Set Theory $\mathrm{INC}^{\#}_{\infty^{\#}}$ Based on Infinitary Intuitionistic Logic with Restricted Modus Ponens Rule (Part.II) Hyper inductive definitions

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Abstract

In this paper intuitionistic set theory $\mathrm{INC}^{\#}_{\infty^{\#}}$ in infinitary set theoretical language is considered. External induction principle in nonstandard intuitionistic arithmetic were derived. Non trivial application in number theory is considered.The Goldbach-Euler theorem is obtained without any references to Catalan conjecture.

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Content

11.References.

1.Introduction

In this paper intuitionistic set theory $\mathrm{INC}^{\#}_{\infty^{\#}}$ based on infinitary intuitionistic logic with restricted modus ponens rule is considered [1]. External induction principle in nonstandard intuitionistic arithmetic were derived. Non trivial application in number theory is considered. The Goldbach-Euler theorem is obtained without any references to Catalan conjecture.

2.Axiom of nonregularity and axiom of hyperinfinity

2.1.Axiom of nonregularity

Remind that a non-empty set u is called regular iff

$$\forall x[x \neq \varnothing \to (\exists y \in x)(x \cap y = \varnothing)]. \tag{2.1}$$

Let's investigate what it says: suppose there were a non-empty x such that $(\forall y \in x)(x \cap y \neq \varnothing)$. For any $z_1 \in x$ we would be able to get $z_2 \in z_1 \cap x$. Since $z_2 \in x$ we would be able to get $z_3 \in z_2 \cap x$. The process continues forever: $\ldots \in z_{n+1} \in z_n \ldots \in z_4 \in z_3 \in z_2 \in z_1 \in x$. Thus we wish to rule out such an infinite regress.

2.1.Axiom of hyperinfinity.

Definition 2.1.(i) A non-empty transitive non regular set u is a well formed non regular set iff:

(i) there is unique countable sequence $\{u_n\}_{n=1}^{\infty}$ such that

$$\ldots \in u_{n+1} \in u_n \ldots \in u_4 \in u_3 \in u_2 \in u_1 \in u, \tag{2.2}$$

(ii) for any $n \in \mathbb{N}$ and any $u_{n+1} \in u_n$:

$$u_n = u_{n+1}^{+}, \tag{2.3}$$

where $a^{+} = a \cup \{a\}$.

(ii) we define a function $a^{+[k]}$inductively by $a^{+[k+1]} = (a^{+[k]})^{+}$

Definition 2.2. Let u and w are well formed non regular sets. We write $w \prec u$ iff for any $n \in \mathbb{N}$

$$w \in u_n. \tag{2.4}$$

Definition 2.3. We say that an well formed non regular set u is infinite (or hyperfinite) hypernatural nuber iff:

(I) For any member $w \in u$ one and only one of the following conditions are satified:

(i) $w \in \mathbb{N}$ or

(ii) $w = u_n$ for some $n \in \mathbb{N}$ or

(iii) $w \prec u$.

(II) Let ${}_{\prec}u$ be a set ${}_{\prec}u = \{z | z \prec u\}$, then by relation $(\bullet \prec \bullet)$ a set ${}_{\prec}u$ is densely ordered with no first element.

(III) $\mathbb{N} \subset u$.

Axiom of hyperinfinity

There exists unique set $\mathbb{N}^{\#}$ such that:

(i) $\mathbb{N} \subset \mathbb{N}^{\#}$

(ii) if u is infinite (hypernatural) number then $u \in \mathbb{N}^{\#} \backslash \mathbb{N}$

(iii) if u is infinite (hypernatural) number then there exists infinite (hypernatural) number v

such that $v \prec u$

(iv) if u is infinite hypernatural number then there exists infinite (hypernatural) number w

such that $u \prec w$

(v) set $\mathbb{N}^{\#} \backslash \mathbb{N}$ is patially ordered by relation $(\cdot \prec \cdot)$ with no first and no last element.

In this paper we introduced a set $\mathbb{N}^{\#} \backslash \mathbb{N}$ of the infinite numbers axiomatically without any references to non-standard model of arithmetic via canonical ultraproduct approach, see [2]-[5].

4.Infinitary and hyperinfinitary logics.

4.1.Classical infinitary logic.

By a vocabulary, we mean a set L of constant symbols, and relation and operation symbols with finitely many argument places. As usual,by an L-structure M , we mean a universe set M with an interpretation for each symbol of L. In cases where the vocabulary L is clear, we may just say structure. For a given vocabulary L and infinite cardinals $\mu \leq \kappa, L_{\kappa\mu}$ is the infinitary logic with κ variables, conjunctions and disjunctions over sets of formulas of size less than κ, and existential and universal quantifiers over sets of variables of size less than μ. All logics that we consider also have equality, and are closed under negation. The equality symbol is always available, but is not counted as an element of the vocabulary L.

During last sentury canonical infinitary logic many developed, see for example [6]-[10].

4.2.Why we need infinitary logic

It well known that some classes of mathematical structures, such as algebraically closed fields of a given characteristic, are characterized by a set of axioms in $L_{\omega\omega}$. Other classes cannot be characterized in this way, but can be axiomatized by a single sentence of $L_{\omega_1\omega}$.

Remark 4.1. In the practice of the contemporary model theory, and in more general mathematics as well, it often becomes necessary to consider structures satisfying certain collections of sentences rather than just single sentences. This consideration leads to the familiar notion of a theory in a logic. For example, in ordinary finitary logic, $L_{\omega\omega}$, if φ_n is a sentence which expresses that there are at least n elements, then the theory $\{\varphi_n | n \in \omega\}$ would express that there are infinitely many elements. Similarly, in the theory of groups, if φn is the sentence $\forall x[x^n \neq 1]$, then $\{\psi_n : n \in \omega\}$ expresses that a group is torsion free.

Remark 4.2. Suppose we want to express the idea that a set is finite, or that a group is torsion. A simple compactness argument would immediately reveal that neither of these notions can be expressed by a theory in $L_{\omega\omega}$. What we need to express in each case is that a certain theory is not satisfied, that is, that at least one of the sentences is false. While theories are able to simulate infinite conjunctions, there is no apparent way to simulate infinite disjunctions–which is just what is needed in this case.

Example 4.1. The Abelian torsion groups are the models of a sentence obtained by taking the conjunction of the usual axioms for Abelian groups (a finite set) and the following infinite disjunction:

$$\forall x\left[\bigvee_{n\in\mathbb{N}}\underbrace{x+x+\ldots+x}_{n}=0\right]. \tag{4.1}$$

Example 4.2. The Archimedean ordered fields are the models of a sentence obtained by taking the conjunction of the usual axioms for ordered fields and the following infinite disjunction:

$$\forall x\left[\bigvee_{n\in\mathbb{N}}\underbrace{1+1+\ldots+1}_{n}>x\right]. \tag{4.2}$$

Example 4.3. Let L be a countable vocabulary. Let T be an elementary first order theory, and let $\Gamma(\bar{x})$ be a set of finitary formulas in a fixed tuple of variables $\bar{x}$. The models of T that omit Γ are the models of the single $L_{\omega_1\omega}$ sentence obtained by taking the conjunction of the sentences of T and the following infinite disjunction:

$$\forall\bar{x}\left[\bigvee_{\gamma\in\Gamma}\neg\gamma(\bar{x})\right]. \tag{4.3}$$

Example 4.4. The non Archimedean ordered fields are the models of a sentence obtained by taking the conjunction of the usual axioms for non Archimedean ordered fields i.e., the following infinite conjunction:

$$\exists x\left[\bigwedge_{n\in\mathbb{N}}\underbrace{1+1+\ldots+1}_{n}<x\right]. \tag{4.4}$$

4.3. Bivalent hyperinfinitary first-order logic $IL^{\#}_{\infty^{\#}}$ with restricted rules of conclusion.

Hyperinfinitary language $L^{\#}_{\infty^{\#}}$ are defined according to the length of infinitary conjunctions/disjunctions as well as quantification it allows. In that way, assuming a supply of $\kappa<\infty^{\#}=card(\mathbb{N}^{\#})$ variables to be interpreted as ranging over a nonempty domain, one includes in the inductive definition of formulas an infinitary clause for conjunctions and disjunctions, namely, whenever the hypernturals indexed hypersequence $\{A_\delta\}_{\delta\in\mathbb{N}^{\#}}$ of formulas has length less than κ, one can form the hyperfinite conjunction/disjunction of them to produce a formula. Analogously, whenever an hypernaturals indexed sequence of variables has length less than λ, one can introduce one of the quantifiers $\forall$ or $\exists$ together with the sequence of variables in front of a formula to produce a new formula. One also stipulates that the length of any well-formed formula is less than $\infty^{\#}$ itself.

The syntax of bivalent hyperinfinitary first-order logics $L^{\#}_{\infty^{\#}}$ consists of a (ordered) set of sorts and a set of function and relation symbols, these latter together with the corresponding type, which is a subset with less than $\infty^{\#}=card(\mathbb{N}^{\#})$ many sorts. Therefore, we assume that our signature may contain relation and function symbols on $\gamma<\infty^{\#}$ many variables, and we suppose there is a supply of $\kappa<\infty^{\#}$ many fresh variables of each sort. Terms and atomic formulas are defined as usual, and general formulas are defined inductively according to the following rules:If $\phi, \psi, \{\phi_\alpha : \alpha < \gamma\}$ (for each $\gamma < \kappa$) are formulas of $\mathcal{L}_{\kappa,\kappa}$, the following are also formulas: $\bigwedge_{\alpha<\gamma} \phi_\alpha$, $\bigvee_{\alpha<\gamma} \phi_\alpha$, $\phi \to \psi$, $\forall_{\alpha<\gamma} x_\alpha \phi$ (also written $\forall \mathbf{x}_\gamma \phi$ if $\mathbf{x}_\gamma = \{x_\alpha : \alpha < \gamma\}$), $\exists_{\alpha<\gamma} x_\alpha \phi$ (also written $\exists \mathbf{x}_\gamma \phi$ if $\mathbf{x}_\gamma = \{x_\alpha : \alpha < \gamma\}$).

The axioms of hyperinfinitary first-order logic $L^{\#}_{\infty^{\#}}$ consist of the following schemata:

I. **Logical axiom**

1. $A \to [B \to A]$
2. $[A \to [B \to C] \to [[A \to B] \to [A \to C]]]$
3. $[\neg B \to \neg A] \to [A \to B]$
4. $[\bigwedge_{i<\alpha} [A \to A_i]] \to [A \to \bigwedge_{i<\alpha} A_i], \alpha \in \mathbb{N}^{\#}$
5. $[\bigwedge_{i<\alpha} A_i] \to A_j, \alpha \in \mathbb{N}^{\#}$
6. $[\forall \mathbf{x}[A \to B] \to [A \to \forall \mathbf{x} B]]$
   provided no variable in $\mathbf{x}$ occurs free in A;
7. $\forall \mathbf{x} A \to S_f(A)$
   where $S_f(A)$ is a substitution based on a function f from $\mathbf{x}$ to the terms of the language;

II.**Restricted rules of conclusion**.

