SOME CONTRIBUTIONS TO REGULAR POLYGONS

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Abstract. The aim of this work is to use Napoleon’s Theorem in different regular polygons, and decide whether we can prove Napoleon’s Theorem is only limited with triangles or it could be done in other regular polygons that can create regular polygons.

1. Introduction

The famous theorem of Napoleon is one of the most interesting assertions from elementary geometry of planar figures. Although over 150 years have passed, mathematicians still continues to be of interest to Napoleon’s Theorem as both professional and amateur alike. Because, this theorem is an important and useful tool to expand the mathematical horizon for many mathematicians. In the Euclidean Plane, Napoleon’s Theorem is easily proven. A wide variety of proofs of this theorem have been given in a lot of manuscripts.

In this work, we give a well known simple proof of Napoleon’s Theorem based on Sine and Cosine Laws. Further, we apply the Theorem to regular polygon such as regular hexagon, square and octagon.

Napoleon’s Theorem states the fact that if equilateral triangles are drawn outside of any triangle, the centers of the equilateral triangles will form an equilateral triangle.

We take a main triangle $\triangle ABC$, three equilateral triangles, which are outside $\triangle ABC$ are $\triangle ADB$, $\triangle BCE$, $\triangle AFC$. We denote the discovered triangle by $\triangle PQR$. Then, $\hat{FAC} = \hat{ACF} = \hat{CFA} = \hat{ADB} = \hat{BDA} = \hat{BCE} = \hat{ECB} = \hat{CBE} = 60^\circ$ (Figure 1).

We give a well known simple proof of Napoleon’s Theorem as follows:

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Proof. [1] Since $\triangle ECB$, $\triangle FCA$, $\triangle ADB$ are equilateral, then $\overrightarrow{FAC} = \overrightarrow{ACF} = \overrightarrow{CFA} = ADB = BDA = DAB = BCE = ECB = CBE = 60^\circ$. We take $|CQ|$, $|BQ|$, $|AP|$, $|AR|$, $|CR|$ is an angle bisector. Thus, $\angle FAC = \angle ACF = \angle CFA = \angle ADB = \angle BAD = \angle DBA = \angle BCE = \angle ECB = \angle CBE = 60^\circ$. We take $|CQ|$, $|BQ|$, $|AP|$, $|AR|$, $|CR|$ is an angle bisector. Thus, $\angle PAB = \angle PBA = \angle QBC = \angle QCB = \angle RCA = \angle RAC = 30^\circ$. Isosceles triangles have two equal sides, that is, $x = x_1$, $y = y_1$, $z = z_1$ and so use the fact that the centroid of an equilateral triangle $\triangle ADB$, $\triangle BCE$, $\triangle AFC$ lies along each median, $2/3$ of the distance from the vertex to the midpoint of the opposite side, $x = x_1 = \frac{2\sqrt{3}}{3} = \frac{a\sqrt{3}}{3}$, $y = y_1 = \frac{c}{\sqrt{3}}$, $z = z_1 = \frac{b}{\sqrt{3}}$. If we use the Cosine formula for $\triangle PQR$, then, we have

\[
|RP|^2 = y^2 + z^2 - 2yz \cos(\alpha + 60^\circ)
\]

\[
|RP|^2 = \left(\frac{c}{\sqrt{3}}\right)^2 + \left(\frac{b}{\sqrt{3}}\right)^2 - 2 \cdot \frac{c}{\sqrt{3}} \cdot \frac{b}{\sqrt{3}} \cos(\alpha + 60^\circ)
\]

\[
3|RP|^2 = b^2 + c^2 - 2bc \cos(\alpha + 60^\circ)
\]

\[
3|RP|^2 = b^2 + c^2 - 2bc \left(\cos \alpha \cos 60^\circ - \sin \alpha \sin 60^\circ\right)
\]

\[
3|RP|^2 = b^2 + c^2 - 2bc \left(\frac{1}{2} \cos \alpha - \frac{\sqrt{3}}{2} \sin \alpha\right).
\]

