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On an Inequality Analogous to the Nesbitt Inequality

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Abstract

In this paper, we first examine a cyclic inequality analogous to the Nesbitt inequality, and subsequently establish generalized versions using convex functions and the Jensen inequality. Several applications are provided to illustrate the main results.

1 Introduction

A cyclic inequality is an algebraic inequality involving multiple variables (typically $a, b, c, \dots$) that remains invariant when its variables are cyclically permuted. For example, in a three-variable system, applying the shift $a \to b \to c \to a$ leaves the entire expression unchanged. These inequalities often appear in competitive mathematics, such as Olympiads. Proving them generally involves advanced algebraic manipulations, regrouping, or the application of major inequalities like the arithmetic mean-geometric mean, Cauchy-Schwarz, or Jensen inequality. One of the most famous examples in this domain is the Nesbitt inequality. For any $a, b, c > 0$, the inequality states that

$$\frac{a}{b+c} + \frac{b}{c+a} + \frac{c}{a+b} \geq \frac{3}{2}.$$

The equality holds for $a = b = c$. Although the Nesbitt inequality serves as a foundational benchmark, contemporary research frequently focuses on extending this result. In particular, a well-known variant introduces a factor of 2 to one variable in each denominator. For any $a, b, c > 0$, this yields the following bound:

$$\frac{a}{b+2c} + \frac{b}{c+2a} + \frac{c}{a+2b} \geq 1. \tag{1.1}$$

While this coefficient breaks the symmetry within each individual fraction, the expression as a whole maintains its cyclic symmetry. As with the classic Nesbitt inequality, the equality holds for $a = b = c$. For further details, see [1–8] and the references cited therein.

In this paper, we examine another cyclic inequality analogous to the Nesbitt inequality that remains largely unexplored. It is formulated as follows: For any $a, b, c > 0$, we have

$$\frac{a}{a+2b} + \frac{b}{b+2c} + \frac{c}{c+2a} \geq 1. \tag{1.2}$$

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The equality holds for $a = b = c$. Compared to the main sum in Equation (1.1), the variables in the denominators have been systematically shifted so that each fraction now includes its own numerator in the denominator. A direct proof follows immediately from the Titu lemma. By multiplying the numerator and denominator of each fraction by its respective numerator, the lemma gives

$$\begin{aligned}\frac{a}{a+2b}+\frac{b}{b+2c}+\frac{c}{c+2a} &= \frac{a^2}{a^2+2ab}+\frac{b^2}{b^2+2bc}+\frac{c^2}{c^2+2ca}\\ &\overset{Titu's\ lemma}{\geq} \frac{(a+b+c)^2}{(a^2+2ab)+(b^2+2bc)+(c^2+2ca)}\\ &= \frac{(a+b+c)^2}{a^2+b^2+c^2+2(ab+bc+ca)}\\ &= \frac{(a+b+c)^2}{(a+b+c)^2}=1.\end{aligned}$$

Thus, a single inequality drives the entire proof, which is relatively uncommon in this domain.

Beyond its simple form, the inequality in Equation (1.2) is of interest because it arises naturally as a solution to the following problem: Find three real numbers A, B, and C in terms of the variables a, b, and c such that $A, B, C \in [0, 1]$ and

$$A + B + C \geq 1.$$

Building on the approach developed in [4], we generalize this inequality using convex functions and explore the theoretical implications of this broader framework. Specifically, we propose two distinct convexity-based extensions, illustrating our results with a variety of concrete examples.

The remainder of the paper is organized as follows: The main result is established in Section 2, followed by applications in Section 3 and two extensions in Section 4. A conclusion is provided in Section 5.

2 Main Theorem

We present our main result below, emphasizing the core role played by the convex function f.

Theorem 2.1. *Let $f : (0, \infty) \to \mathbb{R}$ be a convex function. Then, for any $a, b, c > 0$, we have*

$$af(a + 2b) + bf(b + 2c) + cf(c + 2a) \geq (a + b + c)f(a + b + c).$$

The equality holds for $a = b = c$.

