

Intuitionistic analysis

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1 Constructive analysis



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In mathematics¹¹, **constructive analysis** is mathematical analysis¹² done according to some principles of constructive mathematics¹³. This contrasts with *classical analysis*, which (in this context) simply means analysis done according to the (more common) principles of classical mathematics¹⁴.

Generally speaking, constructive analysis can reproduce theorems of classical analysis, but only in application to separable spaces¹⁵; also, some theorems may need to be approached by approximations¹⁶. Furthermore, many classical theorems can be stated in ways that are logically equivalent¹⁷ according to classical logic¹⁸, but not all of these forms will be valid in constructive analysis, which uses intuitionistic logic¹⁹.

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1.1 Examples

1.1.1 The intermediate value theorem

For a simple example, consider the intermediate value theorem²⁰ (IVT). In classical analysis, IVT implies that, given any continuous function²¹ f from a closed interval²² $[a,b]$ to the real line²³ R , if $f(a)$ is negative²⁴ while $f(b)$ is positive²⁵, then there exists a real number²⁶ c in the interval such that $f(c)$ is exactly zero²⁷. In constructive analysis, this does not hold, because the constructive interpretation of existential quantification²⁸ (“there exists”) requires one to be able to *construct* the real number c (in the sense that it can be approximated to any desired precision by a rational number²⁹). But if f hovers near zero during a stretch along its domain, then this cannot necessarily be done.

However, constructive analysis provides several alternative formulations of IVT, all of which are equivalent to the usual form in classical analysis, but not in constructive analysis. For example, under the same conditions on f as in the classical theorem, given any natural number³⁰ n (no matter how large), there exists (that is, we can construct) a real number c_n in the interval such that the absolute value³¹ of $f(c_n)$ is less than $1/n$. That is, we can get as close to zero as we like, even if we can't construct a c that gives us *exactly* zero.

Alternatively, we can keep the same conclusion as in the classical IVT—a single c such that $f(c)$ is exactly zero—while strengthening the conditions on f . We require that f be *locally non-zero*, meaning that given any point x in the interval $[a,b]$ and any natural number m , there exists (we can construct) a real number y in the interval such that $|y - x| < 1/m$ and $|f(y)| > 0$. In this case, the desired number c can be constructed. This is a complicated condition, but there are several other conditions that imply it and that are commonly met; for example, every analytic function³² is locally non-zero (assuming that it already satisfies $f(a) < 0$ and $f(b) > 0$).

For another way to view this example, notice that according to classical logic³³, if the *locally non-zero* condition fails, then it must fail at some specific point x ; and then $f(x)$ will equal 0, so that IVT is valid automatically. Thus in classical analysis, which uses classical logic, in order to prove the full IVT, it is sufficient to prove the constructive version. From this perspective, the full IVT fails in constructive analysis simply because constructive analysis does not accept classical logic. Conversely, one may argue that the true meaning of IVT, even in classical mathematics, is the constructive version involving the *locally non-zero* condition, with the full IVT following by “pure logic” afterwards. Some logicians, while

20 https://en.wikipedia.org/wiki/Intermediate_value_theorem
21 https://en.wikipedia.org/wiki/Continuous_function
22 https://en.wikipedia.org/wiki/Closed_interval
23 https://en.wikipedia.org/wiki/Real_line
24 https://en.wikipedia.org/wiki/Negative_number
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accepting that classical mathematics is correct, still believe that the constructive approach gives a better insight into the true meaning of theorems, in much this way.

1.1.2 The least-upper-bound principle and compact sets

Another difference between classical and constructive analysis is that constructive analysis does not accept the least-upper-bound principle³⁴, that any subset³⁵ of the real line \mathbf{R} has a least upper bound³⁶ (or supremum), possibly infinite. However, as with the intermediate value theorem, an alternative version survives; in constructive analysis, any *located* subset of the real line has a supremum. (Here a subset S of \mathbf{R} is *located* if, whenever $x < y$ are real numbers, either there exists an element s of S such that $x < s$, or³⁷ y is an upper bound³⁸ of S .) Again, this is classically equivalent to the full least upper bound principle, since every set is located in classical mathematics. And again, while the definition of located set is complicated, nevertheless it is satisfied by many commonly studied sets, including all intervals³⁹ and all compact sets⁴⁰.

Closely related to this, in constructive mathematics, fewer characterisations of compact spaces⁴¹ are constructively valid—or from another point of view, there are several different concepts that are classically equivalent but not constructively equivalent. Indeed, if the interval $[a,b]$ were sequentially compact⁴² in constructive analysis, then the classical IVT would follow from the first constructive version in the example; one could find c as a cluster point⁴³ of the infinite sequence⁴⁴ $(c_n)_{n \in \mathbb{N}}$.

1.1.3 Uncountability of the real numbers

The diagonal construction in Cantors theorem⁴⁵ is intuitionistically⁴⁶ valid. Indeed, the constructive component of the diagonal argument already appeared in Cantor's work.^[1] According to Kanamori⁴⁷, *a historical misrepresentation has been perpetuated that associates diagonalization with non-constructivity*. As a result, the real numbers \mathbb{R} are uncountable in any constructive system. In some models⁴⁸, \mathbb{R} is subcountable⁴⁹.

A variant found in constructive analysis textbooks may go as follows: "Let $\{a_n\}$ be a sequence of real numbers. Let x_0 and y_0 be real numbers, $x_0 < y_0$. Then there exists a real number x with $x_0 \leq x \leq y_0$ and $x \neq a_n$ ($n \in \mathbb{N}$) . . . The proof is essentially Cantor's

34 https://en.wikipedia.org/wiki/Least-upper-bound_principle

35 <https://en.wikipedia.org/wiki/Subset>

36 https://en.wikipedia.org/wiki/Least_upper_bound

37 https://en.wikipedia.org/wiki/Logical_disjunction

38 https://en.wikipedia.org/wiki/Upper_bound

39 [https://en.wikipedia.org/wiki/Interval_\(mathematics\)](https://en.wikipedia.org/wiki/Interval_(mathematics))

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45 https://en.wikipedia.org/wiki/Cantors_theorem

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47 https://en.wikipedia.org/wiki/Akihiro_Kanamori

48 https://en.wikipedia.org/wiki/Constructive_set_theory

49 <https://en.wikipedia.org/wiki/Subcountability>

'diagonal⁵⁰' proof." (Theorem 1 in Errett Bishop⁵¹, *Foundations of Constructive Analysis*, 1967, page 25.)

Sequences of reals appear commonly in analysis. Forms of constructive analysis that reject not just the law of excluded middle⁵² but also the limited principle of omniscience⁵³ and even Markov's principle⁵⁴ may make use of the axiom of dependent choice⁵⁵ for sequences of reals.

1.2 See also

-  Mathematics portal⁵⁶
- Computable analysis⁵⁷
- Indecomposability (constructive mathematics)⁵⁸

1.3 References

1. Akihiro Kanamori⁵⁹, "The Mathematical Development of Set Theory from Cantor to Cohen", *Bulletin of Symbolic Logic*⁶⁰ / Volume 2 / Issue 01 / March 1996, pp 1-71

1.4 Further reading

- BRIDGER, MARK (2007). *Real Analysis: A Constructive Approach*. Hoboken: Wiley. ISBN⁶¹ 0-471-79230-6⁶².

Non-classical logic

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