If we apply the Law of Cosine to $\triangle ABC$ and the Law of Sine for the area of $\triangle ABC$, then, we can write $a^2 = b^2 + c^2 - 2bc \cos \alpha$ and $2 \cdot (\text{Area of } \triangle ABC) = bc \sin \alpha$, respectively. Substituting these statement into the $3|RP|^2 = b^2 + c^2 - 2bc \left(\frac{1}{2} \cos \alpha - \frac{\sqrt{3}}{2} \sin \alpha\right)$ gives

\[
3|RP|^2 = \frac{1}{2} \left(a^2 + b^2 + c^2\right) + 2\sqrt{3}(\text{Area of } \triangle ABC).
\]
In the same idea, we can compute the length of $|PQ|$ and $|RQ|$. Since, the $\triangle APB$, $\triangle BQC$, $\triangle CRA$ are isosceles triangles, we say $\alpha = \beta = \theta$ and also $|RQ| = |PQ| = |RP|$. Then, it follows that the $\triangle PQR$ connecting the three centroids is equilateral.

\[ \square \]

2. Main Results

In this section, we will apply Napoleon’s Theorem to some regular polygon and prove as in Section 1.

2.1. Application to Regular Hexagon. Consider the regular hexagon $ABCDEF$ and the six regular hexagons, which are outside the main regular hexagon(Figure 2).

Each interior of this hexagon is $120^\circ$, because the sum of the interior angles of any hexagon is $720^\circ$. Now, we divide regular hexagons into six pieces by using its diagonals. It will make six equilateral triangles, which are all $60^\circ$. Then, $G_1ED = G_1DE = < H_1DC = H_1CD = I_1CB = I_1BC = J_1BA = J_1AB =$
\( \widehat{K_1 AF} = \widehat{K_1 FA} = \widehat{L_1 EF} = \widehat{L_1 FE} = 60^\circ. \)

The diagonals of regular hexagon are equal. Hence half of the diagonals are equal too. Hence, \( c_5 = e_3, m_3 = n_3, f_3 = i_3, t_3 = a_4, r_3 = s_3, q_3 = p_3. \) Also, \( a = b = c = d = e, \) since regular hexagon has equal sides. We know that the equilateral triangles have equal sides. From this, we can write \( \hat{m} \), \( \hat{g}, \) \( \hat{c} \) equal too. Hence, \( \hat{a} \), \( \hat{f} \), \( \hat{h} \). Thus, \( \hat{a} \).

Let’s think that one side of the main hexagon is \( x \), \( x \in \mathbb{Z} \).

\[
\sin 60^\circ = \frac{\sin 60^\circ}{|CH_1|} \quad x = |CH_1|
\]

\( \Delta H_1 DC \) is isosceles triangle since \( |CH_1| = |DH_1| \).

Also, \( \Delta H_1 DC \) and \( \Delta I_1 CB \) are equal hence \( |DH_1| = |BI_1| \), the edges \( c = c_5 = e_3 = x. \) Hence, from the special triangle \((30 - 60 - 90)\) in the \( \Delta CH_1 T_1 \)

\[
\frac{\sin 90^\circ}{x} = \frac{\sin 60^\circ}{|H_1 T_1|} \quad \frac{\sqrt{3}}{2} x = |H_1 T_1|.
\]

Since \( |H_1 I_1| \) is the double of \( |H_1 T_1| \) because the edges see the same degree, \( 60^\circ \)

\[
|H_1 I_1| = \sqrt{3} x.
\]

The one side of the main hexagon is \( x \) then, one side of the discovered hexagon need to be \( \sqrt{3} x, \) since the ratio between sides won’t change no matter the size of the hexagon because same sine law will be applied with the same, equal angles.

2.2. Application to Square. The main square is \( ABCD \) and the four squares, which are outside the main square(Figure 3).

Each interior of a square is \( 90^\circ, \) because the sum of the interior angles of any quadrilateral is \( 360^\circ. \) \( DG \) and \( CH, BJ \) and \( CI, BK \) and \( AL, MA \) and \( ND \) are the bisection of the squares. Then, \( \overrightarrow{ODC} = \overrightarrow{OCD} = \angle PCB = \overrightarrow{PBC} = \overrightarrow{QBA} = \overrightarrow{QAB} = \overrightarrow{H_1 AD} = \overrightarrow{H_1 DA} = \overrightarrow{ODC} = \overrightarrow{OCD} = 45^\circ. \)