Proof. Modifying the weights and applying the Jensen inequality to the convex function f, we obtain

$$\begin{aligned}
&af(a+2b)+bf(b+2c)+cf(c+2a)\\
&=(a+b+c)\left(\frac{a}{a+b+c}f(a+2b)+\frac{b}{a+b+c}f(b+2c)+\frac{c}{a+b+c}f(c+2a)\right)\\
&\overset{\text{Jensen's inequality}}{\geq}(a+b+c)f\left(\frac{a(a+2b)}{a+b+c}+\frac{b(b+2c)}{a+b+c}+\frac{c(c+2a)}{a+b+c}\right)\\
&=(a+b+c)f\left(\frac{a(a+2b)+b(b+2c)+c(c+2a)}{a+b+c}\right)\\
&=(a+b+c)f\left(\frac{a^2+2ab+b^2+2bc+c^2+2ca}{a+b+c}\right)\\
&=(a+b+c)f\left(\frac{a^2+b^2+c^2+2(ab+bc+ca)}{a+b+c}\right)\\
&=(a+b+c)f\left(\frac{(a+b+c)^2}{a+b+c}\right)=(a+b+c)f(a+b+c).
\end{aligned}$$

The equality holds trivially for $a=b=c$, reducing both sides to $3af(3a)$. This completes the proof. □

An equivalent formulation of this inequality is

$$\sum_{cyc}af(a+2b)\geq(a+b+c)f(a+b+c),$$

where $\sum_{cyc}$ denotes the cyclic sum over a, b, and c.

Note that if f is concave instead of convex, the inequality is reversed.

Requiring only convexity, without any assumption of monotonicity, imposes a mild constraint on f. This flexibility enables a wide range of applications, several of which are detailed in the subsequent section.

3 Applications of Theorem 2.1

We recall that Theorem 2.1 is valid for a convex function $f:(0,\infty)\to\mathbb{R}$.

The function $f(x)=x^p$ with $p\in\mathbb{R}\backslash(0,1)$ is convex (since $f''(x)=p(p-1)x^{p-2}\geq 0$ for $p(p-1)\geq 0$). It follows from Theorem 2.1 that

$$a(a+2b)^p+b(b+2c)^p+c(c+2a)^p\geq(a+b+c)(a+b+c)^p=(a+b+c)^{p+1}.$$

In particular,

- choosing $p=2$, we obtain

$$a(a+2b)^2+b(b+2c)^2+c(c+2a)^2\geq(a+b+c)^3,$$

- choosing $p = -1/2$, we have

$$\frac{a}{\sqrt{a+2b}} + \frac{b}{\sqrt{b+2c}} + \frac{c}{\sqrt{c+2a}} \geq \sqrt{a+b+c},$$

- choosing $p = -1$, we get

$$\frac{a}{a+2b} + \frac{b}{b+2c} + \frac{c}{c+2a} \geq 1,$$

which corresponds to Equation (1.2),

- choosing $p = -2$, we have

$$\frac{a}{(a+2b)^2} + \frac{b}{(b+2c)^2} + \frac{c}{(c+2a)^2} \geq \frac{1}{a+b+c}.$$

The function $f(x) = e^{qx}$ with $q \in \mathbb{R}$ is convex. Theorem 2.1 yields

