On Some Special Property of The Farey Sequence

Ripan Saha

Department of Mathematical Sciences, Raiganj University, University Road-733134, India.

Email: ripanjumaths@gmail.com

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ABSTRACT

In this paper, some special property of the Farey sequence is discussed. We prove in each term of the Farey sequence, the sum of elements in the denominator is two times of the sum of elements in the numerator. We also prove that the Farey sequence contains a palindrome structure.

Keywords: Farey sequence, Palindrome, Euler’s Totient function.

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1. Introduction

Farey sequence is named after British geologist John Farey, Sr., who published a result in Philosophical Magazine in 1816 about this sequence without giving a proof. Later, Cauchy proved the result conjectured by Farey. Though, Charles Haros proved a similar result in 1802 which were not known to both Farey and Cauchy. Later, Farey sequence appeared in many different areas of mathematics, including number theory, topology, geometry, see, (Hardy and Wright 1979), (Cobeli and Zaharescu 2003), (Ainsworth, Dawson, Pianta and Warwick 2012). Farey sequence is also related to Ford’s circle and Riemann hypothesis, (Kanemitsu and Yoshimoto 1996). Farey sequence (Hardy and Wright 1979), $F_n$ in the interval $[0, 1]$ is defined as a sequence of ascending rational numbers in reduced form starting at $0$ and ending at $1$ such that the elements in the nth term, denominator are less than or equal to n. First few terms of Farey sequence are listed as follows,

$$F_1 = \frac{0}{1}, \frac{1}{1}$$
$$F_2 = \frac{0}{1}, \frac{1}{1}, \frac{1}{2}, \frac{1}{1}$$
$$F_3 = \frac{0}{1}, \frac{1}{1}, \frac{1}{2}, \frac{2}{1}, \frac{1}{3}, \frac{3}{1}$$
$$F_4 = \frac{0}{1}, \frac{1}{1}, \frac{1}{2}, \frac{2}{1}, \frac{1}{3}, \frac{3}{1}, \frac{2}{2}, \frac{3}{1}, \frac{1}{4}, \frac{4}{1}$$

For all the terms of the Farey sequence given above, one can note that the summation of the elements in the denominator is always two times of the summation of the elements in the numerator. In $F_1$, sum of numerators is 1 and sum of denominators is 2. In $F_2$, sum of numerators is 2 and sum of denominators is 4. Likewise in $F_3$, $F_4$, sum of denominators is always two times the sum of numerators. So, one may ask if this result holds for all $F_n$ or not. In this paper, we will show that in general this result is true. In the second section of this article, we introduce this special property of Farey sequence. A palindrome is a word or sequence if it reads same from forward and backward direction. Palindrome appears in many different areas. In the final section, we show that denominators of each fraction in $F_n$ has a palindrome structure for all n.

2. A Special Property of The Farey Sequence

In this section, we prove our first result on Farey sequence. We show the summation of the elements in the denominator is two times of the summation of elements in the numerator for all positive integer n.

2.1 Lemma [1] The length of each term of Farey sequence $F_n$ is given by the following recurring formula:

$$|F_n| = |F_{n-1}| + \varphi(n).$$
2.2. Remark. From the Lemma 2.1, we get the information that number of new elements appears in \( F_n \) compare to \( F_{n-1} \) is \( \varphi(n) \). The numbers \( 1 \leq k < n \) which are co-prime to \( n \), appears to the numerator in the new terms of \( F_n \) and the denominator of each new terms in \( F_n \) is always \( n \).

2.3. Lemma [2]. For all integer \( n \geq 0 \) and \( k \geq 0 \),

\[
\sum_{(n,k)=1} k = \frac{n\varphi(n)}{2}.
\]

Proof. If \( \gcd(n, k) = 1 \), then \( \gcd(n, n-k) = 1 \). Note that, \( k \) cannot be equal to \( n-k \), otherwise, \( \gcd(k, n) \) will not be 1. The number of elements co-prime to \( n \) is \( \varphi(n) \). So pairing \( k \) and \( n - k \), we get the total sum is \( \frac{n\varphi(n)}{2} \).

2.4. Theorem. In the Farey sequence \( F_n \), the summation of the elements in the denominator is two times of the summation of elements in the numerator for all positive integer \( n \).

Proof. We use induction to prove this result. Let \( N_n \) denotes the summation of the elements in the numerator of the \( n \)th term of Farey sequence \( F_n \) and \( D_n \) denotes the summation of elements in the denominator of \( n \)th term of Farey sequence.

For \( n = 1 \), \( N_1 = 1 \) and \( D_1 = 2 \).

For \( n = 1 \), \( D_1 = 2N_1 \). Now assume the result holds for \( n - 1 \). We prove that the result holds for all \( n \), we have,

\[
N_n = N_{n-1} + \sum_{\gcd(n,k)=1} k, \text{ using remark 2.2}
\]
\[
= N_{n-1} + \frac{n\varphi(n)}{2}, \text{ using lemma 2.3}
\]
\[
D_n = D_{n-1} + n\varphi(n), \text{ using remark 2.2}
\]
\[
= 2N_{n-1} + n\varphi(n), \text{using induction.}
\]
\[
= 2 \left( N_{n-1} + \frac{n\varphi(n)}{2} \right)
\]
\[
= 2N_n
\]

So, by induction our result follows.

