsymbol{r} \in \mathcal{A}$ with a second coordinate that is smaller than s_2, contradicting the assumed minimality of s_2. It follows that, if we set $\mathcal{J}_{\boldsymbol{r}} = (0,1] \cap (-r_1, 1-r_1]$ and $\mathcal{J}_{\boldsymbol{s}} = (0,1] \cap (-s_1, 1-s_1]$, then one of these intervals is of the form $(0,q]$ and the other is of the form $(q',1]$, for some $q,q' \in (0,1)$. Note that both intervals are nonempty since $\boldsymbol{r}, \boldsymbol{s} \in \mathcal{A}$ by construction, and thus $|r_1|, |s_1| < 1$. More explicitly,

$$\mathcal{J}_{\boldsymbol{r}} = \begin{cases} (-r_1, 1] & \text{if } -1 < r_1 \le 0 \\ (0, 1-r_1] & \text{if } 0 \le r_1 < 1, \end{cases} \tag{18}$$

and similarly for $\mathcal{J}_{\boldsymbol{s}}$. Now in view of definition (8), we obtain

$$F(M,t) = \begin{cases} r_2 & \text{if } t \in \mathcal{J}_{\boldsymbol{r}} \\ s_2 & \text{if } t \in \mathcal{J}_{\boldsymbol{s}} \setminus \mathcal{J}_{\boldsymbol{r}} \\ r_2 + s_2 & \text{if } t \in (0,1] \setminus (\mathcal{J}_{\boldsymbol{r}} \cup \mathcal{J}_{\boldsymbol{s}}). \end{cases} \tag{19}$$

(Here the set $(0,1] \setminus (\mathcal{J}_{\boldsymbol{r}} \cup \mathcal{J}_{\boldsymbol{s}})$ may be empty.) Thus, for any fixed M, the function $F(M, \cdot\,)$ can only take one of the three values $r_2, s_2, r_2 + s_2$.

Now consider the remaining case $s_2 = r_2$. We choose $\boldsymbol{r}, \boldsymbol{s} \in \mathcal{A} \cap \mathcal{L}$ so that $\boldsymbol{r} = (r_1, r_2)$ has minimal $r_1 \ge 0$, and $\boldsymbol{s} = (s_1, r_2)$ has maximal $s_1 < 0$. We can then proceed as above to obtain $F(M,t) = r_2$ for $t \in (0, 1-r_1] \cup (-s_1, 1]$ and $F(M,t) = 2r_2$ for all other t in $(0,1]$.

□

Acknowledgment. We thank both referees for their valuable feedback. The research leading to these results has received funding from the European Research Council under the European Union's Seventh Framework Programme (FP/2007-2013) / ERC Grant Agreement n. 291147. A.S. is supported by a grant from the Göran Gustafsson Foundation for Research in Natural Sciences and Medicine, and also by the Swedish Research Council Grant 621-2011-3629.

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