

From Calculus to Analysis: Limits

R (Chandra) Chandrasekhar

2024-03-24 | 2024-05-21

The fundamental concept on which the whole of mathematical analysis ultimately rests is that of the limit of an infinite sequence a_n .

RICHARD COURANT AND FRITZ JOHN
Introduction to Calculus and Analysis, Volume I, p 60.

This is the first of several blogs that are devoted to the transition from calculus to analysis. The focus in this blog is the concept of limits, as applied to an infinite real sequence.

Parts of this blog have been lifted from the chapter entitled “Mathematics at University” from my book, *Secrets of Academic Success*, which is [available as a free PDF download](#). However, since that chapter was written, I have myself gained greater understanding on why calculus at high school needed to morph into analysis at university. Accordingly, the material has been augmented, but kept simple enough to be accessible to a high school student just entering university.

I am not a professional mathematician, and make no claim to rigour in this blog. Rather, I hope to demystify analysis from the grip of symbols by explaining its *raison d'être* in plain English. In the process, I hope analysis appears less forbidding and more friendly.

The transition from high school to university

At high school you were taught how to integrate and differentiate. You were exposed to all sorts of tricks and special techniques—such as the chain rule for differentiation, and integration by parts for integration. If you revelled in mastering and applying such techniques, you might find that what succeeds high school *calculus*, is a *horse of an entirely different colour*, called *analysis*, at university.

You might even be alarmed that rather than having to solve routine problems for the value of some quantity, or simply to work through and demonstrate a fact in a straightforward fashion, you are now required to *prove* theorems: something that requires a different mindset and skill set.

Why the change?

High school calculus appeals to intuition and the visual sense, through *geometric* ideas like slopes and areas. Words like “approaches”, “tends to”, etc., signify motion and resonate with our sense of space and time.

Analysis, on the other hand, is logically precise and uses *arithmetic* as the basis for deriving results. Intuition has given way to logical precision, and pictures have yielded to symbols. The implicit scaffolding of familiar ideas like space and time—borrowed from our everyday experience—has been replaced with the clinical precision of inequalities and **universal and existential quantifiers**.

The logically indefensible infinitesimals of calculus have given way to the rigorously justifiable limits and infinite sums of analysis. Numbers alone provide the foundation, and this required the idea of a number itself to be strengthened as an abstraction beyond question or doubt.

All this takes some getting used to. We have moved from an innocent nature-hewn cave to a fabricated apartment block that reaches for the sky. Questions such as, “Is this change really necessary?” and “If it ain’t broke, why fix it?” arise in consequence.

But the sober truth is that high school calculus is “broke”. It is fun-filled, but nevertheless, a convenient fiction by mathematical standards. Two centuries passed between the discovery of the calculus as a magical computing machine, and the recognition of the need to fix it so that it would work robustly in all circumstances.

In this sense, the progression from calculus to analysis is similar to the accretion of zero and the negative numbers to the natural numbers, or the introduction of imaginary numbers to account for roots of certain polynomials. All such changes were resisted at first, just like a new pair of shoes that initially pinch, but time and usage have borne testament to the wisdom behind the change. The somewhat painful transition from calculus to analysis will prove to be the same.

Geometry’s fall from favour

Mathematics texts at high school level are generously and often colorfully illustrated, especially when dealing with geometry. But, if you look at any university-level analysis textbook, colour would have taken heel, and pictures will be the exception rather than the rule. For those who think in pictures, this will come as a letdown, accompanied by the puzzling question, “Why?”

Geometric intuition, upon which Greek mathematics rested securely for well nigh two centuries, was not infallible. The development of new **non-Euclidean geometries** in the nineteenth century robbed mathematics of its innocent certitude in geometric foundations. And the resulting revolution, called the **Erlangen program**, made algebra the basis of classifying geometry itself.

Our everyday experience is rooted in our sense of space and time. So, I will attempt to illustrate the ideas of analysis using pictures wherever I can, so that the alien syntax and symbology of analysis is buttressed by the reassuring presence of equivalent pictures. Unfortunately, many introductory analysis books are illustrated scantily, if at all.