$$ae^{q(a+2b)} + be^{q(b+2c)} + ce^{q(c+2a)} \geq (a+b+c)e^{q(a+b+c)}.$$

In particular,

- choosing $q = 2$, we get

$$ae^{2(a+2b)} + be^{2(b+2c)} + ce^{2(c+2a)} \geq (a+b+c)e^{2(a+b+c)},$$

- choosing $q = 1$, we obtain

$$ae^{a+2b} + be^{b+2c} + ce^{c+2a} \geq (a+b+c)e^{a+b+c},$$

- choosing $q = -1$, we have

$$ae^{-(a+2b)} + be^{-(b+2c)} + ce^{-(c+2a)} \geq (a+b+c)e^{-(a+b+c)}.$$

The function $f(x) = e^{1/x}$ is convex. It follows from Theorem 2.1 that

$$ae^{1/(a+2b)} + be^{1/(b+2c)} + ce^{1/(c+2a)} \geq (a+b+c)e^{1/(a+b+c)}.$$

The function $f(x) = -\ln(x)$ is convex. Theorem 2.1 gives

$$-a\ln(a+2b) - b\ln(b+2c) - c\ln(c+2a) \geq -(a+b+c)\ln(a+b+c),$$

which is equivalent to

$$(a+2b)^a(b+2c)^b(c+2a)^c \leq (a+b+c)^{a+b+c}.$$

In particular, this yields the elegant two-sided inequality

$$a^a b^b c^c \leq (a+2b)^a (b+2c)^b (c+2a)^c \leq (a+b+c)^{a+b+c}.$$

The function $f(x) = x\ln(x)$ is convex. It follows from Theorem 2.1 that

$$\begin{aligned} &a(a+2b)\ln(a+2b) + b(b+2c)\ln(b+2c) + c(c+2a)\ln(c+2a) \\ &\geq (a+b+c)(a+b+c)\ln(a+b+c) = (a+b+c)^2\ln(a+b+c), \end{aligned}$$

which is equivalent to

$$(a+2b)^{a(a+2b)}(b+2c)^{b(b+2c)}(c+2a)^{c(c+2a)} \geq (a+b+c)^{(a+b+c)^2}.$$

As a last example, the function $f(x) = \ln(1+e^{qx})$ with $q \in \mathbb{R}$ is convex. Theorem 2.1 yields

$$\begin{aligned} &a\ln\left(1+e^{q(a+2b)}\right) + b\ln\left(1+e^{q(b+2c)}\right) + c\ln\left(1+e^{q(c+2a)}\right) \\ &\geq (a+b+c)\ln\left(1+e^{q(a+b+c)}\right), \end{aligned}$$

which is equivalent to

$$\left(1+e^{q(a+2b)}\right)^a \left(1+e^{q(b+2c)}\right)^b \left(1+e^{q(c+2a)}\right)^c \geq \left(1+e^{q(a+b+c)}\right)^{a+b+c}.$$

In particular,

- choosing $q = 2$, we have

$$\left(1+e^{2(a+2b)}\right)^a \left(1+e^{2(b+2c)}\right)^b \left(1+e^{2(c+2a)}\right)^c \geq \left(1+e^{2(a+b+c)}\right)^{a+b+c},$$

- choosing $q = 1$, we get

$$\left(1+e^{a+2b}\right)^a \left(1+e^{b+2c}\right)^b \left(1+e^{c+2a}\right)^c \geq \left(1+e^{a+b+c}\right)^{a+b+c},$$

- choosing $q = -1$, we obtain

$$\left(1+e^{-(a+2b)}\right)^a \left(1+e^{-(b+2c)}\right)^b \left(1+e^{-(c+2a)}\right)^c \geq \left(1+e^{-(a+b+c)}\right)^{a+b+c}.$$

Two extensions of Theorem 2.1 are the subject of the subsequent section.

4 Extensions of Theorem 2.1

The convexity approach is now used to extend Theorem 2.1. In the theorem below, we emphasize the role of the function g in the statement.

Theorem 4.1. *Let $f : (0, \infty) \to \mathbb{R}$ be a convex function, and $g : \mathbb{R} \to \mathbb{R}$ be a convex and increasing function. Then, for any $a, b, c > 0$, we have*

$$g\left(af(a+2b)\right) + g\left(bf(b+2c)\right) + g\left(cf(c+2a)\right) \geq 3g\left(\frac{a+b+c}{3} f(a+b+c)\right).$$

The equality holds for $a = b = c$.

