

Title	On intuitionistic functional calculus
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Citation	Osaka Mathematical Journal. 1953, 5(2), p. 203-209
Version Type	VoR
URL	https://doi.org/10.18910/5707
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On Intuitionistic Functional Calculus

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This paper is separated into two parts; the first one is devoted to logical calculus, and the second one to the intuitionistic theory of real numbers based on Kuroda's treatment¹⁾.

The next schema is due to A. Heyting²⁾:

1. $\forall x F(x) \rightarrow \neg\neg \forall x F(x) \rightarrow \forall x \neg\neg F(x) \Leftrightarrow \neg\neg \forall x \neg\neg F(x) \Leftrightarrow \neg \exists x \neg F(x),$
2. $\exists x F(x) \rightarrow \exists x \neg\neg F(x) \rightarrow \neg\neg \exists x F(x) \Leftrightarrow \neg\neg \exists x \neg\neg F(x) \Leftrightarrow \neg \forall x \neg F(x),$
3. $\forall x \neg F(x) \Leftrightarrow \neg\neg \forall x \neg F(x) \Leftrightarrow \neg \exists x \neg\neg F(x) \Leftrightarrow \neg \exists x F(x),$
4. $\exists x \neg F(x) \rightarrow \neg\neg \exists x \neg F(x) \Leftrightarrow \neg \forall x \neg\neg F(x) \rightarrow \neg \forall x F(x).$

Explanations for the symbols used here: $\forall x$ and $\exists x$ are universal and existential quantifiers with respect to the individual variable x respectively. $F(*)$ is functional variable with certain (finite) number of arguments. \rightarrow is one-way implication and \Leftrightarrow is (logical) equivalence of ante- and succedent formulae. (Hence these two are meta-logical symbols.) \neg is negation and $\neg\neg$ is double negation of the remaining sub-formula after it.

1. Iterated quantifications.

Starting from the above schema by Heyting let us consider the case of iterated quantifications, where we shall be mainly concerned with the implicative relations between such formulae as follows: $\forall x F(x)$, $\exists x F(x)$, $\forall x \exists y F(xy)$, $\exists x \forall y F(xy)$, $\forall x \exists y \forall z F(xyz)$, $\exists x \forall y \exists z F(xyz)$ and their weakened forms to which $\neg\neg$'s are attached.

1.1. Formulae with one quantifier. In this case the implicative relations are:

- (1) $\forall x F(x) \rightarrow \neg\neg \forall x F(x) \rightarrow \forall x \neg\neg F(x) \Leftrightarrow \neg\neg \forall x \neg\neg F(x),$
- (2) $\exists x F(x) \rightarrow \exists x \neg\neg F(x) \rightarrow \neg\neg \exists x F(x) \Leftrightarrow \neg\neg \exists x \neg\neg F(x).$

Hereafter some conventions will be used. The attached symbol $\neg\neg$

1) Kuroda (3).
 2) Heyting (2).

indicating weakened modality of succeeding formula or quantifier³⁾, we might denote the above relations as follows:

$$1.11. \quad \mathcal{V}(++) \rightarrow (-+) \rightarrow (+-) \rightleftarrows (--),$$

$$1.12. \quad \mathcal{H}(++) \rightarrow (+-) \rightarrow (-+) \rightleftarrows (--).$$

1.2. Formulae with two quantifiers.

1.21. **$\mathcal{V}\mathcal{H}$ -schema.** We shall find the implicative relations between the following eight formulae: $\mathcal{V}x \mathcal{H}y F(xy)$, $\mathcal{V}x \mathcal{H}y \supset\supset F(xy)$, $\mathcal{V}x \supset\supset \mathcal{H}y F(xy)$, $\mathcal{V}x \supset\supset \mathcal{H}y \supset\supset F(xy)$, and the four to each of which $\supset\supset$ is prefixed; using the above denotations these are: $\mathcal{V}\mathcal{H}(+++)$, $(+++)$, $(+-+)$, $(+--)$, $(-++)$, $(-+-)$, $(--+)$, $(---)$. First we write the \mathcal{V} -schema:

$$\mathcal{V}(++) \rightarrow (-+) \rightarrow \left\{ \begin{array}{l} (+-) \\ (--) \end{array} \right\}$$

