

## A MARRIAGE OF BROUWER'S INTUITIONISM AND HILBERT'S FINITISM I: ARITHMETIC

TAKAKO NEMOTO AND SATO KENTARO

**Abstract.** We investigate which part of Brouwer's Intuitionistic Mathematics is finitistically justifiable or guaranteed in Hilbert's Finitism, in the same way as similar investigations on Classical Mathematics (i.e., which part is equiconsistent with **PRA** or consistent provably in **PRA**) already done quite extensively in proof theory and reverse mathematics. While we already knew a contrast from the classical situation concerning the continuity principle, more contrasts turn out: we show that several principles are finitistically justifiable or guaranteed which are classically not. Among them are: (i) fan theorem for decidable fans but arbitrary bars; (ii) continuity principle and the axiom of choice both for arbitrary formulae; and (iii)  $\Sigma_2$  induction and dependent choice. We also show that Markov's principle MP does not change this situation; that neither does lesser limited principle of omniscience LLPO (except the choice along functions); but that limited principle of omniscience LPO makes the situation completely classical.

### §1. Introduction.

**1.1. Brouwer's Intuitionism and Hilbert's Finitism.** *Brouwer's Intuitionism* is considered as the precursor of many varieties of constructivism and finitism which reject the law of excluded middle (LEM) for statements concerning infinite objects. It is said that even Hilbert, a most severe opponent of Brouwer's, adopted a part of Brouwer's idea in his proposal for meta-mathematics or proof theory, and this partial adoption is now called *Hilbert's Finitism*. However, there are several essential differences between these two varieties of constructivism or finitism.

First, they are different in their original aims. Brouwer's Intuitionism is a claim how mathematics in its entirety should be, and the mathematics practiced according to this is called *Intuitionistic Mathematics* (INT). On the other hand,

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Hilbert's Finitism was intended to apply only to a particular part of mathematics, called *proof theory* or *meta-mathematics*. The aim of this part was "saving" the entirety of mathematics from the fear of inconsistency. The "entirety of mathematics" in Hilbert's idea is far beyond finitism and now called *Classical Mathematics* (CLASS) in the context of comparison among kinds of mathematics.

This difference might explain why Hilbert's Finitism is stricter than Brouwer's Intuitionism: for example, the induction schema on numbers is granted for free in the latter whereas it is allowed only if restricted to finitely checkable statements in the former. The acceptance of the schema for properties not finitely checkable (even though LEM for such properties is not allowed) seems to be reason enough not to call Brouwer's Intuitionism a finitism, and moreover it requires transcendental assumptions which basically assert that everything is to be constructed (cf. the notion of *choice sequence*) contradicting CLASS.

It is worth mentioning Bishop's constructivism, a third variety of constructivism. *Bishop-style constructive mathematics* (BISH) is considered to be completely constructive, in the sense that it does not assume any transcendental assertion. Thus all the theorems of BISH, as formal sentences, are contained in those of CLASS and INT. Nonetheless, it does not seem plausible to call it a finitism either, for it also accepts the induction schema applied to properties not finitely checkable. It accepts the axiom of choice applied to such properties as well, which is also beyond the finitistically justifiable part of CLASS.

Another contrast between Brouwer and Hilbert is in their attitudes towards formalization: while Brouwer did not formalize INT, Hilbert tried to formalize CLASS and since then his Finitism (now identified with what is formalizable in *Primitive Recursive Arithmetic* **PRA**; see [41]) has been established as the meta-theory of handling formalization, or, in which proof theory is practiced. This contrast has, however, been gradually losing significance: followers of Brouwer formalized INT, and now our interest is in how different it is, as a formal theory,<sup>1</sup> from CLASS and from BISH as well as from *Russian Recursive Mathematics* RUSS. The last requires a different transcendental assumption asserting that everything is computable.

Unfortunately a difference is also in popularity: CLASS has been investigated extensively, e.g., identifying the finitistically secured part, while there seems to have been no similar systematic investigation for INT.

Given these contrasts, the aim of the present series of articles, the identification of the part of INT and addable axioms that Hilbert would recognize as secured, has multi-fold motivations. To repeat: from the viewpoint that Brouwer's Intuitionism is the precursor of various kinds of constructivism and finitism; from the historical perspective that Brouwer and Hilbert were severe opponents of each other; and from the necessity of the identification as has been done for CLASS in order to develop INT in parallel to CLASS.