Proof. Modifying the weights, applying the Jensen inequality to the convex function g and using Theorem 2.1 combined with the increasing property of g, we obtain

$$\begin{aligned}
& g\left(af(a+2b)\right) + g\left(bf(b+2c)\right) + g\left(cf(c+2a)\right) \\
& = 3\left(\frac{1}{3} g\left(af(a+2b)\right) + \frac{1}{3} g\left(bf(b+2c)\right) + \frac{1}{3} g\left(cf(c+2a)\right)\right) \\
& \overset{\textit{Jensen's inequality}}{\geq} 3g\left(\frac{1}{3} af(a+2b) + \frac{1}{3} bf(b+2c) + \frac{1}{3} cf(c+2a)\right) \\
& = 3g\left(\frac{af(a+2b) + bf(b+2c) + cf(c+2a)}{3}\right) \\
& \overset{\textit{Theorem 2.1 and increasing property}}{\geq} 3g\left(\frac{a+b+c}{3} f(a+b+c)\right).
\end{aligned}$$

The equality holds trivially for $a = b = c$, reducing both sides to $3g\left(af(3a)\right)$. This concludes the proof. □

An equivalent formulation of this inequality is

$$\sum_{cyc} g\left(af(a+2b)\right) \geq 3g\left(\frac{a+b+c}{3} f(a+b+c)\right).$$

Note that if g is concave and decreasing instead of convex and increasing, the inequality is reversed.

We now present several applications of Theorem 4.1 for functions $f : (0, \infty) \to (0, \infty)$ and $g : (0, \infty) \to (0, \infty)$.

As a first example, the function $g(x) = x^p$ with $p \geq 1$ is convex and increasing. It follows from Theorem 4.1 that

$$(af(a+2b))^p + (bf(b+2c))^p + (cf(c+2a))^p \geq 3\left(\frac{a+b+c}{3} f(a+b+c)\right)^p,$$

so that

$$a^p f(a+2b)^p + b^p f(b+2c)^p + c^p f(c+2a)^p \geq \frac{(a+b+c)^p}{3^{p-1}} f(a+b+c)^p.$$

Choosing $f(x) = 1/x$, we derive

$$\frac{a^p}{(a+2b)^p} + \frac{b^p}{(b+2c)^p} + \frac{c^p}{(c+2a)^p} \geq \frac{1}{3^{p-1}}.$$

Therefore, the lower bound is independent of a, b, and c.

In particular,

- choosing $p = 1$, we obtain

$$\frac{a}{a+2b} + \frac{b}{b+2c} + \frac{c}{c+2a} \geq 1,$$

  which corresponds to Equation (1.2),

- choosing $p = 2$, we have

$$\frac{a^2}{(a+2b)^2} + \frac{b^2}{(b+2c)^2} + \frac{c^2}{(c+2a)^2} \geq \frac{1}{3}.$$

As another example, the function $g(x) = e^{qx}$ with $q > 0$ is convex and increasing. Theorem 4.1 gives

$$e^{qaf(a+2b)} + e^{qbf(b+2c)} + e^{qcf(c+2a)} \geq 3e^{(q/3)(a+b+c)f(a+b+c)}.$$

Choosing $f(x) = 1/x$, we obtain

$$e^{qa/(a+2b)} + e^{qb/(b+2c)} + e^{qc/(c+2a)} \geq 3e^{q/3}.$$

As a last example, the function $g(x) = x\ln(1+x)$ is convex and increasing. It follows from Theorem 4.1 that

$$\begin{aligned}
&af(a+2b)\ln(1+af(a+2b)) + bf(b+2c)\ln(1+bf(b+2c)) \\
&+ cf(c+2a)\ln(1+cf(c+2a)) \\
&\geq 3\frac{a+b+c}{3}f(a+b+c)\ln\left(1+\frac{a+b+c}{3}f(a+b+c)\right) \\
&= (a+b+c)f(a+b+c)\ln\left(1+\frac{a+b+c}{3}f(a+b+c)\right),
\end{aligned}$$

which is equivalent to

$$\begin{aligned}
&(1+af(a+2b))^{af(a+2b)}\,(1+bf(b+2c))^{bf(b+2c)}\,(1+cf(c+2a))^{cf(c+2a)} \\
&\geq \left(1+\frac{a+b+c}{3}f(a+b+c)\right)^{(a+b+c)f(a+b+c)}.
\end{aligned}$$

Choosing $f(x) = 1/x$, we get

$$\left(1+\frac{a}{a+2b}\right)^{a/(a+2b)}\left(1+\frac{b}{b+2c}\right)^{b/(b+2c)}\left(1+\frac{c}{c+2a}\right)^{c/(c+2a)} \geq \frac{4}{3}.$$

By applying an approach similar to that of Theorem 4.1, we obtain the result below for the sums of two consecutive terms.