(here the last two are equivalent), then adjoining the symbol + and - *after* each member of it, we get the following two schemata:

$$(+++) \rightarrow (-++) \rightarrow \left\{ \begin{array}{l} (+-+) \\ (--+) \end{array} \right\},$$

and

$$(++-) \rightarrow (-+-) \rightarrow \left\{ \begin{array}{l} (+--) \\ (-- -) \end{array} \right\}.$$

Next beginning from \mathcal{H} -schema we get the following two by adjoining + and - *before* each member:

$$(+++) \rightarrow (++) \rightarrow \left\{ \begin{array}{l} (+-+) \\ (+--) \end{array} \right\},$$

$$(-++) \rightarrow (-+) \rightarrow \left\{ \begin{array}{l} (- - +) \\ (- - -) \end{array} \right\}.$$

It is almost evident that we are now able to establish the full $\mathcal{V}\mathcal{H}$ -schema which comes out from the above four schemata, namely,

$$\mathcal{V}\mathcal{H}(+++) \begin{array}{l} \nearrow (-++) \\ \searrow (++) \end{array} \rightarrow (-+-) \rightarrow \left\{ \begin{array}{ll} (- - +) & \\ (+ - +) & (- - -) \\ & (+ - -) \end{array} \right\}.$$

Herein the last four formulae within a bracket { } are found to be equivalent. It might be useful to rewrite this schema in its original form:

3) Cf. Kuroda (4).

$$\begin{aligned} & \forall x \exists y F(xy) \begin{cases} \nearrow \forall x \exists y F(xy) \\ \searrow \forall x \exists y \forall F(xy) \end{cases} \rightarrow \forall x \exists y \forall F(xy) \rightarrow \\ & \rightarrow \forall x \forall \exists y F(xy) \begin{cases} \nearrow \forall x \forall \exists y F(xy) \\ \searrow \forall x \forall \exists y \forall F(xy) \end{cases} \rightarrow \forall x \forall \exists y \forall F(xy). \end{aligned}$$

1.22. **$\exists V$ -schema.** In an analogous way to above we get from the four schemata :

$$\begin{aligned} (+ + +) \rightarrow (+ - +) & \rightarrow \left\{ \begin{array}{l} (- + +) \\ (- - +) \end{array} \right\}, \\ & (+ \text{ is adjoined after } \exists\text{-schema}) \end{aligned}$$

$$\begin{aligned} (+ + -) \rightarrow (+ - -) & \rightarrow \left\{ \begin{array}{l} (- + -) \\ (- - -) \end{array} \right\}, \\ & (- \text{ is adjoined after } \exists\text{-schema}) \end{aligned}$$

$$\begin{aligned} (+ + +) \rightarrow (+ - +) & \rightarrow \left\{ \begin{array}{l} (+ + -) \\ (+ - -) \end{array} \right\}, \\ & (+ \text{ is adjoined before } \forall\text{-schema}) \end{aligned}$$

$$\begin{aligned} (- + +) \rightarrow (- - +) & \rightarrow \left\{ \begin{array}{l} (- + -) \\ (- - -) \end{array} \right\}, \\ & (- \text{ is adjoined before } \forall\text{-schema}) \end{aligned}$$

the following $\exists V$ -schema :

$$\exists V(+ + +) \rightarrow (+ - +) \begin{cases} \nearrow \left\{ \begin{array}{l} (- + +) \\ (- - +) \end{array} \right\} \\ \searrow \left\{ \begin{array}{l} (+ + -) \\ (+ - -) \end{array} \right\} \end{cases} \rightarrow \left\{ \begin{array}{l} (- + -) \\ (- - -) \end{array} \right\}.$$

That is,

$$\begin{aligned} & \exists x \forall y F(xy) \rightarrow \exists x \forall \forall y F(xy) \begin{cases} \nearrow \exists x \forall y F(xy) \\ \searrow \exists x \forall y \forall F(xy) \end{cases} \rightleftharpoons \\ & \rightleftharpoons \forall \exists x \forall \forall y F(xy) \searrow \forall \exists x \forall y \forall F(xy) \rightleftharpoons \forall \exists x \forall \forall y \forall F(xy). \end{aligned}$$