Holes in the real number line

What do irrational numbers have to do with analysis? Quite a lot, really.

Real analysis lives on the real number line. From the time of the Pythagoreans, the irrational numbers have caused mathematicians’ hearts to skip a beat. “Are irrational numbers really numbers? If so, where do they live?” The absence of irrational numbers meant that there were holes in the real number line.

The Greeks circumvented this by limiting the irrational numbers to geometric contexts. The ratio of the circumference of a unit circle to its diameter is π . The diagonal of a unit square is $\sqrt{2}$. “Let them live geometrically as *lengths*, but let us remain silent about their existence elsewhere.” It was a dichotomy between *counting* and *measurement* or between the *discrete* and the *continuous*.

Even today, the sets for the *natural numbers*, the *integers*, the *rational numbers* all have their own symbols— \mathbb{N} , \mathbb{Z} , \mathbb{Q} , respectively, but not the irrational numbers. That should be clue enough to indicate that the irrationals were more than a handful for mathematicians to contend with, especially if they were doubts about where they rightfully belonged.

The rational numbers, when expressed as decimals, either have a *finite* decimal representation, like $\frac{1}{2} = 0.5$,¹ or an *infinitely recurring* decimal representation like $\frac{1}{3} = 0.333 \dots$

The irrational number $\sqrt{2}$ —when expressed as a decimal—neither terminates nor recurs without end. Its unpredictable digits go on and on and on. So, where exactly does $\sqrt{2}$ sit on the real line?

This troubling question went unanswered until **Richard Dedekind** skilfully introduced the **Dedekind cut** to legitimately accommodate the irrationals as first-class citizens of the real number line, fully capable of undergoing all the arithmetic operations of the rational numbers.²

The inclusion of the irrational numbers into the fold of real numbers along with the rational numbers \mathbb{Q} , **completes** the set of real numbers, \mathbb{R} . Strengthening the foundations of the real numbers was a prerequisite to the introduction of rigour in analysis. There are no more holes in the real line.

Numbers such as π and $\sqrt{2}$ arising from the simplest plane geometry can now be accommodated legitimately as first-class citizens of the real number line.

Approximating an irrational

When we use a calculator to key in $\sqrt{2}$, we see a sequence of digits on the display. But that sequence is only an *approximation*. *The exact decimal representation of an irrational number does not exist*. So, when we calculate or compute with irrationals, we are using *rational approximations* in their stead. And for real world purposes, that approximation suffices.

A real sequence $S(n)$, also written as (a_n) , is a function from the set of natural numbers to the set of real numbers. Symbolically, this is stated as $S : \mathbb{N} \rightarrow \mathbb{R}$, and as $n \mapsto a_n$.

My calculator gives me the following approximation for $\sqrt{2}$: 1.414213562 Suppose we form the sequence

$$S = (a_n) = 1, 1.4, 1.41, 1.414, 1.4142, 1.41421, 1.414213, 1.4142135, 1.41421356, 1.414213562 \dots$$

¹To muddy matters even more, $\frac{1}{2} = 0.4999 \dots$ is an equally a valid representation!

²Cauchy gave an alternative justification—to accommodate the rationals into the reals—via the **sequence that bears his name**

obtained by *truncating* the decimal representation, with $a_1 = 1$, $a_2 = 1.4$, until $a_9 = 1.41421356$. Note that S is an *infinite*, real sequence. The successive terms in the sequence are successive rational approximations to the value $\sqrt{2}$ —each more accurate than the previous one—but with the proviso that there is *no exact decimal representation* for the value of $\sqrt{2}$, except via the symbol itself.