$\mathbf{R}^{\#}$1.RMP (Restricted Modus Ponens).

From A and $A \to B$, conclude B iff $A \notin \Delta_1$and $(A \to B) \notin \Delta_2$,where $\Delta_1, \Delta_2 \subsetneqq \mathcal{F}_{\mathbf{wff}}$

We abbraviate by $A, A \to B \vdash_{RMP} B$.

$\mathbf{R}^{\#}$2.MT (Restricted Modus Tollens)

$P \to Q, \neg Q \vdash_{RMT} \neg P$ iff $P \notin \Delta'_1$and $(P \to Q) \notin \Delta'_2$,where $\Delta'_1, \Delta'_2 \subsetneqq \mathcal{F}_{\mathbf{wff}}$.

III.**Equality axioms**:

(a) $t = t$

(b) $[\bigwedge_{i<\alpha} t_i = t'_i] \to [\phi(t_0, \ldots, t_\xi, \ldots) = \phi(t'_0, \ldots, t'_\xi, \ldots)]$

(c) $[\bigwedge_{i<\alpha} t_i = t'_i] \to [P(t_0, \ldots, t_\xi, \ldots) \to P(t'_0, \ldots, t'_\xi, \ldots)]$

for each $\alpha \in \mathbb{N}^{\#}$, where t, t_i are terms and ϕ is a function symbol of arity α and P a relation symbol of arity $\alpha \in \mathbb{N}^{\#}$.

IV.**Distributivity axiom**:

$$\bigwedge_{i<\gamma} \bigvee_{j<\gamma} \psi_{ij} \to \bigvee_{f \in \gamma^\gamma} \bigwedge_{i<\gamma} \psi_{if(i)} \tag{4.5}$$

V.**Dependent choice axiom**:

$$\bigwedge_{\alpha<\gamma} \forall_{\beta<\alpha} \mathbf{x}_\beta \exists \mathbf{x}_\alpha \psi_\alpha \to \exists_{\alpha<\gamma} \mathbf{x}_\alpha \bigwedge_{\alpha<\gamma} \psi_\alpha \tag{4.6}$$

provided the sets $\mathbf{x}_\alpha$ are pairwise disjoint and no variable in $\mathbf{x}_\alpha$ is free in ψ_β for $\beta < \alpha \in \mathbb{N}^{\#}$.

5.Intuitionistic hyperinfinitary logic $L^{\#}_{\infty^{\#}}$ with restricted rules of conclusion.

We will denote the class of hypernaturals by $\mathbb{N}^{\#}$, the class of binary sequences of hypernatural length by $2^{<\mathbb{N}^{\#}}$, and the class of sets of hypernatural numbers by $\Sigma(\mathbb{N}^{\#})$.

We fix a class of variables x_i for each $i \in \mathbb{N}^{\#}$. Given an $\alpha \in \mathbb{N}^{\#}$, a context of length α is a sequence $\mathbf{x} = \langle x_{i_j} | j < \alpha \rangle$ of variables. In this paper we will use boldface letters, $\mathbf{x}, \mathbf{y}, \mathbf{z}, \ldots$, to denote contexts and light-face letters, $x_i, y_i, z_i, \ldots$, to denote the i-th variable symbol of $\mathbf{x}, \mathbf{y},$ and $\mathbf{z},$ respectively.

We will denote the length of a context $\mathbf{x}$ by $l(\mathbf{x})$. The formulas of the hyperinfinitary language $\mathcal{L}^{\#}_{\infty^{\#}}$ of set theory $\mathrm{INC}^{\#}_{\infty^{\#}}$ are defined to be the smallest class of formulas closed under the following rules:

1. $\perp$ is a formula,
2. $x_i \in x_j$ is a formula for any variables x_i and x_j,
3. $x_i = x_j$ is a formula for any variables x_i and x_j,
4. if ϕ and ψ are formulas, then $\phi \to \psi$ are formulas,
5. if ϕ_α is a formula for every $\alpha : \alpha \leq \beta \in \mathbb{N}^{\#}$, then

1. $\bigvee_{\alpha\leq\beta} \phi_\alpha$ is a gyperfinite formula, (5.1)

6. if ϕ_α is a formula for every $\alpha : \alpha \leq \beta \in \mathbb{N}^{\#}$, then

$$\bigwedge_{\alpha\leq\beta} \phi_\alpha \text{ is a gyperfinite formula,} \tag{5.2}$$

7. if $\mathbf{x}$ is a context of length α, then $\exists^\alpha \mathbf{x}\phi$ is a formula, and,
8. if $\mathbf{x}$ is a context of length α, then $\forall^\alpha \mathbf{x}\phi$ is a formula.

By this definition, our language allows set-sized disjunctions and conjunctions as well as quantification over set-many variables at once. However, note that infinite alternating sequences of existential and universal quantifiers are excluded by this definition.

Remark 5.1.Whenever it is clear from the context, we will omit the superscripts from the quantifiers and write $\exists$ and $\forall$ instead of $\exists^\alpha$ and $\forall^\alpha$, respectively. In many situations it will be useful to identify a variable x with the context $\mathbf{x} = \langle x \rangle$ whose unique element is x such that we can write, for example, "$\exists x\phi$" for "$\exists \mathbf{x}\phi$" and "$\forall x\phi$" for "$\forall \mathbf{x}\phi$". A variable x_i is called a free variable of a formula ϕ whenever x_i appears in ϕ but not in any quantification of ϕ. As usual, a formula without free variables is called a sentence. We say that $\mathbf{x}$ is a context of the formula ϕ if all free variables of ϕ are among those in $\mathbf{x}$. As usual, we will write $\phi(\mathbf{x})$ in case that ϕ is a formula and $\mathbf{x}$ is a context of φ. Similarly, given two contexts $\mathbf{x}$ and $\mathbf{y}$ with $x_j \neq y_{j'}$ for all $j < \ell(\mathbf{x})$ and $j' < \ell(\mathbf{y})$, we will write $\varphi(\mathbf{x},\mathbf{y})$ in case that the sequence obtained by concatenating $\mathbf{x}$ and $\mathbf{y}$ is a context for φ.

Remark 5.2. We extend the classical abbreviations as follows: Given a formula ϕ and an hypernatural $\alpha \in \mathbb{N}^{\#}$ we introduce the bounded quantifiers as abbreviations, namely,

$$\forall^\alpha \mathbf{x} \in y\, \phi \text{ for } \forall^\alpha \mathbf{x}(\mathbf{x} \in y \to \phi), \tag{5.3}$$

and

$$\exists^\alpha \mathbf{x} \in y\, \phi \text{ for } \exists^\alpha \mathbf{x}(\mathbf{x} \in y \wedge \phi). \tag{5.4}$$

Notation 5.1. A sequent $\phi \vdash_{\mathbf{x},\boldsymbol{\alpha}} \psi$ is however equivalent to the formula $\forall^\alpha \mathbf{x}(\phi \to \psi)$.
The system of axioms and rules for hyperinfinitary intuitionistic first-order logic consists of the following schemata:

I. **Logical axiom**

1. $A \to [B \to A]$
2. $[A \to [B \to C] \to [[A \to B] \to [A \to C]]]$
3. $[\bigwedge_{i<\alpha}[A \to A_i]] \ \to [A \to \bigwedge_{i<\alpha} A_i], \alpha \in \mathbb{N}^{\#}$
4. $[\bigwedge_{i<\alpha} A_i] \to A_j, \alpha \in \mathbb{N}^{\#}$
5. $[\forall \mathbf{x}[A \to B] \to [A \to \forall \mathbf{x} B]]$

   provided no variable in $\mathbf{x}$ occurs free in A.

7. $\forall \mathbf{x} A \to S_f(A)$

where $S_f(A)$ is a substitution based on a function f from $\mathbf{x}$ to the terms of the language;

II.**Restricted rules of conclusion**.

$\mathbf{R}^{\#}$1.RMP (Restricted Modus Ponens).
From A and $A \to B$, conclude B iff $A \notin \Delta_1$and $(A \to B) \notin \Delta_2$,where $\Delta_1, \Delta_2 \subsetneqq \mathcal{F}_{\mathbf{wff}}$
We abbraviate by $A, A \to B \vdash_{RMP} B$.
$\mathbf{R}^{\#}$2.MT (Restricted Modus Tollens)
$P \to Q, \neg Q \vdash_{RMT} \neg P$ iff $P \notin \Delta_1'$and $(P \to Q) \notin \Delta_2'$,where $\Delta_1', \Delta_2' \subsetneqq \mathcal{F}_{\mathbf{wff}}$.
III.**Weak distributivity axiom**:

$$\phi \wedge \bigvee_{i<\gamma} \psi_i \vdash_{\mathbf{x}} \bigvee_{i<\gamma} \phi \wedge \psi_i \tag{5.5}$$

for each $\gamma \in \mathbb{N}^{\#}$.
IV.**Frobenius axiom**:

$$\phi \wedge \exists \mathbf{y} \psi \vdash_{\mathbf{x}} \exists \mathbf{y}(\phi \wedge \psi) \tag{5.6}$$

where no variable in $\mathbf{y}$ is in the context $\mathbf{x}$.
V.**Structural rules**:

(a) Identity axiom:

$$\varphi \vdash_{\mathbf{x},\boldsymbol{\alpha}} \varphi \tag{5.7}$$

(b) Substitution rule:

$$\frac{\varphi \vdash_{\mathbf{x},\boldsymbol{\alpha}} \psi}{\varphi[\mathbf{s}/\mathbf{x}] \vdash_{\mathbf{y}} \psi[\mathbf{s}/\mathbf{x}]} \tag{5.8}$$

where $\mathbf{y}$ is a string of variables including all variables occurring in the string of terms $\mathbf{s}$.
(c) Restricted cut rule:

$$\frac{\varphi \vdash_{\mathbf{x},\boldsymbol{\alpha}} \psi, \psi \vdash_{\mathbf{x},\alpha} \theta}{\varphi \vdash_{\mathbf{x},\alpha} \theta} \tag{5.9}$$

iff $\varphi \notin \Delta_1$and $(\psi \vdash_{\mathbf{x},\alpha} \theta) \notin \Delta_2$.
IV.**Equality axioms**:

(a)

$$\top \vdash_{\mathbf{x}} \mathbf{x} = \mathbf{x} \tag{5.10}$$

(b)

$$(\mathbf{x} = \mathbf{y}) \wedge \varphi[\mathbf{x}/\mathbf{w}] \vdash_{\mathbf{z}} \varphi[\mathbf{y}/\mathbf{w}] \tag{5.11}$$

where $\mathbf{x}, \mathbf{y}$ are contexts of the same length and type and $\mathbf{z}$ is any context containing $\mathbf{x}, \mathbf{y}$ and the free variables of φ.
V.**Conjunction axioms and rules**:
(a)

$$\bigwedge_{i<\gamma} \varphi_i \vdash_{\mathbf{x},\alpha} \varphi_j \tag{5.12}$$

for each $\gamma \in \mathbb{N}^{\#}$ and $j < \gamma$

(b)

$$\frac{\{\phi \vdash_{\mathbf{x},\boldsymbol{\alpha}} \psi_i\}_{i<\gamma}}{\phi \vdash_{\mathbf{x},\boldsymbol{\alpha}} \bigwedge_{i<\gamma} \psi_i} \tag{5.13}$$

for each $\gamma \in \mathbb{N}^{\#}$.