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<sup>1</sup>"Intuitionism as an opponent of formalism" is also a quite interesting topic, which has not yet been investigated enough so far. For instance, in the authors' opinion, Brouwer's original proof of bar induction should be analyzed from this viewpoint.

**1.2. Reducibility and interpretability.** By what criterion would Hilbert recognize a fragment of mathematics as secured according to his Finitism? We may distinguish two criteria: a fragment is said to be (i) *finitistically guaranteed* if it is consistent provably in **PRA**; and (ii) *finitistically justifiable* if it is consistent relative to **PRA** provably in **PRA**. It is likely that these were not distinguished in Hilbert's original intention prior to Gödel's incompleteness theorem.

Proof theory, to which Hilbert's Finitism was originally intended to apply, has refined (ii) above (see [30, Section 2.5]): a formal theory  $T_1$  is (*proof theoretically*) *reducible* to another  $T_2$  over a class  $\mathcal{C}$  of sentences if there is a primitive recursive function  $f$  such that provably within **PRA**, for any sentence  $A$  from  $\mathcal{C}$ , if  $x$  is a proof of  $A$  in  $T_1$  then  $f(x)$  is a proof of  $A$  in  $T_2$ . Usually  $\mathcal{C}$  contains the absurdum  $\perp$  and so this notion yields the comparison of *externally defined consistency strengths* (namely, the consistency of  $T_2$  implies that of  $T_1$  or consistency-wise implication) provably in **PRA**. In many interesting cases, the theories essentially contain a fragment of arithmetic and we can assume  $\mathcal{C}$  includes  $\Pi_1^0$  or  $\Pi_2^0$  sentences. As the Gödel sentence (of a reasonable theory) is  $\Pi_1^0$ , it also yields the comparison of *internally defined consistency strength*: any reasonable formal theory consistent provably in  $T_1$  is consistent provably also in  $T_2$ . Now **IS**<sub>1</sub>, **RCA**<sub>0</sub> and **WKL**<sub>0</sub> are parts of Classical Mathematics that are known to be proof theoretically reducible to **PRA**. As a subtheory is trivially reducible to a supertheory, these four theories are *proof theoretically equivalent*.

For our purposes, however, we can use a stronger notion, interpretability. We will prove reducibility results by giving concrete interpretations, among which are Gödel–Gentzen negative interpretation and realizability interpretation. Our notion of interpretability is slightly broader than that in some literature, in the sense that logical connectives can be interpreted non-trivially (as in the aforementioned examples).<sup>2</sup> An interpretation  $I$  is called  *$\mathcal{C}$ -preserving*, if any  $\mathcal{C}$  sentence  $A$  is implied by its interpretation  $A^I$  in the interpreting theory  $T_2$ . All interpretations in the present article are  $\Pi_1^0$ -preserving, and so imply reducibility with  $\mathcal{C} = \Pi_1^0$ . Whereas reducibility concerns only proofs ending with sentences in  $\mathcal{C}$ , interpretability means that all mathematical practice formalized in one theory can be simulated in another. As each step of proofs in  $T_1$  is transformed into a uniformly bounded number of steps in  $T_2$ , the induced transformation  $f$  of proofs belongs to even lower complexity, and so the consistency-wise implication is proved in meta-theories weaker than **PRA**.

The difference between reducibility and interpretability becomes essential when we talk about the relations between finitistically guaranteed theories (hence weaker than **PRA**): while the reducibility is proved typically by cut elimination, which requires commitment to superexponential functions, such a commitment

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<sup>2</sup>We could give a tentative definition: a map  $I$  from  $\mathcal{L}_1$  to  $\mathcal{L}_2$  is an *interpretation* of an  $\mathcal{L}_1$ -theory  $T_1$  in an  $\mathcal{L}_2$ -theory  $T_2$  iff (a)  $T_2 \vdash \perp^I \rightarrow \perp$ , (b)  $T_2 \vdash A^I$  for any axiom  $A$  of  $T_1$ , and (c) there is a polynomial-time computable function  $p$  such that if  $C$  is from  $A, B$  by a *single* logical rule then  $p(A, B, C)$  is a *derivation* of  $C^I$  from  $A^I, B^I$  in  $T_2$ . However, we will not need such a definition but only basic properties that the word suggests (and which follow from the definition above): (i) a composition of interpretations is an interpretation; (ii) all those we will define with name “interpretation” in this article are interpretations and (iii) the existence of a  $\mathcal{C}$ -preserving interpretation implies both  $\mathcal{C}$  conservation provable in **BS**<sub>1</sub>**ex** and the reducibility over  $\mathcal{C}$ .