The diagonals of square are equal, so half of the diagonals are equal too. From this statement, \( u = w, o = p_1, q_1 = d_2, e_2 = q. \) Then, we can write the isoseles triangles \( \Delta ODC = \Delta PDB = \Delta BQA = \Delta AH_1 D = \Delta DOC. \) Since, square has equal sides, then \( g = f = e = d. \) Using the special triangle \((45-45-90), \)

\[
\frac{\sqrt{2}}{2} = w, \frac{\sqrt{2}}{2} = o, \frac{\sqrt{2}}{2} = d_2, \frac{\sqrt{2}}{2} = q \quad \text{and} \quad \frac{\sqrt{2}}{2} = w = o = d_2 = q. \] Therefore, \( |OP| = |PQ| = |QH_1| = |H_1 O|, \) as we desired.
The ratio between the lengths of edges of the main square and the discovered/new square:

Let’s think that one side of the main square is $x$, ($x \in \mathbb{Z}$).

\[
\frac{\sin 90^\circ}{x} = \frac{\sin 45^\circ}{|OC|} \Rightarrow \frac{\sqrt{2}}{2} x = |OC|.
\]

Since $|OP|$ is the double of $|DC|$ because of edges $w = o$, $|OP| = \sqrt{2}x$. The one side of the main square is $x$, then one side of the discovered square need to be $\sqrt{2}x$ since the ratio between the sides will not change no matter the size of the square is because same sine law will be applied with the same angles.

2.3. Application to Octagon. The main octagon is $ABCDEFGH$ and the eight octagons, which are outside the main octagon(Figure 4).

Now, we know that, the sum of the interior angles of any octagon is $1080^\circ$ and the diagonals are bisectors of the octagon, which are $67.5^\circ$. Thus, we obtain that each of interior angle of a regular octagon is $135^\circ$. And also, we can say that $I_2FE = I_2EF =< J_2ED =< J_2DE =< K_2CD =< K_2DC =< L_2CB =< \cdots$
Diagonals of regular octagon are equal. So half of the diagonals are equal too. Therefore, $|I_2F| = |I_2E| = |J_2E| = |J_2D| = |K_2D| = |K_2C| = |L_2C| = |L_2B| = |BM_2| = |AM_2| = |N_2A| = |N_2H| = |O_2H| = |O_2C| = |P_2C| = |P_2F|$. Since they see the same angle, which is $45^\circ$, then $|CF| = |FE| = |ED| = |DC| = |CB| = |BA| = |AH| = |HC|$. The triangles $\triangle AM_2B = \triangle BL_2C = \triangle CK_2D = \triangle DJ_2F = \triangle FI_2E = \triangle CP_2F = \triangle HO_2C = \triangle AN_2H$ are isosceles triangles. This step completes the proof.

The ratio between the lengths of edges of the main octagon and the discovered/new octagon:
Assume that one side of the main regular octagon is $x$, ($x \in \mathbb{Z}$).

$$\frac{\sin 45^\circ}{x} = \frac{\sin 67.5^\circ}{|K_2C|}$$

$$1.31x = |K_2C|.$$ 

Also $|K_2C|$ and $|CL_2|$ are equal because they see the same angle which is $67.5^\circ$. If we say the edges which see $45^\circ$ will be $x$ then the edges which see $90^\circ$ will be $\sqrt{2}x$.

$$|K_2C| = |CL_2| = 1.31x$$

$$|K_2L_2| = 1.85x.$$ 

The one side of the main octagon is $x$ then, one side of the discovered octagon need to be $1.85x$ since the ratio between sides won’t change no matter the size of the hexagon because same sine law will be applied with the same, equal angles.

### 3. Conclusion

In this work, we have investigated how Napoleon’s Theorem is applied to regular polygons. Firstly, we gave a simple proof of the Theorem using Sine and Cosine Laws. Further, we applied the Theorem to regular polygons such as hexagon, square and octagon, with the same idea. We draw a triangle, which is not equilateral, and then draw equilateral triangles outside the triangle. We got the centroids of the equilateral triangle, unit them with lines.

In our application on hexagon, we found that the main regular hexagon was $x$ and the discovered square was $\sqrt{3}x$. Hence, the main regular hexagon would every time be nearly twice as small as the new regular hexagon. We did the same ratios in the application of square. This times the main square was $x$, and the discovered square was $\sqrt{2}x$. Hence, this time the main square was one and a half smaller than the new square. And also, we used the octagon. Thus, the regular polygons length ratios which are the main and discovered polygon, was transferred in graphs and seen that there was a strong correlation between them.

### References

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