VI.**Disjunction axioms and rules**:

(a)

$$\phi_j \vdash_{\mathbf{x},\boldsymbol{\alpha}} \bigvee_{i<\gamma} \phi_i \tag{5.14}$$

for each $\gamma \in \mathbb{N}^\#$

(b)

$$\frac{\{\phi_i \vdash_{\mathbf{x},\boldsymbol{\alpha}} \theta\}_{i<\gamma}}{\bigvee_{i<\gamma} \phi_i \vdash_{\mathbf{x},\boldsymbol{\alpha}} \theta} \tag{5.15}$$

for each $\gamma \in \mathbb{N}^\#$.

VII. **Implication rule**:

$$\frac{\phi \wedge \psi \vdash_{\mathbf{x},\boldsymbol{\alpha}} \theta}{\phi \vdash_{\mathbf{x},\boldsymbol{\alpha}} \psi \Rightarrow \theta} \tag{5.16}$$

IX.**Existential rule**:

$$\frac{\phi \vdash_{\mathbf{xy}} \psi}{\exists \mathbf{y}(\phi \vdash_{\mathbf{x}} \psi)} \tag{5.17}$$

where no variable in $\mathbf{y}$ is free in ψ.

X.**Universal rule**:

$$\frac{\varphi \vdash_{\mathbf{xy}} \psi}{\phi \vdash_{\mathbf{x}} \forall \mathbf{y}\psi} \tag{5.18}$$

where no variable in $\mathbf{y}$ is free in φ.

6.Intuitionistic set theory INC$^\#_{\infty^\#}$ in hyperinfinitary set theoretical language.

6.1.Axioms and basic definitions.

Intuitionistic set theory $\mathbf{INC}^\#$ is formulated as a system of axioms in the same first order language as its classical counterpart, only based on intuitionistic logic $IL^\#_{\infty^\#}$ with restricted modus ponens rule. The language of set theory is a first-order language $L^\#_{\infty^\#}$ with equality $=$, which includes a binary symbol $\in$. We write $x \neq y$ for $\neg\,(x = y)$ and $x \notin y$ for $\neg(x \neg y)$. Individual variables $x, y, z, \ldots$ of $L^\#_{\infty^\#}$ will be understood as ranging over classical sets. The unique existential quantifier $\exists!$ is introduced by writing, for any formula $\varphi(x), \exists! x\varphi(x)$ as an abbreviation of the formula $\exists x[\varphi(x)\ \&\ \forall y(\varphi(y) \Rightarrow x = y)]$. $L^\#_{\infty^\#}$ will also allow the formation of terms of the form $\{x|\varphi(x)\}$, for any formula φ containing the free variable x. Such terms are called nonclassical sets; we shall use upper case letters $A, B, \ldots$ for such sets. For each nonclassical set $A = \{x|\varphi(x)\}$ the formulas $\forall x[x \in A \Leftrightarrow \varphi(x)]$ and $\forall x[x \in A \Leftrightarrow \varphi(x, A)]$is called the defining axioms for the nonclassical set A.

Remark 6.**1**.Note that the formula $\forall x[x \in A \Leftrightarrow \varphi(x, A)]$ and $\forall x[x \in a \Leftrightarrow \varphi(x, a) \wedge x \in u]$

is not always asserts that $\forall x[x \in A \vdash_{RMP} \varphi(x,A)]$ and (or) $\forall x[\varphi(x,A) \vdash_{RMP} x \in A]$ even for a classical set since for some y possible $y \in A \Rightarrow \varphi(y) \nvdash_{RMP} \varphi(y)$ and (or) $\varphi(y) \Rightarrow y \in A \nvdash_{RMP} x \in A$ and $y \in a \Rightarrow \varphi(y) \wedge y \in u \nvdash_{RMP} \varphi(y) \wedge y \in u$, etc.In order to emphasize this fact we sometimes vrite the defining axioms for the nonclassical set in the following form $\forall x[x \in A \Leftrightarrow_w \varphi(x,A)]$

Remark 6.2.(1) Two nonclassical sets A,B are defined to be equal and we write $A = B$ if $\forall x[x \in A \Leftrightarrow x \in B]$. (2) A is a subset of B, and we write $A \subseteqq B$, if $\forall x[x \in A \Rightarrow x \in B]$. (3) We also write $\mathbf{Cl.Set}(A)$ for the formula $\exists u \forall x[x \in A \Leftrightarrow x \in u]$. (4) We also write $\mathbf{NCl.Set}(A)$ for the formulas $\forall x[x \in A \Leftrightarrow \varphi(x)]$ and $\forall x[x \in A \Leftrightarrow \varphi(x,A)]$.

Remark 6.3.$\mathbf{Cl.Set}(A)$) asserts that the set A is a classical set. For any classical set u, it follows from the defining axiom for the classical set $\{x|x \in u \wedge \varphi(x)\}$ that $\mathbf{Cl.Set}(\{x|x \in u \wedge \varphi(x)\})$.

We shall identify $\{x|x \in u\}$ with u, so that sets may be considered as (special sorts of) nonclassical sets and we may introduce assertions such as $u \subset A, u \subseteqq A, u = A$, etc.

Remark 6.4. If A is a nonclassical set, we write $\exists x \in A\ \varphi(x,A)$ for $\exists x[x \in A \wedge \varphi(x,A)]$ and $\forall x \in A \varphi(x,A)$ for $\forall x[x \in A \Rightarrow \varphi(x,A)]$.

We define now the following sets:

1.$\{u_1,u_2,\ldots,u_n\} = \{x|x = u_1 \vee x = u_2 \vee\ldots\vee x = u_n\}$. 2. $\{A_1,A_2,\ldots,A_n\} =$
$= \{x|x = A_1 \vee x = A_2 \vee\ldots\vee x = A_n\}$. 3.$\bigcup A = \{x|\exists y[y \in A \wedge x \in y]\}$.
4.$\bigcap A = \{x|\forall y[y \in A \Rightarrow x \in y]\}$. 5.$A \cup B = \{x|x \in A \vee x \in B\}$.
5.$A \cap B = \{x|x \in A \wedge x \in B\}$. 6.$A - B = \{x|x \in A \wedge x \notin B\}$. 7.$u^+ = u \cup \{u\}$.
8.$\mathbf{P}(A) = \{x|x \subseteq A\}$. 9.$\{x \in A|\varphi(x,A)\} = \{x|x \in A \wedge \varphi(x,A)\}$. 10.$\mathbf{V} = \{x|: x = x\}$.
11.$\varnothing = \{x|x \neq x\}$.

The system $\mathbf{INC}^{\#}_{\infty^\#}$ of set theory is based on the following axioms:

Extensionality1: $\forall u \forall v[\forall x(x \in u \Leftrightarrow x \in v) \Rightarrow u = v]$

Extensionality2: $\forall A \forall B[\forall x(x \in A \Leftrightarrow x \in B) \Rightarrow A = B]$

Universal Set: $\mathbf{NCl.Set}(\mathbf{V})$

Empty Set: $\mathbf{Cl.Set}(\varnothing)$

Pairing1: $\forall u \forall v\ \mathbf{Cl.Set}(\{u,v\})$

Pairing2: $\forall A \forall B\ \mathbf{NCl.Set}(\{A,B\})$

Union1: $\forall u\ \mathbf{Cl.Set}(\bigcup u)$

Union2: $\forall A\ \mathbf{NCl.Set}(\bigcup A)$

Powerset1: $\forall u\ \mathbf{Cl.Set}(\mathbf{P}(u))$

Powerset2: $\forall A\ \mathbf{NCl.Set}(\mathbf{P}(A))$

Infinity $\exists a[\varnothing \in a \wedge \forall x \in a(x^+ \in a)]$

Separation1$\forall u_1 \forall u_2,\ldots \forall u_n \forall a \exists \mathbf{Cl.Set}(\{x \in a|\varphi(x,u_1,u_2,\ldots,u_n)\})$

Separation2$\forall u_1 \forall u_2,\ldots \forall u_n \mathbf{NCl.Set}(\{x \in A|\varphi(x,A;u_1,u_2,\ldots,u_n)\})$

Comprehension1$\forall u_1 \forall u_2,\ldots \forall u_n \exists A \forall x[x \in A \Leftrightarrow \varphi(x;u_1,u_2,\ldots,u_n)]$

Comprehension 2 $\forall u_1 \forall u_2,\ldots \forall u_n \exists A \forall x[x \in A \Leftrightarrow \varphi(x,A;u_1,u_2,\ldots,u_n)]$

Hyperinfinity: see subsection 2.1.

Remark 6.5. Note that the axiom of hyperinfinity follows from the schemata Comprehension 2.

7.External induction principle and hyperinductive

definitions.

7.1.External induction principle in nonstandard intuitionistic arithmetic.

Axiom of infite ω-induction

(i)

$$\forall S(S \subset \mathbb{N})\left\{\left[\bigwedge_{n\in\omega}(n \in S \Rightarrow n^+ \in S)\right] \Rightarrow S = \mathbb{N}\right\}. \quad (7.1)$$

(ii) Let $F(x)$ be a wff of the set theory $\mathrm{INC}^{\#}_{\infty^{\#}}$, then

$$\left[\bigwedge_{n\in\omega}(F(n) \Rightarrow F(n^+))\right] \Rightarrow \forall n(n \in \omega)F(n). \quad (7.2)$$

Definition 7.1.Let β be a hypernatural such that $\beta \in \mathbb{N}^{\#}\backslash\mathbb{N}$. Let $[0,\beta] \subset \mathbb{N}^{\#}$be a set such that $\forall x[x \in [0,\beta] \Leftrightarrow 0 \leq x \leq \beta]$ and $[0,\beta) = [0,\beta]\backslash\{\beta\}$.

Definition 7.2.(i) Let $F(x)$ be a wff of $\mathrm{INC}^{\#}$with unique free variable x.We will say that a wff $F(x)$ is restricted on a set S such that $S \subsetneqq \mathbb{N}^{\#}$ iff the following conditions are satisfied

$$\forall\alpha(\alpha \in \mathbb{N}^{\#})[F(\alpha) \Rightarrow \alpha \in S] \quad (7.3)$$

and

$$\forall\alpha(\alpha \in \mathbb{N}^{\#})[\neg F(\alpha) \Rightarrow \alpha \in \mathbb{N}^{\#}\backslash S]. \quad (7.4)$$

(ii) Let $F(x)$ be a wff of $\mathrm{INC}^{\#}_{\infty^{\#}}$with unique free variable x.We will say that a wff $F(x)$ is a strongly restricted on a set $S \subsetneqq \mathbb{N}^{\#}$ iff the following condition is satisfied

$$\forall\alpha(\alpha \in \mathbb{N}^{\#})[F(\alpha) \Leftrightarrow \alpha \in S] \quad (7.5)$$

Definition 7.2. Let $F(x)$ be a wff of $\mathrm{INC}^{\#}_{\infty^{\#}}$with unique free variable x.We will say that a wff $F(x)$ is unrestricted if wff $F(x)$ is not restricted on any set S such that $S \subsetneqq \mathbb{N}^{\#}$.