1.3. Formulae with three quantifiers.

1.31. **$\forall \exists V$ -schema.** First we adjoin + and - after $\forall \exists$ -schema, then before $\exists V$ -schema, next combining these four we get the following:

Example. In the development of π into decimal fractions we denote by d_ν the ν -th number after the comma, and when the sequence $d_\nu, d_{\nu+1} \dots d_{\nu+9}$ is equal to 0123456789 for the n -th time, we set $\nu = k_n$. Then we define a sequence $\{a_r\}$ by the following postulates:

- if $r < k_1$, then $a_r = 1$,
- if $k_1 \leq r < k_2$, then $a_r = \frac{1}{2}$,
-

generally, if $k_n \leq r < k_{n+1}$, then $a_r = \left(\frac{1}{2}\right)^n$.

Thus defined sequence $\{a_r\}$ furnishes an example of (2.13)-number, which is unable to be proved (2.12)-number.⁵⁾

Of course there exists neither a sequence which satisfies (2.12) and does not satisfy (2.11) (i. e. for which negation of (2.11) holds), nor one which satisfies (2.13) and does not satisfy (2.12).

2.2. Equality of real numbers. For two real numbers, or what is the same, two sequences $\{a_r\}$ and $\{b_r\}$ which satisfy (2.13), we define the equality of them by the formula:

$$\forall \varepsilon > 0 \exists n \forall r > n \quad |a_r - b_r| < \varepsilon.$$

Again $|a_r - b_r| < \varepsilon$ being equivalent to its double negation, there are three kinds of equalities:

(2.21.) $\forall \varepsilon > 0 \exists n \forall r > n \quad |a_r - b_r| < \varepsilon,$

(2.22.) $\not\forall \varepsilon > 0 \exists n \forall r > n \quad |a_r - b_r| < \varepsilon,$

(2.23.) $\forall \varepsilon > 0 \not\forall \varepsilon > 0 \exists n \forall r > n \quad |a_r - b_r| < \varepsilon.$

Clearly (2.21.) \rightarrow (2.22.) \rightarrow (2.23.).

2.3. Inequality. Let us define inequality of $\{a_r\}$ and $\{b_r\}$ by

$$\exists \varepsilon > 0 \forall n \exists r > n \quad |a_r - b_r| \geq \varepsilon.$$

In this case non-equivalent types are⁶⁾:

(2.31.) $\exists \varepsilon > 0 \forall n \exists r > n \quad |a_r - b_r| \geq \varepsilon,$

(2.32.) $\exists \varepsilon > 0 \not\forall n \exists r > n \quad |a_r - b_r| \geq \varepsilon,$

5) The sequence $\{(\frac{1}{2})^r\}$ satisfies (2.11).

If $r < k_1$, then $a_r = (\frac{1}{2})^r$, and if $r \geq k_1$, then $a_r = 1$. The sequence $\{a_r\}$ defined by these conditions satisfies (2.12) but it cannot be proved (at least now) to satisfy (2.11).

6) $|a_r - b_r| \geq \varepsilon$ is also equivalent to its double negation.

$$(2.33.) \quad \neg\neg \exists \varepsilon > 0 \forall n \exists r > n |a_r - b_r| \geq \varepsilon,$$

$$(2.34.) \quad \exists \varepsilon > 0 \forall n \neg\neg \exists r > n |a_r - b_r| \geq \varepsilon,$$

$$(2.35.) \quad \neg\neg \exists \varepsilon > 0 \forall n \neg\neg \exists r > n |a_r - b_r| \geq \varepsilon.$$

The implicative relations between them are obviously (cf. $\exists V$ -schema):

$$(2.31.) \rightarrow (2.32.) \begin{cases} \nearrow (2.33.) \\ \searrow (2.34.) \end{cases} \rightarrow (2.35.).$$