yields the consistency of  $\mathbf{BS}_1\mathbf{ex}$ ,  $\mathbf{RCA}_0^*$  and  $\mathbf{WKL}_0^*$ , typical finitistically guaranteed theories, and so collapses the hierarchy of the externally defined consistency strengths of such weaker theories.

**1.3. Characteristic axioms of Intuitionistic Mathematics.** Up to the present, there seems to be a consensus on what axiomatizes (the characteristic part of) INT. An informal explanation of such characterizing axioms is as follows, where the terminology might differ from Brouwer's original.

**Intuitionistic logic** neither the law of excluded middle ( $A \vee \neg A$ ) nor double negation elimination ( $\neg\neg A \rightarrow A$ ) is accepted unless  $A$  is finitely checkable (while the explosion axiom  $\perp \rightarrow A$  is accepted);

**Basic arithmetic** basic properties which are finitely checkable and which govern the natural numbers and fundamental operations, are accepted;

**Induction on natural numbers** the induction schema on  $\omega$  for all the legitimate properties<sup>3</sup> (not necessarily finitely checkable) is accepted;

**Bar induction** transfinite induction along the well-founded tree (coded by a *bar*, which intersects any infinite sequence) of finite sequences of numbers, with various restriction,<sup>4</sup> is accepted;

**Fan theorem** classically equivalent to a form of König's lemma or **weak fan theorem**, restricted to binary trees but defined by any legitimate properties, is an important consequence of bar induction in many applications; either of them is taken as an axiom of INT instead of bar induction in some literature;

**Axiom of choice** for any legitimate property  $A$  of sorts  $i$  and  $j$ , if for any  $x$  of sort  $i$  there is  $y$  of  $j$  such that  $A[x, y]$  holds then there exists a function  $f$  of sort  $i \rightarrow j$  such that  $A[x, f(x)]$  holds for any  $x$  of  $i$ ;

**Continuity principle** a function on Baire space  $\omega^\omega$  defined by any legitimate property is locally continuous.

The last contradicts CLASS, and the others, except the first two and weak fan theorem, are classically beyond Finitism. Since *Heyting arithmetic*, consisting only of the first three, is mutually interpretable with Peano arithmetic, and hence already beyond Finitism, we need to restrict these axioms, as in CLASS.

The first half of the main purpose of the present series of articles is thus to clarify how large fragments of these axioms are *jointly* reducible to Hilbert's Finitism (i.e., finitistically justifiable) or jointly consistent provably in Finitism (i.e., finitistically guaranteed). This article, the first in the series, addresses this question, in the language  $\mathcal{L}_F$  of function-based second order arithmetic (similar to that of  $\mathbf{EL}$  from [42, Chapter 3, 6.2]), where we need some twist to state the existence of choice functions on Baire space (see Section 2.5.5) or where we could say that the axiom of choice for such sorts is illegitimate at all (see f.n.11).

<sup>3</sup>It is debatable whether the properties involving third or higher-order quantifiers are legitimate in Brouwer's Intuitionism. If not, it is also plausible not to call them properties. However, to emphasize the limitation on what we can consider, we call a property legitimate if we can consider it. This terminology is parallel to Feferman's (e.g. [15]) in the context of predicativity.

<sup>4</sup>There is a debate on the right formulation of Brouwer's intension. See Section 2.5.1.

The expositions of axioms here are informal or pre-formal, and it is quite delicate how to formalize them. We follow a standard way, but some discussions are unavoidable and will be addressed in Section 2.

We define fragments of the axioms basically by requiring the relevant properties to be in classes of formulae, e.g.,  $\Sigma_n^0$ 's and  $\Pi_n^0$ 's (which however do not exhaust all arithmetical formulae because of the lack of prenex normal form theorem), and by controlling the sorts in the axiom of choice.