Example 7.1.(i) Let $\mathbf{fin}(\alpha), \alpha \in \mathbb{N}^{\#}$be a wff formula such that $\mathbf{fin}(\alpha) \Leftrightarrow \alpha \in \mathbb{N}$. Obviously wff $\mathbf{fin}(\alpha)$ is a strongly restricted on a set $S = \mathbb{N}$ since $\forall\alpha(\alpha \in \mathbb{N}^{\#})[\mathbf{fin}(\alpha) \Leftrightarrow \alpha \in \mathbb{N}]$.

(ii) Let $\mathbf{ifin}(\alpha), \alpha \in \mathbb{N}^{\#}$be a wff formula such that $\mathbf{ifin}(\alpha) \Leftrightarrow \alpha \in \mathbb{N}^{\#}\backslash\mathbb{N}$.Obviously wff $\mathbf{ifin}(\alpha)$ is a strongly restricted on a set $\mathbb{N}^{\#}\backslash\mathbb{N}$.

Axiom of hyperfinite induction 1

$$\forall\beta(\beta \in \mathbb{N}^{\#})\forall S(S \subseteq [0,\beta]) \searrow$$
$$\left\{\forall\alpha(\alpha \in [0,\beta])\left[\bigwedge_{0\leq\alpha<\beta}(\alpha \in S \Rightarrow \alpha^+ \in S)\right] \Rightarrow S = [0,\beta]\right\}. \quad (7.6)$$

Axiom of hyperinfinite induction 1

$$\forall S(S \subset \mathbb{N}^{\#})\left\{\forall\beta(\beta \in \mathbb{N}^{\#})\left[\bigwedge_{0\leq\alpha<\beta}(\alpha \in S \Rightarrow \alpha^+ \in S)\right] \Rightarrow S = \mathbb{N}^{\#}\right\}. \quad (7.7)$$

Remark 7.1.Note that from comprechesion shemata 2 (see subsection 6.1) follows that

$$\forall\beta\exists S(S \subset [0,\beta])\forall\bar{\beta}(\bar{\beta} \in [0,\beta])\left[\bar{\beta} \in S \Leftrightarrow \bigwedge_{0\leq\alpha<\bar{\beta}}(\alpha \in S \Rightarrow \alpha^+ \in S)\right]. \quad (7.8)$$

Therefore for any $\bar{\beta} \in [0, \beta]$ from (7.8) it follows that

$$\bigwedge_{0 \leq \alpha < \overline{\beta}} (\alpha \in S \Rightarrow \alpha^+ \in S) \vdash \overline{\beta} \in S. \tag{7.9}$$

Thus axiom of hyperfinite induction 1,i.e., (7.6) holds, since from (7.9) it follows that $\forall \overline{\beta}[\overline{\beta} \in [0, \beta] \Rightarrow \overline{\beta} \in S]$.

Remark 7.2.Note that from comprechesion shemata 2 (see subsection 6.1) follows that

$$\exists S(S \subset \mathbb{N}^{\#}) \forall \beta(\beta \in \mathbb{N}^{\#}) \left[\beta \in S \Leftrightarrow \bigwedge_{0 \leq \alpha < \beta} (\alpha \in S \Rightarrow \alpha^+ \in S) \right]. \tag{7.10}$$

Therefore for any $\beta \in \mathbb{N}^{\#}$ from (7.10) it follows that

$$\bigwedge_{0 \leq \alpha < \beta} (\alpha \in S \Rightarrow \alpha^+ \in S) \vdash \beta \in S \tag{7.12}$$

Thus axiom of hyperinfinite induction 1,i.e., (7.8) holds, since it follows from (7.12) that $\forall \beta[\beta \in \mathbb{N}^{\#} \Rightarrow \beta \in S]$.

Axiom of hyperfinite induction 2

Let $F(x)$ be a wff of the set theory $\mathrm{INC}^{\#}_{\infty^{\#}}$ strongly restricted on a set $[0, \beta]$ then

$$\left[\forall \beta(\beta \in [0, \beta]) \left[\bigwedge_{0 \leq \alpha < \beta} (F(\alpha) \Rightarrow F(\alpha^+)) \right] \right] \Rightarrow \forall \alpha(\alpha \in [0, \beta]) F(\alpha). \tag{7.13}$$

Axiom of hyperinfinite induction 2

Let $F(x)$ be anrestricted wff of the set theory $\mathrm{INC}^{\#}_{\infty^{\#}}$ then

$$\left[\forall \beta(\beta \in \mathbb{N}^{\#}) \left[\bigwedge_{0 \leq \alpha < \beta} (F(\alpha) \Rightarrow F(\alpha^+)) \right] \right] \Rightarrow \forall \beta(\beta \in \mathbb{N}^{\#}) F(\beta). \tag{7.14}$$

Remark 7.3.Note that from comprechesion shemata 2 (see subsection 6.1) follows that

$$\forall \beta \exists S(S \subset [0, \beta]) \forall \overline{\beta}(\overline{\beta} \in [0, \beta]) \left[\overline{\beta} \in S \Leftrightarrow \bigwedge_{0 \leq \alpha < \overline{\beta}} (F(\alpha) \Rightarrow F(\alpha^+)) \right]. \tag{7.15}$$

Therefore for any $\overline{\beta} \in [0, \beta]$ from (7.15) it follows that

$$\bigwedge_{0 \leq \alpha < \overline{\beta}} (F(\alpha) \Rightarrow F(\alpha^+)) \vdash \overline{\beta} \in S \tag{7.16}$$

Thus axiom of hyperfinite induction 2,i.e., (7.13) holds, since it follows from (7.16) that $\forall \overline{\beta}[\overline{\beta} \in [0, \beta] \Rightarrow \overline{\beta} \in S]$.

Remark 7.4.Note that from comprechesion shemata 2 (see subsection 6.1) follows that

$$\exists S(S \subset \mathbb{N}^{\#}) \forall \overline{\beta}(\overline{\beta} \in \mathbb{N}^{\#}) \left[\overline{\beta} \in S \Leftrightarrow \bigwedge_{0 \leq \alpha < \overline{\beta}} (F(\alpha) \Rightarrow F(\alpha^+)) \right]. \tag{7.17}$$

Therefore for any $\overline{\beta} \in \mathbb{N}^{\#}$ from (7.17) it follows that

$$\bigwedge_{0 \leq \alpha < \overline{\beta}} (F(\alpha) \Rightarrow F(\alpha^+)) \vdash \overline{\beta} \in S. \tag{7.18}$$

Thus axiom of hyperinfinite induction 2,i.e., (7.14) holds, since From (7.18) it follows that $\forall \overline{\beta}\left[\overline{\beta} \in \mathbb{N}^{\#} \Rightarrow \overline{\beta} \in S\right]$.

Axiom of hyperfinite induction 3

Let $F(x)$ be a wff of the set theory $\mathrm{INC}^{\#}_{\infty^{\#}}$ strongly restricted on inductive set $W_{\mathbf{ind}}$ such that

$\mathbb{N} \subseteq W_{\mathbf{ind}} \subsetneqq \mathbb{N}^{\#}$ then

$$\forall W\left[(\mathbb{N} \subseteq W_{\mathbf{ind}} \subsetneqq \mathbb{N}^{\#}) \wedge \left[\bigwedge_{\alpha \in W_{\mathbf{ind}}} (F(\alpha) \Rightarrow F(\alpha^{+}))\right]\right] \Rightarrow \forall\alpha(\alpha \in W_{\mathbf{ind}})F(\alpha). \qquad (7.19)$$

Proposition 7.1. (a) For any natural or hypernatural number $k \in \mathbb{N}^{\#}$,

$$\vdash \bigvee_{0 \leq m \leq k} (x = m) \Leftrightarrow x \leq k. \qquad (7.20)$$

(a′) For any hypernatural number κ and any wff B

$$\vdash \bigwedge_{0 \leq m \leq k} B(m) \Leftrightarrow \forall x(x \leq k \Rightarrow B(x)). \qquad (7.21)$$

(b) For any hypernatural number $k \in \mathbb{N}^{\#}$ such that $k > 0$,

$$\vdash \bigvee_{1 \leq m \leq k} (x = m - 1) \Leftrightarrow x < k. \qquad (7.22)$$

(b′) For any hypernatural number $k \in \mathbb{N}^{\#}$ such that $k > 0$ and any wff $B(x)$,

$$\vdash \bigwedge_{0 \leq m \leq k-1} B(m) \Leftrightarrow \forall x(x < k \Rightarrow B(x)). \qquad (7.23)$$

(c) $\vdash (\forall x(x < y \Rightarrow B(x))) \wedge (\forall x(x \geq y \Rightarrow E(x))) \Rightarrow \forall x(B(x) \vee E(x))$.

Proof. (a) We prove $\bigvee_{0 \leq m \leq k} (x = m) \Leftrightarrow x \leq k$ by hyperfinite induction in the metalanguage on k. The case for $k = 0, \vdash x = 0 \Leftrightarrow x \leq 0$, is obvious from the definitions.

Assume as inductive hypothesis that

$$\bigvee_{0 \leq m \leq k} (x = m) \Leftrightarrow x \leq k. \qquad (7.24)$$

Now assume that

$$\left[\bigvee_{0 \leq m \leq k} (x = m)\right] \vee (x = k + 1). \qquad (7.25)$$

But $\vdash x = k + 1 \Rightarrow x \leq k + 1$ and, by the inductive hypothesis,

$$\bigvee_{0 \leq m \leq k} (x = m). \qquad (7.26)$$

Also $\vdash x \leq k \Rightarrow x < k + 1$. Thus, $x \leq k + 1$. So,

$$\vdash \bigvee_{0 \leq m \leq k+1} (x = m) \Rightarrow x \leq k + 1. \qquad (7.27)$$

Conversely, assume $x \leq k + 1$. Then $x = k + 1 \vee x < k + 1$. If $x = k + 1$, then

$$\bigvee_{0 \leq m \leq k+1} (x = m). \qquad (7.28)$$

If $x < k + 1$, then we have $x \leq k$. By the inductive hypothesis,

$$\bigvee_{0 \leq m \leq k} (x = m) \qquad (7.29)$$

and,therefore,

$$\bigvee_{0 \leq m \leq k+1} (x = m). \tag{7.30}$$

Thus in either case,

$$\bigvee_{0 \leq m \leq k+1} (x = m). \tag{7.31}$$

This proves

$$\vdash x \leq k + 1 \Rightarrow \bigvee_{0 \leq m \leq k+1} (x = m). \tag{7.32}$$

From the inductive hypothesis, we have derived

$$\bigvee_{0 \leq m \leq k+1} (x = m) \Leftrightarrow x \leq k + 1 \tag{7.33}$$

and this completes the proof. Note that this proof has been given in an informal manner that we shall generally use from now on. In particular, the deduction theorem, the replacement theorem, and various rules and tautologies will be applied without being explicitly mentioned.