Note the following points:

1. The sequence S goes on without end.
2. The sequence S has been constructed, one digit at a time, to approximate the value of $\sqrt{2}$. Its terms therefore represent *rational approximations* to $\sqrt{2}$.
3. We may assert—by virtue of the construction of S —that a later term in the sequence is a more accurate approximation to $\sqrt{2}$ than an earlier term. The sequence **converges** to $\sqrt{2}$.
4. a_n inexorably *tends to* the value $\sqrt{2}$, as we keep on adding successive terms to the sequence.
5. Because a_n can never equal $\sqrt{2}$, we *cannot equate* a_n to $\sqrt{2}$ for any *finite* $n \in \mathbb{N}$.
6. The **limit** in this case, $\sqrt{2}$, is therefore *not* a member of the sequence.

In symbols, we write $a_n \rightarrow \sqrt{2}$ as $n \rightarrow \infty$.³ Alternatively, we may write

$$\lim_{n \rightarrow \infty} a_n = \sqrt{2}.$$

But the equality sign here pertains to an *infinite process* and cannot be treated in the same cavalier way as we would the garden variety equality sign in $2 + 3 = 5$.

But this symbology is imprecise because we are handwaving with the words “tends to” indicated by \rightarrow and “infinity” indicated by ∞ . We will re-visit the issue of how to make precise and watertight the idea of a limit when we shed intuitive notions like “tends to” and “infinity” and replace it with a strict arithmetical criterion.

Ordered Archimedean field

Two properties of real numbers are highlighted as being essential for real analysis:

- a. The **trichotomy** of the real numbers, which states that every real number is either positive, zero, or negative. Given any two real numbers, x and y , *only one* of the following three statements is true: $x < y$, or $x = y$, or $x > y$.
- b. The **Archimedean property** which forbids **infinities**⁴ and **infinitesimals** from being real numbers. It states that:

(i) For *any* real number x , there is a natural number n such that $n > x$.⁵

(ii) For *any positive* real number y , there is a natural number n such that $\frac{1}{n} < y$.⁶

³Infinity is not a natural number.

⁴Which may be colloquially stated as there is no largest natural number.

⁵ $\forall x \in \mathbb{R}, \exists n \in \mathbb{N}$ such that $n > x$.

⁶ $\forall y \in \mathbb{R}, y > 0, \exists n \in \mathbb{N}$ such that $\frac{1}{n} < y$.

Inequalities and distances

Calculus problems are generally concerned with *evaluating* some quantity and are therefore centred around *equalities*.

Analysis, on the other hand, relies heavily on logical statements about quantities whose exact values may not be known, but about whom statements of *relative size* need to be made. This is where *inequalities* enter the discourse.⁷

This change in emphasis can be disconcerting. Students seeking to familiarize themselves with manipulations of inequalities should consult entry-level texts dealing with this subject [1–3].

When the derivative⁸ was defined geometrically, in high school, as the value of the slope of a tangent to the graph of the function at a particular point, the geometrical relationship alone sufficed to encapsulate the definition and to help compute the value.

However, when the derivative is defined as a *limit*, using arithmetic instead of geometry, we do not have *intuitive* markers to guide us. And while such markers are serviceable, they are not infallible. Therefore, we need some symbols and operations to contend with ideas like the “closeness” of two points, etc.

This is where we encounter two mathematical devices quintessential to analysis and much of modern mathematics:

- a. Inequalities: by understanding and manipulating the symbols $>$ and $<$, we can work toward watertight definitions that serve to constrain what we are talking about.
- b. Distance: by using a sensible definition of the distance between two points, we may measure their “closeness”. Geometry and intuition would then have been replaced by arithmetic and precision.

If there are two *distinct* real numbers p and q , $|p - q|$ defines the positive number that quantifies their separation or distance. Since we are on the real line, the *absolute value function* is used for this purpose. See Figure 1 for the graph of $y = |x|$.

The “arbitrarily close” condition of calculus may then be couched more precisely thus:

For arbitrary $\varepsilon > 0 \dots |p - q| < \varepsilon$.⁹

This incantation will become so familiar that it will become unremarkable when you devote time and practice to analysis. And notice the usefulness of inequalities here.

Approximation for $\sqrt{2}$ revisited

We now have a quantitative description for a measure of closeness. Let us put it to use in the example from [Approximating an irrational](#) above. We know that our approximation becomes better as n increases.