**1.4. Finitistically justifiable and guaranteed parts of Intuitionistic Mathematics.** We will see that the following with  $\mathbf{EL}_0^-$  (i.e., the logic and basic arithmetic) are jointly reducible to **PRA**:

- induction on natural numbers restricted to  $\Sigma_2^0$  properties ( $\Sigma_2^0$ -Ind);
- bar induction restricted to  $\Pi_1^0$  properties ( $\Pi_1^0$ -BI, see the exact formulation in Definition 2.26);
- fan theorem for fans (decidable by definition) and bars defined by any legitimate properties ( $\mathcal{L}_F$ -FT);
- axiom of choice for all legitimate properties and dependent choice of numbers for  $\Sigma_2^0$  ones ( $\Sigma_2^0$ -DC<sup>0</sup>);
- continuity principle for functions defined by any legitimate properties ( $\mathcal{L}_F$ -WC!<sup>0</sup> and  $\mathcal{L}_F$ -WC!<sup>1</sup>),

and that, with the following further restrictions, jointly consistent provably in **PRA**: induction on numbers to decidable properties; dependent choice and bar induction omitted; fans to be complete binary ( $\mathcal{L}_F$ -WFT).

Besides the well known contrast with the classical situation concerning the continuity principle, we see further contrasts, as any of the following is, classically, beyond **PRA**:  $\Sigma_2^0$ -Ind; fan theorem restricted either to decidable bars  $\Delta_0^0$ -FT or to complete binary fans and  $\Pi_1^0$  bars  $\Pi_1^0$ -WFT; and  $\Pi_1^0$  axiom of choice.

Our method is *Kleene's functional realizability*, known to be able to interpret most part of INT in CLASS. We examine which fragments of INT are interpreted by this in  $\mathbf{WKL}_0$  or  $\mathbf{WKL}_0^*$ . As it is based on a  $\Pi_2^0$ -definable application “|” for functions, unlike the number realizability, naïve attempts of proof easily rely on  $\Pi_2^0$  or higher induction. The proof is, in general, not straightforward from previously known one.

As a byproduct, we can add *Markov's principle* MP (i.e.,  $\Sigma_1^0$ -DNE double negation elimination restricted to  $\Sigma_1$  assertions) to the combinations above. MP is accepted from some constructive views and called *semi-constructive*. While it seems agreed not to accept MP in Intuitionism, it is not agreed to accept its negation.<sup>5</sup> We need no interpretations that exclude MP, as the interpretability of  $T$ +MP trivially implies that of  $T$ .

Moreover, we will see that these fragments are optimal: none of  $\Pi_2^0$ -Ind,  $\Sigma_1^0$ -BI<sub>D</sub> (restricted to decidable bars),  $\Pi_2^0$ -DC!<sup>0</sup> (with uniqueness in the premise) and  $\Pi_1^0$ -DC!<sup>1</sup> (dependent choice of functions) can *only* with  $\mathbf{EL}_0^-$  be reducible to **PRA**; none of  $\Pi_1^0$ -Ind,  $\Sigma_1^0$ -Ind,  $\Delta_0^0$ -BI<sub>D</sub>,  $\Delta_0^0$ -DC!<sup>0</sup> and  $\Delta_0^0$ -FT only with  $\mathbf{EL}_0^-$  is

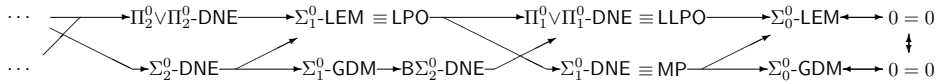
<sup>5</sup> Brouwer's *creative subject*, a method controversial even among Intuitionists, or its formalization *Kripke's schema* yields the negation of MP. However we confine ourselves to “objective Intuitionism” in Beeson's [5] term, excluding such “subjectivities”.

consistent provably in **PRA**. For the former, we interpret  $\mathbf{IS}_2$ , which proves the consistency of **PRA**, by generalizing Coquand and Hofmann's method [11]. For the latter, we interpret  $\mathbf{IS}_1$  which is equiconsistent with **PRA**.

Note that, by Gödel's second incompleteness, if a theory  $T_1$  proves the consistency  $\text{Con}(T_2)$  of another  $T_2$ , then  $T_1$  is not reducible to (nor interpretable in)  $T_2$ , since otherwise  $T_1$  proves its own consistency.