Parts (a′), (b), and (b′) follow easily from part (a). Part (c) follows almost immediately from the statement $t \neq r \Rightarrow (t < r) \vee (r < t)$, using obvious tautologies.

There are several stronger forms of the hyperinfinite induction principles that we can prove at this point.

Theorem 7.1.(Complete hyperinfinite induction) Let $B(x)$ be anrestricted wff of the set theory $\mathrm{INC}^{\#}_{\infty^{\#}}$ then

$$\forall x(x \in \mathbb{N}^{\#})[\forall z(z < x \Rightarrow B(z)) \Rightarrow B(x)] \Rightarrow \forall x(x \in \mathbb{N}^{\#})B(x) \tag{7.34}$$

In ordinary languageI consider a property $B(x)$ such that, for any x, if $B(x)$ holds for all hypernatural numbers less than x, then $B(x)$ holds for x also. Then $B(x)$ holds for all hypernatural numbers $x \in \mathbb{N}^{\#}$.

Proof.Let $E(x)$ be a wff $\forall z(z \leq x \Rightarrow B(z))$.

(i) 1.Assume that $\forall x(x \in \mathbb{N}^{\#})[\forall z(z < x \Rightarrow B(z)) \Rightarrow B(x)]$,then

2.$[\forall z(z < 0 \Rightarrow B(z)) \Rightarrow B(0)]$ it follows from 1.

3. $z \nless 0$,then

4. $\forall z(z < 0 \Rightarrow B(z))$ it follows from 1,

5. $B(0)$ it follows from 2,4 by MP

6. $\forall z(z \leq 0 \Rightarrow B(z))$ i.e.,$E(0)$ holds it follows from Proposition7.1(a′)

7.$\forall x(x \in \mathbb{N}^{\#})[\forall z(z < x \Rightarrow B(z)) \Rightarrow B(x)] \vdash E(0)$ it follows from 1,6 by MP

(ii) 1.Assume that: $\forall x(x \in \mathbb{N}^{\#})[\forall z(z < x \Rightarrow B(z)) \Rightarrow B(x)]$.

2.Assume that: $E(x) \equiv \forall z(z \leq x \Rightarrow B(z))$,then

3.$\forall z(z < x^{+} \Rightarrow B(z))$ it follows from 2 since $z \leq x \Rightarrow z < x^{+}$.

4.$\forall x(x \in \mathbb{N}^{\#})[\forall z(z < x^{+} \Rightarrow B(z)) \Rightarrow B(x^{+})]$ it follows from 1 by rule A4:if t is free for x in $B(x)$, then $\forall x B(x) \vdash B(t)$.

5. $B(x^{+})$ it follows from 3,4 by unrestricted MP rule.

6. $z \leq x^{+} \Rightarrow z < x^{+} \vee z = x^{+}$ it follows from definitions.

7. $z < x^{+} \Rightarrow B(z)$ it follows from 3 by rule A4.

8. $z = x^+ \Rightarrow B(z)$ it follows from 5.
9. $E(x^+) \equiv \forall z(z \leq x^+ \Rightarrow B(z))$ it follows from 6,7,8,rule Gen.
10.$\forall x(x \in \mathbb{N}^\#)[\forall z(z < x \Rightarrow B(z)) \Rightarrow B(x)] \vdash \forall x(x \in \mathbb{N}^\#)[E(x) \Rightarrow E(x^+)]$
it follows from 1,9 by deduction theorem,rule Gen.

Now by (i), (ii) and the induction axiom, we obtain $D \vdash \forall x(x \in \mathbb{N}^\#)E(x)$ that is $D \vdash \forall x(x \in \mathbb{N}^\#)[\forall z(z < x \Rightarrow B(z))]$, where $D \equiv \forall x(x \in \mathbb{N}^\#)[\forall z(z < x \Rightarrow B(z)) \Rightarrow B(x)]$.

Hence, by rule A4 twice, $D \vdash x \leq x \Rightarrow B(x)$. But $\vdash x \leq x$. So,$D \vdash B(x)$, and, by Gen and
the deduction theorem, $D \vdash \forall x(x \in \mathbb{N}^\#)B(x)$.

Theorem 7.2.(Complete hyperfinite induction) Let $B(x)$ be wff of the set theory $\mathrm{INC}^\#_{\infty^\#}$ strongly restricted on inductive set $W_{\mathbf{ind}}$ such that $\mathbb{N} \subseteq W_{\mathbf{ind}} \subsetneqq \mathbb{N}^\#$ then

$$\forall x(x \in W_{\mathbf{ind}})[\forall z(z < x \Rightarrow B(z)) \Rightarrow B(x)] \Rightarrow \forall x(x \in W_{\mathbf{ind}})B(x) \qquad (7.35)$$

Proof. Similarly as Theorem 7.1.

Remark 7.5.Remind that the following statement holds in standard bivalent arithmetic [11]:Least-number principle (LNP)

$$\exists x B(x) \Rightarrow \exists y[B(y) \wedge \forall z(z < y \Rightarrow \neg B(z))]. \qquad (7.36)$$

In ordinary language:if a property expressed by wff $B(x)$ holds for some natural number n,
then there is a least number satisfying $B(x)$.Obviously LNP (7.23) is not holds in nonstandard arithmetic, since there is no a least number in a set $\mathbb{N}^\# \backslash \mathbb{N}$.

Theorem 7.3.(Weak least-number principle) Let $B(x)$ be a wff of the set theory $\mathrm{INC}^\#_{\infty^\#}$ such that a wff $\neg B(x)$ strongly restricted on inductive set $W_{\mathbf{ind}}$ such that $\mathbb{N} \subseteq W_{\mathbf{ind}} \subsetneqq \mathbb{N}^\#$ and $W^{\complement}_{\mathbf{ind}} = \mathbb{N}^\# \backslash W_{\mathbf{ind}}$ then

$$\begin{gathered} \exists x\left(x \in W^{\complement}_{\mathbf{ind}}\right)B(x) \Rightarrow \\ \neg\exists y\left(y \in W^{\complement}_{\mathbf{ind}}\right)[B(y) \wedge \forall z(z < y \Rightarrow \neg B(z))] \Rightarrow \forall y(y \in W_{\mathbf{ind}})[\neg B(y)] \end{gathered} \qquad (7.37)$$

Proof.We assume now that
1.$\neg\exists y\left(y \in W^{\complement}_{\mathbf{ind}}\right)[B(y) \wedge \forall z(z < y \Rightarrow \neg B(z))]$
2.$\forall y\left(y \in W^{\complement}_{\mathbf{ind}}\right)\neg[B(y) \wedge \forall z(z < y \Rightarrow \neg B(z))]$ it follows from 1.
3.$\forall y\left(y \in W^{\complement}_{\mathbf{ind}}\right)[\forall z(z < y \Rightarrow \neg B(z)) \Rightarrow \neg B(y)]$it follows from 2 by tautology.
4.$\forall y(y \in W_{\mathbf{ind}})[\neg B(y)]$ it follows from 3 by Theorem 7.2 with wff $\neg B(y)$ instead wff $B(y)$
5.$\neg\exists y\left(y \in W^{\complement}_{\mathbf{ind}}\right)[B(y) \wedge \forall z(z < y \Rightarrow \neg B(z))] \Rightarrow \forall y(y \in W_{\mathbf{ind}})[\neg B(y)]$ it follows from 1,4.

Hyperinductive definitions in general.

A function $f : \mathbb{N}^\# \to A$ whose domain is the set $\mathbb{N}^\#$ is colled an hyperinfinite sequence and denoted by $\{f_n\}_{n \in \mathbb{N}^\#}$ or by $\{f(n)\}_{n \in \mathbb{N}^\#}$The set of all hyperinfinite sequences whose terms belong to A is clearly $A^{\mathbb{N}^\#}$; the set of all hyperfinite sequences of $n \in \mathbb{N}^\#$ terms in A is A^n. The set of all hyperfinite sequences with terms in A can be defined as

$$\left\{R \subset \mathbb{N}^\# \times A : (R \text{ is a function}) \wedge \bigvee\nolimits_{n \in \mathbb{N}^\#}(D_1(R) = n)\right\}, \qquad (7.38)$$

where $D_1(R)$ is domain of R.This definition implies the existence of the set of all hyperfinite sequences with terms in A.The simplest case is the inductive definition of a hyperinfinite sequence $\{\varphi(n)\}_{n\in\mathbb{N}^\#}$ (with terms belonging to a certain set Z) satisfying the following conditions:

(a) $\varphi(0) = z, \varphi(n^+) = e(\varphi(n), n),$

where $z \in Z$ and e is a function mapping $Z \times \mathbb{N}^\#$ into Z.

More generally, we consider a mapping f of the cartesian product $Z \times \mathbb{N}^\# \times A$ into Z and seek a function $\varphi \in Z^{\mathbb{N}^\# \times A}$ satisfying the conditions :

(b) $\varphi(0,a) = g(a), \varphi(n^+,a) = f(\varphi(n,a),n,a),$

where $g \in Z^A$. This is a definition by induction with parameter a ranging over the set A. Schemes (a) and (b) correspond to induction "from n to $n^+ = n+1$",i.e. $\varphi(n^+)$ or $\varphi(n^+,a)$ depends upon $\varphi(n)$ or $\varphi(n,a)$ respectively. More generally, $\varphi(n^+)$ may depend upon all values $\varphi(m)$ where $m \leq n$ (i.e. $m \in n^+$). In the case of induction with parameter, $\varphi(n^+,a)$ may depend upon all values $\varphi(m,a)$, where $m \leq n$; or even upon all values $\varphi(m,a)$, where $m \leq n^+$ and $b \in A$. In this way we obtain the following schemes of definitions by induction:

(c) $\varphi(0) = z, \varphi(n^+) = h(\varphi|n^+, n),$

(d) $\varphi(0,a) = g(a), \quad \varphi(n^+,a) = H(\varphi|(n^+ \times A), n, a).$

In the scheme (c), $z \in Z$ and $h \in Z^{C \times \mathbb{N}^\#}$, where C is the set of hyperfinite sequences whose terms belong to Z; in the scheme (d), $g \in Z^A$ and $H \in Z^{T \times \mathbb{N}^\# \times A}$, where T is the set of functions whose domains are included in $\mathbb{N}^\# \times A$ and whose values belong to Z.

It is clear that the scheme (d) is the most general of all the schemes considered above.