⁷You would have already seen from above how inequalities are used to define an Archimedean field.

⁸To be covered in a later blog.

⁹The arbitrariness is still there via ε but the closeness has been strictly quantified by the distance function and the equality.

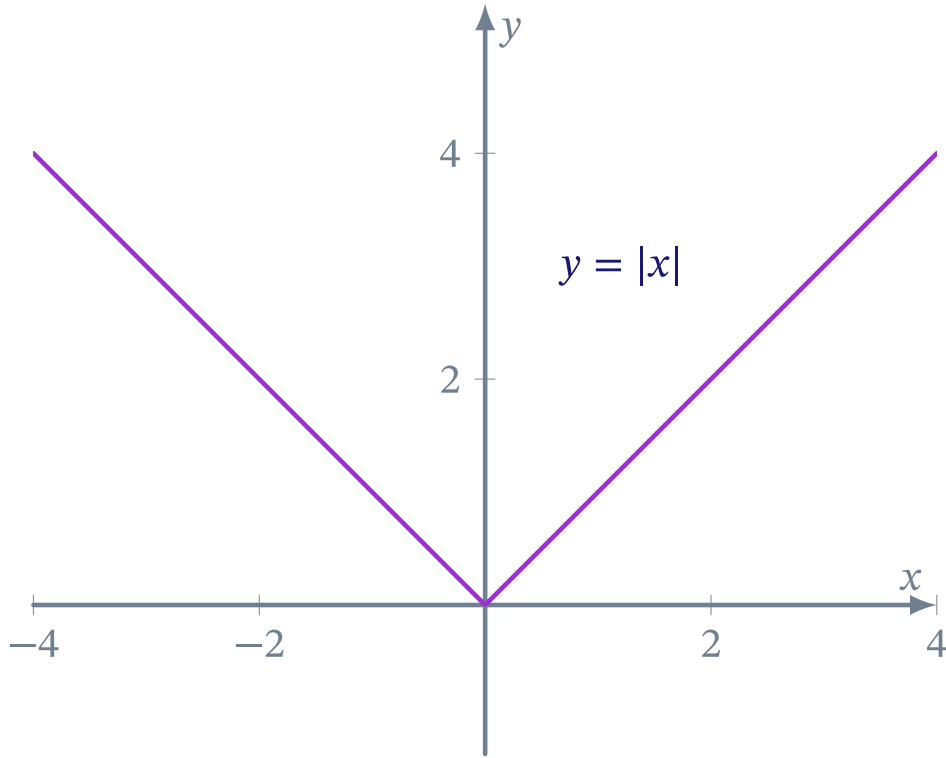


Figure 1: The non-negative, absolute value function, $y = |x|$, which is the distance function on the real line.

Let us *fix the admissible error* to be some positive real number ε . This means that the error is never zero: which is as it should be. We may then say that as long as n is larger than some number, say m , the error or difference between a_n and $\sqrt{2}$ will be less than ε .

To express this with few words and many symbols, we take recourse to two ideas from logic:

- a. The **universal quantifier**, \forall , which is spoken as “for all”, “for any”, or “given any”.
- b. The **existential quantifier**, \exists , which is spoken, as “there exists”, “there is at least one”, or “for some”.

Strangely, these symbols generalize rather than particularize. So, how do they tighten up and make more precise those statements whose truth we wish to establish? Along with inequalities, how do they help make precise the notions that were handwaved away in calculus?

We may now precisely state:

$$\forall \varepsilon > 0, \exists m \in \mathbb{N} \text{ such that } n > m \implies |a_n - \sqrt{2}| < \varepsilon. \quad (1)$$

In plain English, this reads: “For all values of the **Greek letter epsilon**, ε , greater than zero, there exists a natural number m such that whenever the natural number n is greater than m , the distance between the n^{th} term of the sequence, a_n , and the square root of two, $\sqrt{2}$, is less than epsilon.”

This definition of a limit starts out with the error variable ε rather than with the index m , above which the specified error is not exceeded. This may appear counter-intuitive, but if you think of it like a shepherd does, you would want to corral your flock before counting it.