Theorem 4.2. *Let $f : (0,\infty) \to \mathbb{R}$ be a convex function, and $g : \mathbb{R} \to \mathbb{R}$ be a convex and increasing function. Then, for any $a, b, c > 0$, we have*

$$\begin{aligned} & g\left(af(a+2b)+bf(b+2c)\right)+g\left(bf(b+2c)+cf(c+2a)\right) \\ & +g\left(cf(c+2a)+af(a+2b)\right) \geq 3g\left(\frac{2(a+b+c)}{3}f(a+b+c)\right). \end{aligned}$$

The equality holds for $a = b = c$.

Proof. Modifying the weights, applying the Jensen inequality to the convex function g and using Theorem 2.1 combined with the increasing property of g, we obtain

$$\begin{aligned} & g\left(af(a+2b)+bf(b+2c)\right)+g\left(bf(b+2c)+cf(c+2a)\right) \\ & +g\left(cf(c+2a)+af(a+2b)\right) \\ & =3\left(\frac{1}{3}g\left(af(a+2b)+bf(b+2c)\right)+\frac{1}{3}g\left(bf(b+2c)+cf(c+2a)\right)\right. \\ & \left.+\frac{1}{3}g\left(cf(c+2a)+af(a+2b)\right)\right) \\ & \overset{Jensen's\ inequality}{\geq} 3g\left(\frac{1}{3}\left(af(a+2b)+bf(b+2c)\right)+\frac{1}{3}\left(bf(b+2c)+cf(c+2a)\right)\right. \\ & \left.+\frac{1}{3}\left(cf(c+2a)+af(a+2b)\right)\right) \\ & =3g\left(\frac{2\left(af(a+2b)+bf(b+2c)+cf(c+2a)\right)}{3}\right) \\ & \overset{Theorem\ 2.1\ and\ increasing\ property}{\geq} 3g\left(\frac{2(a+b+c)}{3}f(a+b+c)\right). \end{aligned}$$

The equality holds trivially for $a = b = c$, reducing both sides to $3g\left(2af(3a)\right)$. This completes the proof. □

An equivalent formulation of this inequality is

$$\sum_{cyc} g\left(af(a+2b)+bf(b+2c)\right) \geq 3g\left(\frac{2(a+b+c)}{3}f(a+b+c)\right).$$

Note that if g is concave and decreasing instead of convex and increasing, the inequality is reversed.

We now present several applications of Theorem 4.2 for functions $f\colon (0,\infty) \to (0,\infty)$ and $g\colon (0,\infty) \to (0,\infty)$.

As a first example, the function $g(x) = x^p$ with $p \geq 1$ is convex and increasing. Theorem 4.2 yields

$$\begin{aligned} & \left(af(a+2b)+bf(b+2c)\right)^p+\left(bf(b+2c)+cf(c+2a)\right)^p \\ & +\left(cf(c+2a)+af(a+2b)\right)^p \geq 3\left(\frac{2(a+b+c)}{3}f(a+b+c)\right)^p \\ & =\frac{2^p(a+b+c)^p}{3^{p-1}}f(a+b+c)^p. \end{aligned}$$

Choosing $f(x) = 1/x$, we derive

$$\left(\frac{a}{a+2b}+\frac{b}{b+2c}\right)^p+\left(\frac{b}{b+2c}+\frac{c}{c+2a}\right)^p+\left(\frac{c}{c+2a}+\frac{a}{a+2b}\right)^p \geq \frac{2^p}{3^{p-1}}.$$

Therefore, the lower bound is independent of a, b, and c.

