

A Variant of the Sandwich theorem for two-sided limits

Sandesh Thakuri¹, Bishnu Hari Subedi²

¹Department of Artificial Intelligence, SoE, Kathmandu University, Nepal

²Central Department of Mathematics, IoST, Tribhuvan University, Kirtipur, Nepal

Correspondence to: Sandesh Thakuri, Email: sandesh.775509@cdmath.tu.edu.np

2020 Mathematics Subject Classification. 26A03

Abstract: The criterion for the classical Sandwich theorem for two-sided limits is that the two-side limits must exists for the bounding functions. We show that this criterion can be relaxed. We show that it is sufficient for the existence of the left-hand limit for the lower bound function and the existence of right-hand limit for the upper bound function; and of-course they must be equal. This paper relaxes the criterion of the classical Sandwich theorem by replacing the two-sided limits with one-sided limits in the criterion and gives a new variant of the Sandwich theorem. While Rudin has formulated the Sandwich theorem for the one-sided limits, it still doesn't relax the criterion of the Sandwich theorem for two-sided limits. He has incorporated the one-sided limits for the Sandwich theorem for one-sided limits but has not relax the condition for the Sandwich theorem for two-sided limits [2].

1 Introduction

The Sandwich theorem is simple yet powerful tool in analysis to determine and to analyze the limit of a function at a given point. We can leverage the known limits to calculate the unknown limits. Suppose, we know the limits of $g(x)$ and $h(x)$ at $x = c$ to be the same limit L and here $f(x)$ happens to be sandwich between $g(x)$ and $h(x)$ in some neighborhood of c . Then we can conclude the limit of $f(x)$ at $x = c$ as L by the Sandwich theorem for two-sided limits. The Sandwich theorem for two-sided limits is simply called the Sandwich theorem which is as follows.

Theorem 1.1 (The Sandwich Theorem). [4] Suppose $g(x) \leq f(x) \leq h(x)$ in some open interval containing c , except possibly at $x = c$ itself. Suppose also that

$$\lim_{x \rightarrow c} g(x) = \lim_{x \rightarrow c} h(x) = L.$$

Then $\lim_{x \rightarrow c} f(x) = L$.

As an illustration, we know the limit of $1/x$ is 0 as $x \rightarrow \infty$. This implies the limit of $-1/x$ is also 0 as $x \rightarrow \infty$. These are the known limits.

The value of sine function lies between -1 and 1 so that

$$-\frac{1}{x} \leq \frac{\sin x}{x} \leq \frac{1}{x}$$

31 Now, $\lim_{x \rightarrow \infty} -\frac{1}{x} = 0$ and $\lim_{x \rightarrow \infty} \frac{1}{x} = 0$ so we can use the Sandwich theorem to conclude that
 32 $\lim_{x \rightarrow \infty} \frac{\sin x}{x} = 0$.

33 2 Limitation of the Sandwich Theorem

34 The Sandwich theorem requires the existence of the two sided limits for the lower bound
 35 function $g(x)$ and the upper bound function $h(x)$. This is the limitation of the sandwich
 36 theorem.

37 We know $-|x| \leq \sin x \leq |x|$ which implies

$$-\frac{|x|}{x} \leq \frac{\sin x}{x} \leq \frac{|x|}{x}$$

38 But we cannot conclude the limit of $\lim_{x \rightarrow 0} \frac{\sin x}{x}$ using the Sandwich Theorem with the bounds
 39 above. It is so, because the $\lim_{x \rightarrow 0} \frac{|x|}{x}$ does not exist.

40 The $\lim_{x \rightarrow 0} \frac{|x|}{x}$ does not exist because left hand limit and right hand limit of $\frac{|x|}{x}$ at $x=0$ are
 41 different. They are different but they are finite.

$$42 \quad \lim_{x \rightarrow 0^-} \frac{|x|}{x} = -1 \quad \text{and} \quad \lim_{x \rightarrow 0^+} \frac{|x|}{x} = 1.$$

43 We are not claiming that the limitation of the Sandwich theorem is not being able to
 44 determine the $\lim_{x \rightarrow 0} \frac{\sin x}{x}$. We are stating that the limitation of Sandwich theorem is its
 45 requirement of the existence of the two sided limits for the bounding functions thus not
 46 being able to determine the above limit with the above bounds.

47 3 The Thakuri's Variant of Sandwich Theorem

Theorem 3.1 (The Thakuri's Variant Sandwich Theorem). *Suppose $g(x) \leq f(x) \leq h(x)$ in some open interval containing c , except possibly at $x = c$ itself. Suppose also that*

$$\lim_{x \rightarrow c^-} g(x) = \lim_{x \rightarrow c^+} h(x) = L.$$

48 *Then $\lim_{x \rightarrow c} f(x) = L$.*

49 Now using this variant Sandwich theorem we can use the above bounds to conclude that

50 $\lim_{x \rightarrow 0} \frac{\sin x}{x} = 1$ as follows.

$$51 \quad \lim_{x \rightarrow 0^-} -\frac{|x|}{x} = 1 \quad \quad \quad \lim_{x \rightarrow 0^+} \frac{|x|}{x} = 1$$

52
 53 Hence $\lim_{x \rightarrow 0} \frac{\sin x}{x} = 1$.