The following points are noteworthy:

1. Apart from the limit, which in our case is $\sqrt{2}$, there is no other particular value used in the definition.
2. We use the inequality $|a_n - \sqrt{2}| < \varepsilon$ because no term of S actually equals $\sqrt{2}$.
3. By being silent on the value of ε , except to require it to be positive, we may squeeze the error to as small as we want, and still not run afoul of any constraints regarding non-equality of any a_n with $\sqrt{2}$. This formulation neatly encapsulates the notion of “tends to, or approaches, but does not equal”, with a distance measure that may be made arbitrarily small, but not equal zero.¹⁰
4. The need for \mathbb{R} to be an **Ordered Archimedean field** is apparent here. We have arbitrarily small numbers, but no infinitesimals, and there is no upper bound on the natural numbers.

A pictorial illustration is given in Figure 2 of what is happening on the real number line as we progressively approximate $\sqrt{2}$.



Figure 2: Nested sequences $[a_i, L]$ vis-a-vis the limit L , which represents $\sqrt{2}$ in this case.

Note that this figure is not to scale and is not of the actual values given in **Approximating an irrational** but is rather an illustration of what happens as successive approximations become progressively closer to the limit.¹¹

We know the the limit is $\sqrt{2}$ because we constructed the sequence so. Moreover, we are not approaching the limit from *above* but rather only from *below* by using the successive digits that the calculator spewed out.

The following observations apply to the **closed intervals**, $[a_1, L]$, $[a_2, L]$, $[a_3, L]$, $[a_4, L]$:

- a. L , representing $\sqrt{2}$, is the *upper bound* of all the intervals. We do not exceed L as we are approaching it from below. Note also that we may include $\sqrt{2}$ as the end point of a closed interval in the real line, like $[a_1, \sqrt{2}]$, because the irrationals are first-class citizens of the real line.
- b. As we move from a_1 to a_4 , the intervals $[a_i, L]$, keep getting smaller.
- c. The intervals are **nested**: $[a_1, L] \supset [a_2, L] \supset [a_3, L] \supset [a_4, L]$.

¹⁰In hindsight, analysis started off as tidying up the loose ends of calculus, but ended up strengthening the whole edifice of mathematics, as its very foundations were impacted.

¹¹The figure is purely didactic; if it were literal, the later ticks would be overwritten and the later labels would obscure each other.

Nested sequence of intervals

When a limit is approached from above as well as below—as illustrated in Figure 3—there is a nested sequence of *closed intervals*, $[a_1, b_1]$, $[a_2, b_2]$, $[a_3, b_3]$, and $[a_4, b_4]$, each of which contains the limit L . Since each each interval $[a_{i+1}, b_{i+1}]$ is contained in its predecessor, $[a_i, b_i]$, the limit L is contained in the innermost interval, which also happens to be the *intersection set* of all the intervals.

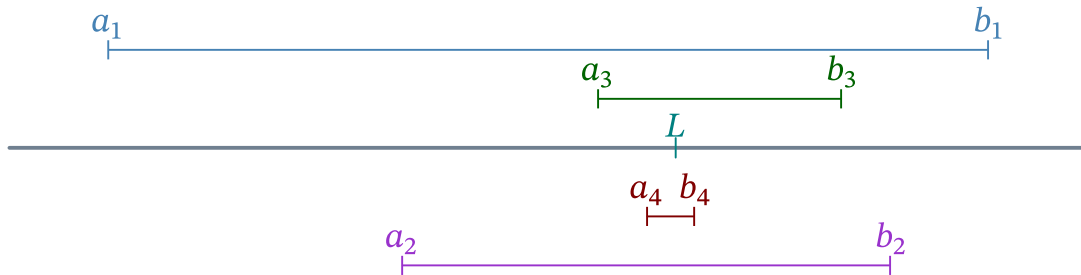


Figure 3: Nested intervals $[a_i, b_i]$ where the limit L lies within the innermost interval, and therefore within all intervals.

