

# Intuitionistic analysis

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March 20, 2022

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# 1 Constructive analysis



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In mathematics<sup>11</sup>, **constructive analysis** is mathematical analysis<sup>12</sup> done according to some principles of constructive mathematics<sup>13</sup>. This contrasts with *classical analysis*, which (in this context) simply means analysis done according to the (more common) principles of classical mathematics<sup>14</sup>.

Generally speaking, constructive analysis can reproduce theorems of classical analysis, but only in application to separable spaces<sup>15</sup>; also, some theorems may need to be approached by approximations<sup>16</sup>. Furthermore, many classical theorems can be stated in ways that are logically equivalent<sup>17</sup> according to classical logic<sup>18</sup>, but not all of these forms will be valid in constructive analysis, which uses intuitionistic logic<sup>19</sup>.

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## 1.1 Examples

### 1.1.1 The intermediate value theorem

For a simple example, consider the intermediate value theorem<sup>20</sup> (IVT). In classical analysis, IVT implies that, given any continuous function<sup>21</sup>  $f$  from a closed interval<sup>22</sup>  $[a, b]$  to the real line<sup>23</sup>  $R$ , if  $f(a)$  is negative<sup>24</sup> while  $f(b)$  is positive<sup>25</sup>, then there exists a real number<sup>26</sup>  $c$  in the interval such that  $f(c)$  is exactly zero<sup>27</sup>. In constructive analysis, this does not hold, because the constructive interpretation of existential quantification<sup>28</sup> (“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 number<sup>29</sup>). 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 number<sup>30</sup>  $n$  (no matter how large), there exists (that is, we can construct) a real number  $c_n$  in the interval such that the absolute value<sup>31</sup> 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 function<sup>32</sup> 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 logic<sup>33</sup>, 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

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20 [https://en.wikipedia.org/wiki/Intermediate\\_value\\_theorem](https://en.wikipedia.org/wiki/Intermediate_value_theorem)

21 [https://en.wikipedia.org/wiki/Continuous\\_function](https://en.wikipedia.org/wiki/Continuous_function)

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33 [https://en.wikipedia.org/wiki/Classical\\_logic](https://en.wikipedia.org/wiki/Classical_logic)

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 principle<sup>34</sup>, that any subset<sup>35</sup> of the real line  $\mathbf{R}$  has a least upper bound<sup>36</sup> (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  $x < s$ , or<sup>37</sup>  $y$  is an upper bound<sup>38</sup> 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 intervals<sup>39</sup> and all compact sets<sup>40</sup>.

Closely related to this, in constructive mathematics, fewer characterisations of compact spaces<sup>41</sup> 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 compact<sup>42</sup> in constructive analysis, then the classical IVT would follow from the first constructive version in the example; one could find  $c$  as a cluster point<sup>43</sup> of the infinite sequence<sup>44</sup>  $(c_n)_{n \in \mathbf{N}}$ .

### 1.1.3 Uncountability of the real numbers

The diagonal construction in Cantor's theorem<sup>45</sup> is intuitionistically<sup>46</sup> valid. Indeed, the constructive component of the diagonal argument already appeared in Cantor's work.<sup>[1]</sup> According to Kanamori<sup>47</sup>, *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 models<sup>48</sup>,  $\mathbb{R}$  is subcountable<sup>49</sup>.

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  $x \neq a_n$  ( $n \in \mathbf{N}$ ) . . . The proof is essentially Cantor's

34 [https://en.wikipedia.org/wiki/Least\\_upper\\_bound\\_principle](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](https://en.wikipedia.org/wiki/Least_upper_bound)

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48 [https://en.wikipedia.org/wiki/Constructive\\_set\\_theory](https://en.wikipedia.org/wiki/Constructive_set_theory)

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

'diagonal'<sup>50</sup> proof." (Theorem 1 in Errett Bishop<sup>51</sup>, *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 middle<sup>52</sup> but also the limited principle of omniscience<sup>53</sup> and even Markov's principle<sup>54</sup> may make use of the axiom of dependent choice<sup>55</sup> for sequences of reals.

## 1.2 See also

-  Mathematics portal<sup>56</sup>
- Computable analysis<sup>57</sup>
- Indecomposability (constructive mathematics)<sup>58</sup>

## 1.3 References

1. Akihiro Kanamori<sup>59</sup>, "The Mathematical Development of Set Theory from Cantor to Cohen", *Bulletin of Symbolic Logic*<sup>60</sup> / Volume 2 / Issue 01 / March 1996, pp 1-71

## 1.4 Further reading

- BRIDGER, MARK (2007). *Real Analysis: A Constructive Approach*. Hoboken: Wiley. ISBN<sup>61</sup> 0-471-79230-6<sup>62</sup>.

### Non-classical logic

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<sup>50</sup> [https://en.wikipedia.org/wiki/Cantor%27s\\_diagonal\\_argument](https://en.wikipedia.org/wiki/Cantor%27s_diagonal_argument)

<sup>51</sup> [https://en.wikipedia.org/wiki/Errett\\_Bishop](https://en.wikipedia.org/wiki/Errett_Bishop)

<sup>52</sup> [https://en.wikipedia.org/wiki/Law\\_of\\_excluded\\_middle](https://en.wikipedia.org/wiki/Law_of_excluded_middle)

<sup>53</sup> [https://en.wikipedia.org/wiki/Limited\\_principle\\_of\\_omniscience](https://en.wikipedia.org/wiki/Limited_principle_of_omniscience)

<sup>54</sup> [https://en.wikipedia.org/wiki/Markov%27s\\_principle](https://en.wikipedia.org/wiki/Markov%27s_principle)

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<sup>57</sup> [https://en.wikipedia.org/wiki/Computable\\_analysis](https://en.wikipedia.org/wiki/Computable_analysis)

<sup>58</sup> [https://en.wikipedia.org/wiki/Indecomposability\\_\(constructive\\_mathematics\)](https://en.wikipedia.org/wiki/Indecomposability_(constructive_mathematics))

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<sup>35</sup> Chapter 3 on page 15

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