By coise of functions one obtains from (d) any of the schemes (a)-(d). For example, taking the function defined by $H(c,n,a) = f(c(n,a),n,a)$ for $a \in A, n \in \mathbb{N}^\#, c \in Z^{\mathbb{N}^\# \times A}$ as H in (d), one obtain (b). We shall now show that, conversely, the scheme (d) can be obtained from (a). Let g and H be functions belonging to Z^A and $Z^{T \times \mathbb{N}^\# \times A}$ respectively, and let φ be a function satisfying (d). We shall show that the sequence $\Psi = \{\Psi_n\}_{n\in\mathbb{N}^\#}$ with $\Psi_n = \varphi|(n^+,A)$ can be defined by (a).Obviously, $\Psi_n \in T$ for every $n \in \mathbb{N}^\#$. The first term of the sequence Ψ is equal to $\varphi|(0^+,A)$, i.e. to the set: $z^* = \{\langle\langle 0,a\rangle, g(a)\rangle | a \in A\}$.The relation between Ψ_n, and Ψ_{n^+} is given by the formula:$\Psi_{n^+} = \Psi_n \cup \varphi|(\{n^+\} \times A)$, where the second component is

$$\{\langle\langle n^+,a\rangle, \varphi(n^+,a)\rangle | a \in A\} = \{\langle n^+,a\rangle,, H(\Psi_n,n,a) | a \in A\}. \tag{7.39}$$

Thus we see that the sequence Ψ can be defined by (a) if we substitute T for Z, z^* for z and let $e(c,n) = c \cup \{\langle n^+,a\rangle, H(c,n,a) | a \in A\}$ for $c \in T$.

Now we shall prove the existence and uniqueness of the function satisfying (a). This theorem shows that we are entitled to use definitions by induction of the type (a). According to the remark made above, this will imply the existence of functions satisfying the formulas (b), (c), and (d). Since the uniqueness of such functions can be proved in the same manner as for (a), we shall use in the sequel definitions by induction of any of the types (a)-(d).

Theorem 7.4. If Z is any set $z \in Z$ and $e \in Z^{Z \times \mathbb{N}^\#}$, then there exists exactly one hyper sequence φ satisfying formulas (a).

Proof. Uniqueness. Suppose that $\{\varphi_1(n)\}_{n\in\mathbb{N}^\#}$ and $\{\varphi_2(n)\}_{n\in\mathbb{N}^\#}$ satisfy (a) and let

$$K = \{n | n \in \mathbb{N}^\# \wedge \varphi_1(n) = \varphi_2(n)\} \tag{7.40}$$

Then (a) implies that K is hyperinductive. Hence $\mathbb{N}^\# \subseteqq K$ and therefore $\varphi_1(n) \equiv \varphi_2(n)$.

Existence. Let $\Phi(z,n,t)$ be the formula $e(z,n) = t$ and let $\Psi(w,z,F)$ be the following formula:

$$(F \text{ is a function}) \wedge (D_1(F) = n^+) \wedge (F(0) = z) \wedge \bigwedge_{m \in n}(F(m), m, F(m^+)). \qquad (7.41)$$

In other words, F is a function defined on the set of numbers $\leq n \in \mathbb{N}^\#$ such that $F(0) = z$ and $F(m^+) = e(F(m), m)$ for all $m < n \in \mathbb{N}^\#$.

We prove by induction that there exists exactly one function F_n such that $\Psi(n, z, F_n)$. The proof of uniqueness of this function is similar to that given in the first part of Theorem 7.4. The existence of F_n can be proved as follows: for $n = 0$ it suffices to take $\{\langle 0, z\rangle\}$ as F_n; if $n \in \mathbb{N}^\#$ and F_n satisfies $\Psi(n, z, F_n)$, then $F_{n^+} = F_n \cup \{\langle n^+, e(F_n(n), n)\rangle\}$ satisfies the condition $\Psi(n^+, z, F_{n^+})$.

Now, we take as φ the set of pairs $\langle n, s\rangle$ such that $n \in \mathbb{N}^\#, s \in Z$ and

$$\bigvee_F [\Psi(n, z, F) \wedge (s = F(n))]. \qquad (7.42)$$

Since F is the unique function satisfying $\Psi(n, z, F)$, it follows that φ is a function. For $n = 0$ we have $\varphi(0) = F_0(0) = z$; if $n \in \mathbb{N}^\#$, then $\varphi(n^+) = F_{n^+}(n^+) = e(F_n(n), n)$ by the definition of F_n; hence we obtain $\varphi(n^+) = e(\varphi(0), n)$. Theorem 7.4 is thus proved.

We frequently define not one but several functions (with the same range Z) by a simultaneous induction:

$\varphi(0) = z, \qquad \psi(0) = t,$

$\varphi(n^+) = f(\varphi(n), \psi(n), n), \; \psi(n^+) = g(\varphi(n), \psi(n), n)$

where $z, t \in Z$ and $f, g \in Z^{Z \times Z \times N}$.

This kind of definition can be reduced to the previous one. It suffices to notice that the hypersequence $\vartheta_n = \langle \varphi(n), \psi(n)\rangle$ satisfies the formulas: $\vartheta_0 = \langle z, t\rangle, \vartheta_{n^+} = e(\vartheta_n, n),$ where we set

$$e(u, n) = \langle f(K(u), L(u), n), g(K(u), F(w), n)\rangle, \qquad (7.43)$$

and K, L denote functions such that $K(\langle x, y\rangle)$ and $L(\langle x, y\rangle) = y$ respectively. Thus the function ϑ is defined by induction by means of (a). We now define φ and ψ by $\varphi(n) = K(\vartheta_n), \psi(n) = L(\vartheta_n)$.

8.Useful examples of the hyperinductive definitions.

1.Addition operation of gypernatural numbers

The function $+(m, n) \triangleq m + n : \mathbb{N}^\# \times \mathbb{N}^\# \to \mathbb{N}^\#$ is defined by $m + 0 = m, m + n^+ = (m + n)^+$.

This definition is obtained from (b) by seting $Z = A = \mathbb{N}^\#, g(a) = a, f(p, n, a) = p^+$.

This function satisfies all properties of addition such as: for all $m, n, k \in \mathbb{N}^\#$

(i) $m + 0 = m$ (ii) $m + n = n + m$ (iii) $m + (n + k) = (m + n) + k$.

2.Multiplicattion operation of gypernatural numbers

The function $\times(m, n) \triangleq m \times n : \mathbb{N}^\# \times \mathbb{N}^\# \to \mathbb{N}^\#$ is defined by $m \times 1 = 1, m \times n^+ = m \times n + m$.

(i) $m \times 1 = 1$ (ii) $m \times n = n \times m$ (iii) $m \times (n \times k) = (m \times n) \times k$.

4.Distributivity with respect to multiplication over addition.

$m \times (n + k) = m \times n + m \times k$.

5. Let $Z = A = X^X, g(a) = I_X, f(u, n, a) = u \circ a$ in (b). Then (b) takes on the following form

$$\varphi(0, a) = I_X, \varphi(n^+, a) = \varphi(n, a) \circ a. \qquad (8.1)$$

The function $\varphi(n, a)$ is denoted by a^n and is colled n-th iteration of the function a :

$$a^0(x) = x, a^{n^+}(x) = a^n(a(x)), x \in X, a \in X^X, n \in \mathbb{N}^\#. \tag{8.2}$$

6.Let $A = (\mathbb{N}^\#)^{\mathbb{N}^\#}, g(a) = a_0, f(u,n,a) = u + a_{n^+}$. Then (b) takes on the following form

$$\varphi(0,a) = a_0, \varphi(n^+,a) = \varphi(n,a) + a_{n^+} \tag{8.3}$$

The function is defined by the Eqs.(8.3) is denoted by

$$\sum_{i=0}^{n} a_i \tag{8.4}$$

7.Let $A = (\mathbb{N}^\#)^{\mathbb{N}^\#}, g(a) = a_0, f(u,n,a) = u \times a_{n^+}$. Then (b) takes on the following form

$$\varphi(0,a) = a_0, \varphi(n^+,a) = \varphi(n,a) \times a_{n^+} \tag{8.5}$$

The function is defined by the Eqs.(8.5) is denoted by

$$\prod_{i=0}^{n} a_i \tag{8.6}$$

8. Similarly we define $\max_{i \leq n}(a_i), \min_{i \leq n}(a_i), n \in \mathbb{N}^\#$.

Theorem 8.1. The following equalities holds for any $n, k_1, l_1 \in \mathbb{N}^\#$:

(1) using distributivity

$$b \times \sum_{i=0}^{n} a_i = \sum_{i=0}^{n} b \times a_i \tag{8.7}$$

(2) using commutativity and associativity

$$\sum_{i=0}^{n} a_i \pm \sum_{i=0}^{n} b_i = \sum_{i=0}^{n} (a_i \pm b_i) \tag{8.8}$$

(3) splitting a sum, using associativity

$$\sum_{i=0}^{n} a_i = \sum_{i=0}^{j} a_i + \sum_{i=j+1}^{n} a_i \tag{8.9}$$

(4) using commutativity and associativity, again

$$\sum_{i=k_0}^{k_1} \sum_{j=l_0}^{l_1} a_{ij} = \sum_{j=l_0}^{l_1} \sum_{i=k_0}^{k_1} a_{ij} \tag{8.10}$$

(5) using distributivity

$$\left(\sum_{i=0}^{n} a_i\right) \times \left(\sum_{j=0}^{n} b_j\right) = \sum_{i=0}^{n} \sum_{j=0}^{n} a_i \times b_j \tag{8.11}$$

(6)

$$\left(\prod_{i=0}^{n} a_i\right) \times \left(\prod_{i=0}^{n} b_i\right) = \prod_{i=0}^{n} a_i \times b_i \tag{8.12}$$

(7)

$$\left(\prod_{i=0}^{n} a_i\right)^m = \prod_{i=0}^{n} a_i^m \tag{8.13}$$

Proof. Imediately from Theorem 7.4 and hyperinfinite induction principle.

Definition 8.1.A non-empty non regular sequence $\{u_n\}_{n \in \mathbb{Z}}$ is a blok corresponding to gyperfinite number $u = u_0 \in \mathbb{N}^\# \backslash \mathbb{N}$ iff there is gyperfinite number u such that $\ldots \in u_{-(n+1)} \in u_{-n} \ldots \in u_{-4} \in u_{-3} \in u_{-2} \in u_{-1} \in u$ and the following conditions are satisfied

$$\ldots\in u_{-(n+1)} \in u_{-n}\ldots\in u_{-4} \in u_{-3} \in u_{-2} \in u_{-1} \in u \in u_1 \in u_2 \in\ldots\in u_n \in u_{n+1} \in\ldots \quad (8.14)$$

where for any $n \in \mathbb{N}$: $u_{-(n+1)} \in u_{-n}$, where $u_{-n} = u^{+}_{-(n+1)}$.

Thus beginning with an infinite integer $u \in \mathbb{N}^{\#}\backslash\mathbb{N}$ we obtain a block (8.20) of infinite integers.However, given a “block,” there is another block consisting of even larger infinite integers. For example, there is the integer $u+u$, where $u+k < u+u$ for each $k \in \mathbb{N}$. And $v = u+u$ is itself part of the block:

$$\ldots< v-3 < v-2 < v-1 < v < v+1 < v-2 <\ldots \quad (8.15)$$

Of course, $v < v+u < v+v$, and so forth. There are even infinite integers $u \times u$ and u^u, and so forth.Proceeding in the opposite direction, if $u \in \mathbb{N}^{\#}\backslash\mathbb{N}$, either u or $u+1$ is of the form $v+v$. Here v must be infinite. So there is no first block, since $v < u$. In fact, the ordering of the blocks is dense. For let the block containing v precede the one containing u, that is,

$v-2 < v-1 < v < v+1 <\ldots<\ldots< u-2 < u-1 < u < u+1 <\ldots \quad (8.16)$ Either $u+v$ or $u+v+1$ can be written $z+z$ where $v+k < z < u-l$ for all $k,l \in \mathbb{N}$.