For those seeking a concrete image for this abstract “nested intervals on the real line” idea, **Matryoshka dolls, or Russian dolls**, are a very serviceable, accurate, and unforgettable metaphor, as shown in Figure 4.



Figure 4: Nested matryoshka dolls, or Russian dolls, serve as a memorable metaphor for nested intervals.¹²

¹²From [Wikimedia](#) by user [Fanghong](#) GFDL.

Cauchy sequence

A **Cauchy sequence** is a sequence of numbers whose successive terms are spaced apart more and more closely as the sequence progresses. In symbols, if the sequence is denoted by $S = (a_n)$, then for a Cauchy sequence,

$$\forall \varepsilon > 0, \exists N \in \mathbb{N} \text{ such that } n > N \text{ and } m > N \implies |a_n - a_m| < \varepsilon.$$

This “bunching” property of later terms in the sequence is intuitively reassuring, as it is what we would expect when a sequence converges. It is also a necessary and sufficient condition for a sequence to converge to a limit.

Core texts on analysis

I am aware of three classic two-volume texts that, to me, are remarkably well-written. The authors of these texts have taken pains to make the material accessible to students commencing analysis courses. The texts are:

1. Richard Courant and Fritz John: *Introduction to Calculus and Analysis, Volumes I and II*, 1989. This is a classic from a different vintage that has stood the test of time. It is more generously illustrated than most analysis texts [4,5].
2. Terence Tao: *Analysis I* and *Analysis II*, 2022. This text was especially written to ease students into analysis. It could have as well been called “Analysis from Scratch”. It is a well-paced, student-friendly text, where the author has taken pains to explain issues, as if talking to a beginner student. [6,7].
3. Vladimir A Zorich: *Analysis I* and *Analysis II*, 2015 and 2016. These are translations of the original texts in Russian. Besides rigour, these texts are grounded in actual applications of analysis, and should appeal to physicists and engineers as well [8,9].

You, the student must find out which author’s writing resonates best with you, and use that book as your anchor text. My favourite text on introductory analysis is Rosenlicht’s *Introduction to Analysis* [10]. It is a marvel of clarity and is not too expensive to own. Read and work through it if you can.

Other texts on analysis

Besides the core texts I have referred to above, several others have been written to highlight the differences between calculus and analysis, and to ease the transition from the one to the other. Their focus and flavour vary. This list is based on my personal experience and bias: choose the texts that echo with your own predilections.

A very readable and fascinating recountal of the reasons why analysis *had to arise* is given in Bressoud’s text [11] *A Radical Approach to Real Analysis*. The time spent reading it will be well rewarded with a quantum jump in your mathematical understanding and maturity.

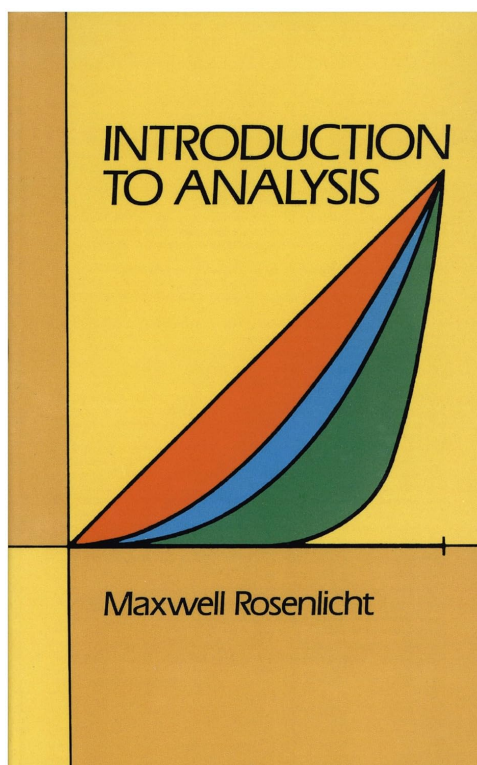


Figure 5: Maxwell Rosenlicht's *Introduction to Analysis*, which is my favourite text on analysis.