3. Palindromic Structure in The Farey Sequence

In this final section, we show that there is a palindromic structure in denominators of \( F_n \) for all \( n \). Thus from the Farey sequence we can get palindromic numbers.

3.1 Definition. A word or sequence is called a Palindrome if it reads same from forward and backward direction. Palindrome appears in many different areas. In names, numbers or musical notes appearance of palindromes is noticeable. For example, English word BOB, MADAM, MOM and numbers 101, 1001, 12321, are examples of palindromes.

3.2. Definition. Two fractions \( \frac{a}{b} \) and \( \frac{c}{d} \) in \( F_n \) are called Farey neighbours if \( \frac{a}{b} < \frac{c}{d} \) and there is no fraction in \( F_n \) between them.

The following lemma gives a condition for two fraction to be Farey neighbour.

3.3 Lemma: [1]: Let, \( 0 \leq \frac{a}{b} < \frac{c}{d} \leq 1 \) then \( \frac{a}{b}, \frac{c}{d} \in F_n \) are neighbours in the Farey sequence if and only if \( be - ad = 1 \).

3.4 Corollary: If \( 0 \leq \frac{a}{b} < \frac{c}{d} \leq \frac{1}{2} \) are Farey neighbours, then \( \frac{1}{2} \leq \frac{b-a}{b} < \frac{b-a}{b} < \frac{1}{2} \) are also Farey neighbours

Proof. Using lemma 3.3, on the given first Farey neighbours, we have,
\[
b_a - a_b = 1
\]

So, \( b_2 (b_1 - a_1) - b_1 (b_2 - a_2) = b_a - a_b = 1 \)

Now, \( \frac{a}{b} \geq \frac{1}{2} \) and \( \frac{0}{1} \leq \frac{a}{b} \leq \frac{1}{2} \). Thus, \( b_a - a_b \geq \frac{1}{2} \).

Similarly, \( \frac{1}{2} \leq \frac{b-a}{b} \leq \frac{1}{2} \). Thus, our corollary follows.

3.5. Theorem. Denominators of each fraction in \( F_n \) for all \( n \) in the Farey sequence is a palindrome.

Proof. We prove this theorem by induction.

In \( F_1 \), denominators are 1,1, which is a palindrome sequence. In \( F_2 \), denominators are 1,2,1, which is also a palindrome sequence.

Now, suppose that denominators in \( F_{n-1} \) are in a palindrome sequence. We need to show that denominators in \( F_n \) is also in a palindrome sequence. Using corollary 3.4 and palindrome structure of denominators in \( F_{n-1} \), we can write \( F_{n-1} \) in the following form,

\[
F_{n-1} = \begin{bmatrix}
0 & \frac{r_1}{s_1} & \frac{r_2}{s_2} & \frac{1}{2} & \frac{s_2 - r_1}{s_1} & \frac{1}{2} & \frac{1}{1}
\end{bmatrix}
\]

Suppose in the next term \( F_n \), a new term appears between \( \frac{r_1}{s_1} \) and \( \frac{r_2}{s_2} \).

Let, \( r_1 + s_2 = k \). We have following relations by using remark 2.2, \( s_1 + s_2 = n \) and \( \gcd(n, k) = 1 \).

Now, \( (r_1 - s_2) + (s_2 - r_1) = n - k \).

Thus we write \( F_n \) in terms of \( n, k \) as follows:

\[
\begin{bmatrix}
0 & r_1 & r_2 & \frac{1}{2} & s_2 - r_1 & \frac{1}{2} & 1
\end{bmatrix}
\]

\[
\begin{bmatrix}
1 & s_1 & n & s_2 & \frac{n - k}{n} & s_1 - r_1 & \frac{1}{1}
\end{bmatrix}
\]
As \( \frac{r_1}{s_1} < \frac{k}{n} < \frac{r_2}{s_2} \) are Farey neighbours, we have,

\[
k_1 - n r_1 = 1 \quad \text{and} \quad n r_2 - k s_2 = 1
\]

(3.2)

Note that,

\[
(n - k) s_2 - n (s_2 - r_2) = n r_2 - k s_2 = 1.
\]

So, \( \frac{s_2 - r_2}{s_2} < \frac{n - k}{n} \) \( < \frac{s_1 - r_1}{s_1} \) are Farey neighbours. Thus, we have proved that denominators in \( F_n \) are palindrome. Our desired result follows from induction.

3.6 Remark. By length of a palindrome, we mean the number of element appearing in the palindrome. From the lemma 2.1, it is clear that palindromic length of denominator palindrome in \( F_n \) is \( |F_{n-1}| + \varphi(n) \). Thus using the Farey sequence one can get very large palindrome numbers.

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