**1.5. Effects of semi-constructive or semi-classical principles.** Hilbert's Finitism did not intend to restrict the mathematics, but to maximize the set of acceptable axioms that are directly beyond Finitism but that are secured on his Finitistic ground through meta-mathematics. So we should continue to clarify which axioms beyond Intuitionism can be added to the secure parts of INT without losing finitistic guaranteedness or justifiability. The aforementioned byproduct on MP is a part of answer, and it is natural to try to answer more generally: which part of classical logic, or even of CLASS, is finitistically guaranteed or justifiable jointly with major parts<sup>6</sup> of INT? As many classically valid principles are known not to imply full classical logic, the other half of our purpose is to ask: how does the secured part change from the intuitionistic situation to classical one, along the hierarchy of such *semi-classical* principles?<sup>7</sup>

Among famous ones are *limited principle of omniscience* LPO (i.e.,  $\Sigma_1^0$ -LEM the law of excluded middle for  $\Sigma_1^0$ ) and *lesser limited principle of omniscience* LLPO (i.e.,  $\Pi_1^0 \vee \Pi_1^0$ -DNE double negation elimination for  $\Pi_1^0 \vee \Pi_1^0$ ). LLPO is implied by LPO and, as shown in [1], independent of MP. In the presence of full induction, LLPO is equivalent to  $\text{B}\Sigma_2^0$ -DNE and to  $\Sigma_1^0$ -GDM, *generalized De Morgan's law*  $\neg(\forall x < y)A \rightarrow (\exists x < y)\neg A$  for  $\Sigma_1^0$  properties. With restricted induction, however, all the implications we know among these are as follows.



<sup>6</sup>Since the entirety of INT is not finitistically justifiable, we do not need to stick to the consistency with full INT.

<sup>7</sup>We can ask the same for RUSS, characterized by MP,  $\mathcal{L}_F\text{-AC}^{0i}$  and  $\text{CT} \forall \alpha \exists e \forall x (\alpha(x) = \{e\}(x))$ , where  $\{-\}$  is Kleene bracket. We knew the inconsistency of  $\mathbf{EL}_0^- + \text{CT} + \Delta_0^0\text{-WFT}$  (by the famous counterexample; cf. [45, Section 3]) and of  $\mathbf{EL}_0^- + \text{CT} + \Pi_2^0\text{-WC}^0$  (as  $\forall x (\alpha(x) = \{e\}(x))$  is  $\Pi_2^0$ ). As the so-called KLS Theorem needs only decidable induction (cf. [42, Chapter 6, 4.12, 5.5]), the combination in 1.4 with (W)FT replaced by CT, i.e.,  $\mathbf{EL}_0^- + \text{CT} + \mathcal{L}_F\{-\text{AC}^{0i}, -\text{WC}^i\}$  (or  $+\Sigma_2^0\{-\text{Ind}, -\text{DC}^0\} + \Sigma_1^0\text{-DC}^1 + \Pi_1^0\text{-BI}$ ) is interpreted by Kleene's number realizability (extended to  $\mathcal{L}_F$  trivially) in  $\mathbf{B}\Sigma_1\text{ex}$  (or in  $\mathbf{IS}_1$ , as our argument will collaterally show; see Proposition 3.49 and below it) and so finitistically guaranteed (or justifiable). Thus only  $\text{CT} + \Pi_1^0\text{-WC}^i$  remains to be asked.

Instead of keeping CT, our proof will also show that the combination in Section 1.4 with (W)FT replaced by a *semi-Russian* axiom  $\text{NCT} \forall \alpha \neg \forall e \neg \forall x (\alpha(x) = \{e\}(x))$  (and so the formula-version, by  $\mathcal{L}_F\text{-AC}^{00}$ ) is finitistically justifiable or guaranteed, as shown in Theorem 5.6. NCT seems to imply that there is no *lawless choice sequence*, which had been rejected in early stages of Intuitionism.

Unlike MP, by *weak counterexample argument*<sup>8</sup> we can presume that Brouwer would reject the idea of LLPO (and hence all principles above it). Thus the status of LLPO in Intuitionism is as that of WKL in Finitism, since WKL is definitely *directly* unacceptable in Finitism, and actually they are equivalent in the presence of axiom of choice (cf. 3.9). Because accepting WKL *indirectly* by consistency proof was the core of Simpson's "partial realizations of Hilbert's Program" from [38], LLPO should be of particular interest in our context.