Gardiner's text *Understanding Infinity: The Mathematics of Infinite Processes* [12] is a re-issue of an earlier book [13], that uses infinite processes as the theme. It is not confined to analysis alone, but will enlighten the reader familiar with calculus, on *why* analysis had to arise.

Abbott's book [14] is another text which gives clear, comprehensible motivations and explanations without losing rigour.

Two more recent texts that bridge the calculus-analysis divide are those by Ghorpade and Limaye [15], and Brannan [16]. Both of them are very well written, and have more illustrations than a standard analysis text: they will find favour with visual learners.

Epilogue

There has been a fair bit of huffing and puffing to get to this point. Has it been worth it?

We have laid a strong foundation for the real numbers by including the irrationals, circumventing infinitesimals, and defining a limit without using ideas from time and space, but rather using measures of distance, and inequalities to denote vanishingly small quantities that, nevertheless, do not ever equal zero. If you think that this is all **much ado about nothing** then, you are unlikely to appreciate analysis any further. **Adios Amigo!**

But if you think that the view from the top was worth the slog of the climb, you will be better placed to appreciate how differentiation, integration, and Fourier analysis benefited from the thorough renovation of the foundations of mathematics that led to analysis. These will be the subjects of future blogs.

We have considered the limit of a real sequence in this blog. We will move from the discrete to the continuous, from sequence to function, in a future blog, and see what that augurs for the concept of a limit. We will then consider differentiation and integration and try to fathom why the changed basis offered by analysis for these two pivotal operations of calculus is the way to go.

A useful metaphor is the renovation of a decrepit house. Renovating while living in it is tedious and inconvenient. But once the renovation has been completed, the pleasure of occupying a solidly built near-new house knows no end. That is how I view the transition from calculus to analysis.

Feedback

I am a non-mathematician working outside academia. So, errors are likely in the exposition. Please [email me](#) your corrections and comments please.

A PDF version of this article is [available for download here](#):

<https://swanlotus.netlify.app/blogs/from-calculus-to-analysis.pdf>

References

- [1] Nicholas D Kazarinoff. 1961. *Geometric inequalities*. The Mathematical Association of America.
- [2] Edwin Beckenbach and Richard Bellman. 1962. *An introduction to inequalities*. The Mathematical Association of America.
- [3] Claudi Alsina and Roger B Nelsen. 2009. *When less is more: Visualizing basic inequalities*. The Mathematical Association of America.
- [4] Richard Courant and Fritz John. 1989. *Introduction to Calculus and Analysis, Volume I*. Springer-Verlag.
- [5] Richard Courant and Fritz John. 1989. *Introduction to Calculus and Analysis, Volume II*. Springer-Verlag.
- [6] Terence Tao. 2022. *Analysis I* (4th ed.). Springer Nature Singapore; Hindustan Book Agency.
- [7] Terence Tao. 2022. *Analysis II* (4th ed.). Springer Nature Singapore; Hindustan Book Agency.
- [8] Vladimir A Zorich. 2015. *Mathematical Analysis I* (2nd ed.). Springer-Verlag Berlin; Heidelberg.
- [9] Vladimir A Zorich. 2016. *Mathematical Analysis II* (2nd ed.). Springer-Verlag Berlin; Heidelberg.
- [10] Maxwell Rosenlicht. 1986. *Introduction to Analysis*. Dover Publications.
- [11] David M Bressoud. 2007. *A Radical Approach to Real Analysis* (2nd ed.). The Mathematical Association of America.
- [12] Anthony Gardiner. 2002. *Understanding infinity: The mathematics of infinite processes*. Dover Publications.
- [13] Anthony Gardiner. 1982. *Infinite processes: Background to analysis*. Springer-Verlag.
- [14] Stephen Abbott. 2001. *Understanding analysis*. Springer-Verlag.
- [15] Sudhir R Ghorpade and Balmohan V Limaye. 2006. *A course in calculus and real analysis*. Springer Nature Switzerland AG.

- [16] David Alexander Brannan. 2006. *A first course in mathematical analysis*. Cambridge University Press.