In particular, choosing $p = 2$, we have

$$\left(\frac{a}{a+2b}+\frac{b}{b+2c}\right)^2+\left(\frac{b}{b+2c}+\frac{c}{c+2a}\right)^2+\left(\frac{c}{c+2a}+\frac{a}{a+2b}\right)^2 \geq \frac{4}{3}.$$

As another example, the function $g(x) = e^{qx}$ with $q > 0$ is convex and increasing. It follows from Theorem 4.2 that

$$\begin{aligned}&e^{q(af(a+2b)+bf(b+2c))}+e^{q(bf(b+2c)+cf(c+2a))}+e^{q(cf(c+2a)+af(a+2b))}\\&\geq 3e^{(2q/3)(a+b+c)f(a+b+c)}.\end{aligned}$$

Choosing $f(x) = 1/x$, we obtain

$$e^{q(a/(a+2b)+b/(b+2c))}+e^{q(b/(b+2c)+c/(c+2a))}+e^{q(c/(c+2a)+a/(a+2b))} \geq 3e^{2q/3}.$$

As a last example, the function $g(x) = x\ln(1+x)$ is convex and increasing. Theorem 4.2 gives

$$\begin{aligned}&(af(a+2b)+bf(b+2c))\ln\left(1+af(a+2b)+bf(b+2c)\right)\\&+(bf(b+2c)+cf(c+2a))\ln\left(1+bf(b+2c)+cf(c+2a)\right)\\&+(cf(c+2a)+af(a+2b))\ln\left(1+cf(c+2a)+af(a+2b)\right)\\&\geq 3\frac{2(a+b+c)}{3}f(a+b+c)\ln\left(1+\frac{2(a+b+c)}{3}f(a+b+c)\right)\\&=2(a+b+c)f(a+b+c)\ln\left(1+\frac{2(a+b+c)}{3}f(a+b+c)\right),\end{aligned}$$

which is equivalent to

$$\begin{aligned}&(1+af(a+2b)+bf(b+2c))^{af(a+2b)+bf(b+2c)}\\&\times(1+bf(b+2c)+cf(c+2a))^{bf(b+2c)+cf(c+2a)}\\&\times(1+cf(c+2a)+af(a+2b))^{cf(c+2a)+af(a+2b)}\\&\geq\left(1+\frac{2(a+b+c)}{3}f(a+b+c)\right)^{2(a+b+c)f(a+b+c)}.\end{aligned}$$

Choosing $f(x) = 1/x$, we derive

$$\begin{aligned}&\left(1+\frac{a}{a+2b}+\frac{b}{b+2c}\right)^{a/(a+2b)+b/(b+2c)}\left(1+\frac{b}{b+2c}+\frac{c}{c+2a}\right)^{b/(b+2c)+c/(c+2a)}\\&\times\left(1+\frac{c}{c+2a}+\frac{a}{a+2b}\right)^{c/(c+2a)+a/(a+2b)}\geq\frac{25}{9}.\end{aligned}$$

Because Theorem 4.2 is versatile, it can be used to generate many more examples, leaving ample room for future investigation.

5 Conclusion

In this paper, we introduce the following comprehensive cyclic inequality analogous to the Nesbitt inequality: For any $a, b, c > 0$, we have

$$\frac{a}{a+2b} + \frac{b}{b+2c} + \frac{c}{c+2a} \geq 1.$$

We then extend this result in several ways using a convexity approach, deriving numerous new cyclic inequalities as applications for various functions. A perspective for future research is to consider more than three variables. However, such an extension is non-trivial; the underlying algebraic identity $a(a+2b)+b(b+2c)+c(c+2a) = (a+b+c)^2$, which drives the three-variable case, does not admit a straightforward generalization. One may consider the following approach: For a cyclic sequence $x_1, x_2, \ldots, x_n$ with $n \in \mathbb{N} \setminus \{0, 1, 2\}$, using the floor function $\lfloor \cdot \rfloor$ and an indicator for even n denoted $\mathbb{I}_{\{n \text{ is even}\}}$, we have

$$\sum_{i=1}^{n} x_i \left(x_i + 2 \sum_{k=1}^{\lfloor \frac{n-1}{2} \rfloor} x_{i+k} + \mathbb{I}_{\{n \text{ is even}\}} x_{i+n/2} \right) = \left(\sum_{i=1}^{n} x_i \right)^2.$$

We leave the resolution of the remaining technical details for future work, with the hope that our approach sparks further interest in the study of cyclic inequalities and convexity.

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