4 Remarks on the our variant of Sandwich theorem

- While the $\lim_{x \rightarrow 0} \frac{\sin x}{x}$ can be determined by the sandwich theorem using the tighter-bound $\cos x \leq \sin x/x \leq 1$ [3], the purpose of our variant of sandwich theorem is not to assert that this limit cannot be determined by the Sandwich theorem. This limit can be determined without the sandwich theorem as well.
- The purpose of our variant of sandwich theorem is to loosen the criterion of the sandwich theorem so that even for the bounds as illustrated above where two sided limits do not exists, it is applicable to use the sandwich theorem.
- The question of whether there exists any limit which can be determined by our variant but not by the classical sandwich theorem is another research problem that our research brings to the mathematics community.

5 Proof of the Variant of the Sandwich Theorem

Definition 5.1 (Precise definition of limit). [4] Let $f(x)$ be defined on an open interval about c , except possibly c itself. We say that the limit of $f(x)$ as x approaches c is the number L , and write

$$\lim_{x \rightarrow c} f(x) = L$$

, if, for every number $\epsilon > 0$, there exists a corresponding number $\delta > 0$ such that for all x ,

$$0 < |x - c| < \delta \implies |f(x) - L| < \epsilon.$$

Definition 5.2 (One-sided limits). [4] We say that $f(x)$ has right-hand limit L at c , and write

$$\lim_{x \rightarrow c^+} f(x) = L$$

if for every number $\epsilon > 0$ there exists a corresponding number $\delta > 0$ such that for all x

$$c < x < c + \delta \implies |f(x) - L| < \epsilon.$$

and we say that f has left-hand limit L at c , and write

$$\lim_{x \rightarrow c^-} f(x) = L$$

if for every number $\epsilon > 0$ there exists a corresponding number $\delta > 0$ such that for all x

$$c - \delta < x < c \implies |f(x) - L| < \epsilon.$$

67 *Proof.* Let $\epsilon > 0$

$$\lim_{x \rightarrow c^-} g(x) = L \implies \exists \delta_1 > 0 : 0 < c - x < \delta_1 \implies |g(x) - L| < \epsilon \quad (1)$$

$$\implies \exists \delta_1 > 0 : -\delta_1 < x - c < 0 \implies -\epsilon < g(x) - L < \epsilon \quad (2)$$

$$\implies \exists \delta_1 > 0 : -\delta_1 < x - c < 0 \implies L - \epsilon < g(x) < L + \epsilon \quad (3)$$

68 Again,

$$\lim_{x \rightarrow c^+} h(x) = L \implies \exists \delta_2 > 0 : 0 < x - c < \delta_2 \implies |h(x) - L| < \epsilon \quad (4)$$

$$\implies \exists \delta_2 > 0 : 0 < x - c < \delta_2 \implies L - \epsilon < h(x) < L + \epsilon \quad (5)$$

69 Let $\delta = \min\{\delta_1, \delta_2\}$. Then for $g(x) < f(x) < h(x)$ and $\delta > 0$ we have, from 3 and 5,

70 $L - \epsilon < g(x) < h(x) < L + \epsilon$ [$\because g(x) < h(x)$] so we have,

$$-\delta < x - c < \delta \implies L - \epsilon < g(x) < f(x) < h(x) < L + \epsilon \quad (6)$$

$$|x - c| < \delta \implies L - \epsilon < f(x) < L + \epsilon \quad (7)$$

$$\implies |f(x) - L| < \epsilon \quad (8)$$

71 Hence, $\lim_{x \rightarrow c} f(x) = L$. This proves the extended theorem. \square

72 6 Rudin's Variant of Sandwich Theorem

73 6.1 Distinction of our Variant from Rudin's Variant

- 74 • While Rudin's variant of Sandwich theorem incorporates one-one sided limits. The
75 Rudin formulation of Sandwich theorem is for one-sided limits only. Our variant of
76 Sandwich theorem not only incorporates the one-sided limits on the criterion and but
77 is for two-sided limits.
- 78 • Rudin variant for one-sided limit is analogous to the classical Sandwich theorem for
79 two-side limits. Our variant is not analogous to the classical Sandwich theorem.
80 Rudin's variant has Sandwich theorem for left-hand side limit and for right-hand side
81 limit separately. Our variant has left-hand limit and right-hand limit only to loosen
82 the criterion and it is not for the one-sided limit. It is for the two-sided limit.

83 References

- 84 [1] Hardy, G. H. (1961) *A Course of Pure Mathematics, 10th edition*. Cambridge University
85 Press, London.
- 86 [2] Rudin, W. (1976) *Principles of Mathematical Analysis, 3rd edition*. McGraw Hill, Lon-
87 don.

- ⁸⁸ [3] Tao, T. (2023) *Analysis I, 2nd edition*. Springer Nature, Singapore.
- ⁸⁹ [4] Thomas, G. B. (2017) *Thomas' Calculus*. Pearson India Education Services Pvt. Ltd,
- ⁹⁰ India.