We show that adding  $\Sigma_1^0$ -GDM (and so LLPO), even jointly with MP, does not change the intuitionistic situation described in Section 1.4, except the axiom of function-number and function-function choice. Though these choices cannot be formalized in  $\mathcal{L}_F$ , continuous choice (CC), whose  $\Pi_1^0$  fragment contradicts LLPO, could be seen as conjunctions of them and continuity principle (cf. Section 2.5.5). Our main tool is van Oosten's *Lifschitz-style functional realizability* from [29], in the definition of which, a bounded  $\Sigma_2^0$  property plays a central role. Thus the arguments on the finitistic ground is much more delicate than in van Oosten's original context.

On the other hand, we will see that LPO already makes the situation completely classical, that is, any of the following *separately*, but together with  $\mathbf{EL}_0^- + \text{LPO}$ , is already non-reducible to  $\mathbf{PRA}$ :

- $\Sigma_2^0$  induction on numbers ( $\Sigma_2^0$ -Ind);
- fan theorem restricted to  $\Delta_0^0$  bars but without the binary constraint ( $\Delta_0^0$ -FT);
- weak fan theorem restricted to (complete binary fans and)  $\Pi_1^0$ -bars ( $\Pi_1^0$ -WFT); and
- $\Pi_1^0$  axiom of choice even with the uniqueness assumption in the premise ( $\Pi_1^0$ -AC!<sup>00</sup>).

For the second and fourth we will show the interpretability of  $\mathbf{ACA}_0$  with Gödel–Gentzen negative interpretation. For the others, we need the combination with intuitionistic forcing to interpret  $\mathbf{IS}_2$  or  $\mathbf{ACA}_0$ .

**1.6. Constructive reverse mathematics on consistency strength.** Our study also contributes to the research field, called *constructive reverse mathematics* (cf. e.g., [18, 19]). There implications, on a constructive ground, between (fragments of) axioms from CLASS, INT and RUSS, are investigated and, for the unprovability of these implications, questions of the following type are of interest:

which combination of axioms (from different kinds of mathematics) is consistent and which is not?

Namely, it has been asked only whether a combination is consistent or inconsistent.

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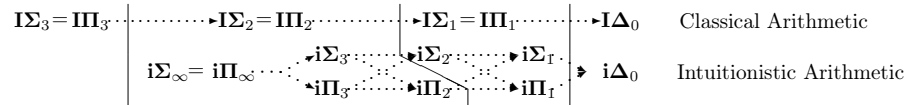
<sup>8</sup>Let  $\alpha(n) \neq 0$  iff the first successive  $m$  occurrence of 9's in the decimal expansion of Napier's constant  $e$  starts at the  $n$ -th digit; then  $\neg(\exists n \neg(\alpha(2n) = 0) \wedge \exists n \neg(\alpha(2n+1) = 0))$  and LLPO implies  $\forall n(\alpha(2n) = 0) \vee \forall n(\alpha(2n+1) = 0)$ ; i.e., either the first successive  $m$  occurrence of 9's, if exists, starts at an odd digit or if it exists it starts at an even digit; however it is open for large enough  $m$  which disjunct holds. Recall that in Intuitionism to claim a disjunction, we need to know which disjunct is true.

Now our investigation is on the proof theoretic or consistency strengths of combinations. In other words, we ask how consistent (or to which extent consistent) the combination is. Thus the question becomes refined:

which combination of axioms (from different kinds of mathematics) is how much consistent?

The proof theoretic investigation of intuitionistic theories seems much less developed than classical ones.