To conclude our consideration: $\mathbb{N}^{\#}$ consists of $\mathbb{N}$ as an initial segment followed by an ordered set of blocks. These blocks are densely ordered with no first or last element. Each block is itself order-isomorphic to the integers

$$-3,-2,-1,0,1,2,3, \quad (8.17)$$

Although $\mathbb{N}^{\#}\backslash\mathbb{N}$ is a nonempty subset of $\mathbb{N}^{\#}$, as we have just seen it has no least element and likewise for any block.

9.Analisys on nonarchimedian field $\mathbb{Q}^{\#}$.

9.1.Basic properties of the hyperrationals $\mathbb{Q}^{\#}$.

Now that we have the hypernatural numbers, defining hyperintegers and hyperrational numbers is well within reach.

Definition 9.1. Let $Z' = \mathbb{N}^{\#} \times \mathbb{N}^{\#}$. We can define an equivalence relation $\approx$ on Z' by $(a,b) \approx (c,d)$ if and only if $a+d = b+c$. Then we denote the set of all hyperintegers by $\mathbb{Z}^{\#} = Z'/\approx$ (The set of all equivalence classes of Z' modulo $\approx$).

Definition 9.2. Let $Q' = \mathbb{Z}^{\#} \times (\mathbb{Z}^{\#} - \{0\}) = \{(a,b) \in \mathbb{Z}^{\#} \times \mathbb{Z}^{\#} | b \neq 0\}$. We can define an equivalence relation $\approx$ on Q' by $(a,b) \approx (c,d)$ if and only if $a \times d = b \times c$.Then we denote the set of all hyperrational numbers by $\mathbb{Q}^{\#} = Q'/\approx$ (The set of all equivalence classes of Q' modulo $\approx$).

Definition 9.3. A linearly ordered set $(P,<)$ is called dense if for any $a,b \in P$ such that $a < b$, there exists $z \in P$ such that $a < z < b$.

Lemma 9.1. $(\mathbb{Q}^{\#},<)$ is dense.

Proof. Let $x = (a,b), y = (c,d) \in \mathbb{Q}^{\#}$ be such that $x < y$.Consider $z = (ad+bc, 2bd) \in \mathbb{Q}^{\#}$.

It is easily shown that $x < z < y$.

Remark 9.1.Consider the ring B of all limited (i.e. finite) elements in $\mathbb{Q}^{\#}$. Then B has a unique maximal ideal $I_{\approx}$, the infinitesimal numbers. The quotient ring $B/I_{\approx}$ gives the field

$\mathbb{R}$ of the classical real numbers.

1.Let $A = (\mathbb{Q}^{\#})^{\mathbb{Q}^{\#}}, g(a) = a_0, f(u,n,a) = u + a_{n^+}$. Then (b) takes on the following form

$$\varphi(0,a) = a_0, \varphi(n^+,a) = \varphi(n,a) + a_{n^+} \tag{9.1}$$

The function is defined by the Eqs.(9.1) is denoted by

$$\sum_{i=0}^{n} a_i. \tag{9.2}$$

2.Let $A = (\mathbb{Q}^{\#})^{\mathbb{Q}^{\#}}, g(a) = a_0, f(u,n,a) = u \times a_{n^+}$. Then (b) takes on the following form

$$\varphi(0,a) = a_0, \varphi(n^+,a) = \varphi(n,a) \times a_{n^+} \tag{9.3}$$

The function is defined by the Eqs.(9.3) is denoted by.

$$\prod_{i=0}^{n} a_i. \qquad (9.3)$$

9.2.Countable summation from gyperfinite sum.

Definition 9.1. Let $\{a_n\}_{n\in\mathbb{N}}$ be $\mathbb{Q}^{\#}$-valued countable sequence. Let $\{a_n\}_k^m$ be any hyperfinite sequence with $m \in \mathbb{N}^{\#}\backslash\mathbb{N}$ and such that $a_n = 0$ if $n \in \mathbb{N}^{\#}\backslash\mathbb{N}$. Then we define summation of the countable sequence $\{a_n\}_{n\in\mathbb{N}}$ by the following hyperfinite summ

$$\sum_{n=k}^{m} a_n \in \mathbb{Q}^{\#} \tag{9.4}$$

and denote such summ by the symbol

$$\sum_{n=k}^{\omega} a_n. \tag{9.5}$$

Remark 9.2. Let $\{a_n\}_{n\in\mathbb{N}}$ be $\mathbb{Q}$-valued countable sequence. Note that: (i) for canonical summation we always apply standard notation

$$\sum_{n=k}^{\infty} a_n. \tag{9.6}$$

(ii) the countable summ (ω-summ) (9.5) in contrast with (9.6) abviously always exists even if a series (9.6) diverges absolutely i.e., $\sum_{n=k}^{\infty} |a_n| = \infty$.

Example 9.1. The ω-summ $\sum_{n=1}^{\omega} \frac{1}{n} \in \mathbb{Q}^{\#}$ exists by Theorem 8.1, however $\sum_{n=1}^{\infty} \frac{1}{n} = \infty$.

Theorem 9.3. Let $\sum_{n=k}^{\omega} a_n = A$ and $\sum_{n=k}^{\omega} b_n = B$, where $A, B, C \in \mathbb{Q}^{\#}$. Then

$$\sum_{n=k}^{\omega} C \times a_n = C \times \sum_{n=k}^{\omega} a_n \qquad (9.6)$$

and

$$\sum_{n=k}^{\omega} (a_n \pm b_n) = A \pm B. \tag{9.7}$$

Proof. It follows from Theorem 8.2.

Example 9.2. Consider the countable summ

$$S_\omega(r) = \sum_{n=0}^{\omega} r^n, -1 < r < 1. \quad (9.5)$$

It follows from (9.5)

$$S_\omega(r) = 1 + \sum_{n=1}^{\omega} r^n = 1 + r\sum_{n=0}^{\omega} r^n = 1 + rS_\omega(r) \quad (9.6)$$

Thus

$$S_\omega(r) = \frac{1}{1-r}. \quad (9.7)$$

Remark 9.3. Note that

$$S_\omega(r) = \sum_{n=0}^{\omega} r^n = \sum_{n=0}^{\infty} r^n \quad (9.8)$$

since as we know

$$S_\infty(r) = \lim_{n\to\infty} \sum_{n=0}^{n} r^n = \sum_{n=0}^{\infty} r^n = \frac{1}{1-r}. \quad (9.9)$$

10.Euler's proof of the Goldbach-Euler theorem revisited.

Theorem 10.1. (Goldbach-Euler theorem 1738)[]. This infinite series, continued to infinity,

$$\frac{1}{3} + \frac{1}{7} + \frac{1}{8} + \frac{1}{15} + \frac{1}{24} + \frac{1}{26} + \frac{1}{31} + \frac{1}{35} + \ldots \quad (10.1)$$

the denominators of which are all numbers which are one less than powers of degree two or higher of whole numbers, that is, terms which can be expressed with the formula $(m^n - 1)^{-1}$, where m and n are integers greater than one, then the sum of this series is $= 1$.

10.1.How Euler did it.

Euler's proof begins with an $18^{\underline{\text{th}}}$ century step that treats any infinite sum as a real number which may be infinite large. Such steps became unpopular among rigorous mathematicians about a hundred years later.

Euler takes Σ to be the sum of the harmonic series

$$\Sigma = \sum_{n=1}^{\infty} \frac{1}{n} = 1 + \frac{1}{2} + \frac{1}{3} + \frac{1}{4} + \frac{1}{5} + \frac{1}{6} + \frac{1}{7} + \frac{1}{8} + \frac{1}{9} + \ldots. \quad (10.2)$$

Next, Euler subtracts from Eq.(10.2) the geometric series

$$1 = \sum_{n=1}^{\infty} \frac{1}{2^n} = \frac{1}{2} + \frac{1}{4} + \frac{1}{8} + \frac{1}{16} + \frac{1}{32} + \ldots \quad (10.3)$$

leaving

$$\Sigma - 1 = 1 + \frac{1}{3} + \frac{1}{5} + \frac{1}{6} + \frac{1}{7} + \frac{1}{9} + \frac{1}{10} + \ldots \quad (10.4)$$

Subtract from Eq.(10.4) geometric series

$$\frac{1}{2} = \frac{1}{3} + \frac{1}{9} + \frac{1}{27} + \frac{1}{81} + \frac{1}{243} + \ldots \quad (10.5)$$

leaving

$$\Sigma - 1 - \frac{1}{2} = 1 + \frac{1}{5} + \frac{1}{6} + \frac{1}{7} + \frac{1}{10} + \frac{1}{11} + \ldots \tag{10.6}$$

Subtract from Eq.(10.6) geometric series

$$\frac{1}{4} = \frac{1}{5} + \frac{1}{25} + \frac{1}{125} + \ldots \tag{10.7}$$

leaving

$$\Sigma - 1 - \frac{1}{2} - \frac{1}{4} = 1 + \frac{1}{6} + \frac{1}{7} + \frac{1}{10} + \ldots \tag{10.8}$$

Remark 9.1.Note that Euler had to skip subtracting the geometric series

$$\frac{1}{3} = \frac{1}{4} + \frac{1}{16} + \frac{1}{64} + \frac{1}{256} + \ldots \tag{10.9}$$

because the series of powers of $1/4$ on the right is already a subseries of the series of powers of $1/2$, so those terms have already been subtracted. This happens because 3 is one less than a power, 4. It happens again every time we reach a term one less than a power. He will have to skip 7, because that is one less than the cube 8, and 8 because it is one less than the square 9, 15 because it is one less than the square 16, etc. Continuing formally in this way to infinity, we see that all of the terms on the right except the term 1 can be eliminated, leaving

$$\Sigma - 1 - \frac{1}{2} - \frac{1}{4} - \frac{1}{5} - \frac{1}{6} - \frac{1}{9} - \ldots = 1. \tag{10.10}$$

Thus

$$\Sigma - 1 - \left[\frac{1}{2} + \frac{1}{4} + \frac{1}{5} + \frac{1}{6} + \frac{1}{9} + \frac{1}{10} + \ldots \right] = 1 \tag{10.11}$$

so

$$\Sigma - 1 = 1 + \frac{1}{2} + \frac{1}{4} + \frac{1}{5} + \frac{1}{6} + \frac{1}{9} + \frac{1}{10} + \ldots \tag{10.12}$$

Remark 10.2.Note that it gets just a little bit tricky. Since Σ is sum of the harmonic series, Euler believes that the 1 on the left must equal the terms of the harmonic series that are missing on the right. Those missing terms are exactly the ones with denominators one less than powers, so finally Euler concludes that

$$1 = \frac{1}{3} + \frac{1}{7} + \frac{1}{8} + \frac{1}{15} + \frac{1}{24} + \frac{1}{26} + \frac{1}{31} + \frac{1}{35} + \ldots \tag{10.13}$$

where the terms on the right have denominators one less than powers.