2.4. Equality and inequality.

2.41. *The negation of (2.23.)-equality coincides with (2.35.)-inequality.*

Proof. We must show that $\neg \forall \varepsilon \neg\neg \exists n \forall r |a_r - a_n| < \varepsilon$ is equivalent to $\neg\neg \exists \varepsilon \forall n \neg\neg \exists r |a_r - a_n| \geq \varepsilon$.

$$\begin{aligned} \text{We have} \quad & \neg \forall \varepsilon \neg\neg \exists n \Leftrightarrow \neg\neg \exists \varepsilon \neg \exists n, \\ & \neg \exists n \forall r \Leftrightarrow \forall n \neg \forall r, \end{aligned}$$

$$\text{and} \quad \neg\neg \exists r |a_r - a_n| \geq \varepsilon \Leftrightarrow \neg \forall r \neg\neg |a_r - a_n| < \varepsilon;$$

on the other hand

$$\neg\neg |a_r - a_n| < \varepsilon \Leftrightarrow |a_r - a_n| < \varepsilon.$$

Combining these equivalences we obtain the desired result.

2.42. *The negations of (2.21.)- and (2.22.)-equality coincide with each other.*

Proof. Clear.

2.43. *Both negations of (2.34.)- and (2.35.)-inequality coincide with (2.23.)-equality.*

Proof. By 2.41. $\neg(2.23.) \Leftrightarrow (2.35.)$, and $(2.35.) \Leftrightarrow \neg\neg(2.34.)$, therefore $\neg(2.34.) \Leftrightarrow \neg(2.35.) \Leftrightarrow \neg\neg(2.23.) \Leftrightarrow (2.23.)$.

2.44. *The negations of (2.31.)-, (2.32.)- and (2.33.)-inequality coincide with each other.*

Proof. Since $(2.31.) \rightarrow (2.32.) \rightarrow (2.33.) \Leftrightarrow \neg\neg(2.31.)$,

$$\text{we have} \quad \neg(2.33.) \rightarrow \neg(2.32.) \rightarrow \neg(2.31.) \Leftrightarrow \neg(2.33.).$$

2.5. (2.11.)-number. Let us consider now only (2.11.)-numbers. Then

2.51. *Three equalities (2.21.), (2.22.) and (2.23.) are equivalent.*

Proof. We have only to show that if two (2.11.)-numbers α and β are (2.23.)-equal then they are also (2.21.)-equal.

Obviously for any positive rational ε it holds that

$$\exists n \forall r > n \quad |a_r - a_n| < \varepsilon, \quad |b_r - b_n| < \varepsilon. \quad (*)$$

Suppose now that $|a_n - b_n| \geq 3\varepsilon$.

Since

$$|a_r - b_r| \geq |a_n - b_n| - |a_r - a_n| - |b_r - b_n|,$$

it follows that $\forall r > n \quad |a_r - b_r| > \varepsilon$ by (*), which contradicts our assumption that α and β are (2.23.)-equal. Therefore $|a_n - b_n| < 3\varepsilon$ is valid because each side of this inequation represents rational number. Again using (*) we infer that

$$\forall r > n \quad |a_r - b_r| \leq |a_n - b_n| + |a_r - a_n| + |b_r - b_n| < 5\varepsilon.$$

ε being arbitrary, we have established our theorem.⁷⁾

2.52. (2.31.)-, (2.32.)- and (2.34.)-inequalities are equivalent.

Proof. The equivalence of (2.31.) and (2.34.) has been proved in Kuroda (3), consequently follows our theorem.

2.53. (2.33.)- and (2.35.)-inequalities are equivalent.

Proof. It holds that $\supset\supset (2.31.) \Leftrightarrow (2.33.)$ and $\supset\supset (2.34.) \Leftrightarrow (2.35.)$; on the other hand $(2.31.) \Leftrightarrow (2.34.)$ by 2.52., therefore $(2.33.) \Leftrightarrow (2.35.)$.

2.54. In Brouwer (1)'s terminology "örtliche Verschiedenheit" of two points (numbers) corresponds to the inequality (2.52.), "Abweichung" to (2.53.) and "Zusammenfallung" to (2.51.).

(Received September 21, 1953)

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7) In Kuroda (3) the equivalence of (2.11) and (2.12) has been proved.