10.2. Proof of the Goldbach-Euler theorem using canonical analysis.

We reproduce the proof here for the sake of completeness.

Lemma 1. For any positive integers n and k with $2 \leq n < k$
$1/n - 1 = 1/(n-1)n + 1/n(n+1) + \cdots + 1/(k-1)k + 1/k$
Lemma 2. For any positive integers n and k with $n \geq 2$
$1/n - 1 = 1/n + 1/n^2 + \cdots + 1/n^k + 1/n^k(n-1)$
We let denote the n-th harmonic number by H_n :

$$H_n = 1 + 1/2 + 1/3 + \ldots + 1/n, \tag{10.14}$$

but we now think of n as either a finite natural number or an infinite nonstandard natural number. Let k_2 be defined by $2^{k_2} \leq n < 2^{k_2+1}$. The existence and uniqueness of k_2 is clear either if we think of n as a finite natural number or as a nonstandard natural number: remember the transfer principle. Using Lemma 2, we can write

$$1 = 1/2 + 1/2^2 + 12^3 + \cdots + 1/2^{k_2} + 1/2^{k_2} \cdot 1,$$

and subtracting this series from (9.14), we obtain

$$H_n - 1 = 1 + 1/3 + 1/5 + 1/6 + 1/7 + 1/9 + \cdots + 1/n - 1/2^{k_2} \cdot 1. \qquad (10.15)$$

Hence, all powers of two, including two itself, disappear from the denominators, leaving the rest of integers up to n. If from (10.15) we subtract

$$1/2 = 1/3 + 13^2 + 1/3^3 + \cdots + 1/3^{k_3} + 1/3^{k_3} \cdot 2, \qquad (10.16)$$

again obtained from Lemma 2 with k_3 defined by $3^{k_3} \leq n < 3^{k_3+1}$, the result will be

$$H_n - 1 - 1/2 = 1 + 1/5 + 1/6 + 1/7 + 1/10 + \cdots + 1/n - [1/2^{k_2} \cdot 1 + 1/3^{k_3} \cdot 2]. \qquad (10.17)$$

Proceeding similarly we end up by deleting all the terms that remain,arriving finally at

$$\begin{aligned} H_n - 1 - 1/2 - 1/4 - 1/5 - 1/6 - 1/7 - 1/10 - \cdots - 1/n &= \\ = 1 - [1/2^{k_2} \cdot 1 + 1/3^{k_3} \cdot 2 + \cdots + 1/n \cdot (n-1)]. \end{aligned} \qquad (10.18)$$

Notice that $k_2 \geq k_3 \geq \cdots$.In fact,when $m > \sqrt{n}$ we get $k_m = 1$. This last expression has been obtained assuming that n is a nonpower. If n is a power, then $1/n$ will have disappeared at some stage of this process,and the last fraction to beremoved from(10.17) will be $1/(n-1)$, whose denominator is a nonpower unless $n = 9$. (This is Catalan's conjecture that 8 and 9 are the only consecutive powers that exist. The conjecture was recently proved by Mihăilescu []. In fact, it does not matter here whether there are more consecutive powers or not.) The corresponding expression will thus be

$$\begin{aligned} H_n - 1 - 1/2 - 1/4 - 1/5 - 1/6 - 1/7 - 1/10 - \cdots - 1/n - 1 \\ = 1 - [1/2^{k_2} \cdot 1 + 1/3^{k_3} \cdot 2 + \cdots + 1/(n-1) \cdot (n-2)]. \end{aligned} \qquad (10.19)$$

Consequently, if we subtract (10.18) from (10.14) we obtain

$$\begin{aligned} 1 - [1/2^{k_2} \cdot 1 + 1/3^{k_3} \cdot 2 + \cdots + 1/n \cdot (n-1)] &= \\ 1/3 + 1/7 + 1/8 + 1/15 + 1/24 + 1/26 + \cdots + 1/n - 1 \end{aligned} \qquad (10.20)$$

or, correspondingly subtracting (10.19) from (10.14),

$$\begin{aligned} 1 - [12k_2 \cdot 1 + 13k_3 \cdot 2 + \cdots + 1/(n-1)(n-2)] &= \\ 1/3 + 1/7 + 1/8 + 1/15 + 1/24 + 1/26 + \cdots + 1/n, \end{aligned} \qquad (10.21)$$

sums that containin their denominators,increased by one,all the power so fthe integers up to n. We must now take care of the “remainder,” that is, the expression between parentheses above or on the right-hand side of (10.17) (respectively, (10.19)).

Since for each $m \geq 2$ we know by the definition of km that $n < m^{k_m+1} \leq m^{2k_m}$, it follows that $\sqrt{n} < m^{k_m}$ and

$$1/[m^{k_m} \cdot (m-1)] \leq 1/\sqrt{n}\,(m-1). \qquad (10.22)$$

This implies that

$$1/2^{k_2} \cdot 1 + 1/3^{k_3} \cdot 2 + \cdots + 1/n \cdot (n-1) \leq H_{n-1}/\sqrt{n} \qquad (10.23)$$

or, if n is a power,

$$1/2^{k_2}\cdot 1+1/3^{k_3}\cdot 2+\cdots+1/(n-1)\cdot(n-2)\leq H_{n-2}/\sqrt{n-1}. \qquad (10.24)$$

If we have chosen to regard n as a finite integer then we can pass to the limit and use Euler's asymptotic value for H_n : $\lim_{n\to\infty}H_{n-1}/\sqrt{n} = \lim_{n\to\infty}[\log(n-1)+\gamma]/\sqrt{n} = 0.$ The proof is now complete.

10.3.Euler proof revisited using elementary analysis on nonarchimedian field $\mathbb{Q}^{\#}$.

We replace Eq.(10.2) by

$$\Sigma_\omega = \sum_{n=1}^{\omega}\frac{1}{n} = \left[1+\frac{1}{2}+\frac{1}{3}+\frac{1}{4}+\frac{1}{5}+\frac{1}{6}+\frac{1}{7}+\frac{1}{8}+\frac{1}{9}+\ldots.\right]^{\#} \qquad (10.22)$$

Remark 10.3.Note that $\Sigma_\omega \in \mathbb{Q}^{\#}\backslash\mathbb{Q}$.

Subtract from Eq.(10.22) the ω-summ

$$1 = \sum_{n=1}^{\omega}\frac{1}{2^n} = \left[\frac{1}{2}+\frac{1}{4}+\frac{1}{8}+\frac{1}{16}+\frac{1}{32}+\ldots\right]^{\#} \qquad (10.23)$$

using Theorem 9.3 we obtain

$$\begin{aligned}\Sigma_\omega - 1 &= \left[1+\frac{1}{2}+\frac{1}{3}+\frac{1}{4}+\frac{1}{5}+\frac{1}{6}+\frac{1}{7}+\frac{1}{8}+\frac{1}{9}+\ldots.\right]^{\#} - \\ &-\left[\frac{1}{2}+\frac{1}{4}+\frac{1}{8}+\frac{1}{16}+\frac{1}{32}+\ldots\right]^{\#} = \\ &\left[1+\frac{1}{3}+\frac{1}{5}+\frac{1}{6}+\frac{1}{7}+\frac{1}{9}+\frac{1}{10}+\ldots\right]^{\#}.\end{aligned} \qquad (10.24)$$

Subtract from Eq.(10.24) the ω-summ

$$\frac{1}{2} = \sum_{n=1}^{\omega}\frac{1}{3^n} = \left[\frac{1}{3}+\frac{1}{9}+\frac{1}{27}+\frac{1}{81}+\frac{1}{243}+\ldots\right]^{\#} \qquad (10.25)$$

using Theorem 9.3 we obtain

$$\begin{aligned}\Sigma_\omega - 1 - \frac{1}{2} &= \left[1+\frac{1}{3}+\frac{1}{5}+\frac{1}{6}+\frac{1}{7}+\frac{1}{9}+\frac{1}{10}+\ldots\right]^{\#} - \\ &-\left[\frac{1}{3}+\frac{1}{9}+\frac{1}{27}+\frac{1}{81}+\frac{1}{243}+\ldots\right]^{\#} = \\ &= \left[1+\frac{1}{5}+\frac{1}{6}+\frac{1}{7}+\frac{1}{10}+\frac{1}{11}+\ldots\right]^{\#}.\end{aligned} \qquad (10.26)$$

Subtract from Eq.(10.26) the ω-summ

$$\frac{1}{4} = \left[\frac{1}{5}+\frac{1}{25}+\frac{1}{125}+\ldots\right]^{\#} \qquad (10.27)$$

using Theorem 9.3 we obtain

$$\Sigma_\omega - 1 - \frac{1}{2} - \frac{1}{4} = \left[1+\frac{1}{6}+\frac{1}{7}+\frac{1}{10}+\ldots\right]^{\#} \qquad (10.28)$$

Remark 10.4.Note that in calculation above we had skip subtracting the ω-summ (see Remark 9.1)

$$\frac{1}{3} = \left[\frac{1}{4}+\frac{1}{16}+\frac{1}{64}+\frac{1}{256}+\ldots\right]^{\#} \qquad (10.29)$$

because the series of powers of $1/4$ on the right is already a subseries of the ω-summ (10.23) of powers of $1/2$, so those terms have already been subtracted. This happens because 3 is one less than a power, 4. It happens again every time we reach a term one less than a power. He will have to skip 7, because that is one less than the cube 8, and 8 because it is one less than the square 9, 15 because it is one less than the square 16, etc. Continuing in this way to an gyperfinite number $m \in \mathbb{Q}^{\#} \backslash \mathbb{Q}$ by using gyperfinite induction principle, we see that all of the terms on the right except the term 1 can be eliminated, leaving

$$\left[\Sigma_{\omega} - 1 - \frac{1}{2} - \frac{1}{4} - \frac{1}{5} - \frac{1}{6} - \frac{1}{9} - \frac{1}{10} - \ldots\right]^{\#} = 1. \tag{10.30}$$

Thus by Theorem 9.3 we obtain

$$\Sigma - 1 - \left[\frac{1}{2} + \frac{1}{4} + \frac{1}{5} + \frac{1}{6} + \frac{1}{9} + \frac{1}{10} + \ldots\right]^{\#} = 1. \tag{10.31}$$

Finally we get

$$1 = \left[\frac{1}{3} + \frac{1}{7} + \frac{1}{8} + \frac{1}{15} + \frac{1}{24} + \frac{1}{26} + \frac{1}{31} + \frac{1}{35} + \ldots\right]^{\#}, \tag{10.32}$$

where the terms on the right have denominators one less than powers.

Note that Eq.(10.32) now is obtained without any references to Catalan conjecture [13],[14].

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