Even the consistency strengths of  $\Sigma_n$  or  $\Pi_n$  induction schemata, the most basic targets of the study, were identified only in 1990s. Then Visser (in his unpublished note, see [48]) pointed out that  $\mathbf{i}\Sigma_\infty = \mathbf{i}\Pi_\infty$ , Heyting arithmetic with induction restricted to prenex formulae, is mutually  $\Pi_2$ -preservingly interpretable with  $\mathbf{i}\Pi_2$ , and so with classical  $\mathbf{I}\Sigma_2$ . This shows the drastic contrast with the classical situation, as classical  $\mathbf{I}\Sigma_n$ 's form a strict hierarchy exhausting Peano arithmetic  $\mathbf{PA}$ .  $\mathbf{i}\Sigma_1$  and  $\mathbf{I}\Sigma_1$  are mutually  $\Pi_2$ -preservingly interpretable (see [11, 3]), and so are  $\mathbf{i}\Pi_1$  and  $\mathbf{I}\Pi_1 = \mathbf{I}\Sigma_1$  as shown easily by Gödel–Gentzen negative interpretation (but only  $\Pi_1$ -preserving, as shown in [48]). Thus any of  $\mathbf{i}\Sigma_n$  ( $n \geq 3$ ) and  $\mathbf{i}\Pi_n$  ( $n \geq 2$ ) has the same strength as classical  $\mathbf{I}\Sigma_2$ , and both  $\mathbf{i}\Sigma_1$  and  $\mathbf{i}\Pi_1$  as classical  $\mathbf{I}\Sigma_1$  (and so  $\mathbf{PRA}$ ). What remains is  $\mathbf{i}\Sigma_2$ , which [10, Corollary 2.27] interpreted in a fragment of Gödel's  $\mathbf{T}$  of the same proof theoretic strength as  $\mathbf{I}\Sigma_1$  by Dialectica interpretation. We will show these results by realizability but also that these strengths are not affected by adding the fragments of Brouwerian axioms. While for this goal we need functional realizability, our proof also shows that Kleene's number realizability, used in [48], interprets intuitionistic  $\mathbf{i}\Sigma_2$  in classical  $\mathbf{I}\Sigma_1$ . Here, realizing in a classical theory is essential; we do not know if  $\mathbf{i}\Sigma_2$  is realizable in intuitionistic  $\mathbf{i}\Sigma_1$ .



As mentioned in Section 1.5,  $\mathbf{i}\Sigma_2$  and LPO jointly have the same strength as classical  $\mathbf{I}\Sigma_2$ . Generally, our method shows that  $\mathbf{i}\Sigma_{n+1} + \Sigma_n$ -LEM is mutually  $\Pi_{n+2}$ -preservingly interpretable with  $\mathbf{I}\Sigma_{n+1}$ , whereas Gödel–Gentzen negative interpretation needs stronger  $\mathbf{i}\Sigma_{n+1} + \Sigma_{n+1}$ -DNE to interpret  $\mathbf{I}\Sigma_{n+1}$ .

Besides induction, there seem to have been no proof theoretic studies (in the sense of Section 1.2) on intuitionistic theories of the strength below  $\mathbf{HA}$ .<sup>9</sup> The present article leads to this large field of proof theoretic study.

**1.7. Conclusions.** Although bar induction (BI) was accepted in Brouwer's original idea, the accumulation of studies has shown that weak fan theorem (WFT), a consequence of BI, and continuous choice (CC) suffice in most cases. These two have been perceived even to characterize Intuitionistic Mathematics (INT) in constructive reverse mathematics (see [9, Chapter 5], [19, p.44, l. –7] or [12, Section 4] where WFT is called fan theorem). If we agree with this

<sup>9</sup>Those above  $\mathbf{HA}$ , e.g., many variants of  $\mathbf{CZF}$ , have been investigated. Some works of proof mining (e.g., [24]) are related but not exactly: e.g., induction for all negative formulae has no strength in their sense, although it interprets full induction.



perception,<sup>10</sup> we could conclude that *Brouwer's Intuitionism is compatible with Hilbert's Finitism*, for WFT and CC both for arbitrary formulae are jointly reducible to, and, even provably consistent in **PRA**.

Moreover, some semi-classical principles, e.g., Markov's principle MP and lesser limited principle of omniscience LLPO, do not destroy the compatibility and are hence consistent with Intuitionism and Finitism<sup>11</sup> (Figure 1) even though Brouwer did not accept them. Thus *MP and LLPO are acceptable in the same (indirect) sense as WKL is acceptable in Hilbert's Finitism*. On the other hand, *limited principle of omniscience LPO is, by no means, consistent with Intuitionism and Finitism*: it is finitistically consistent only with those fragments of Brouwerian axioms with which the entire classical logic is finitistically consistent (Figure 2).

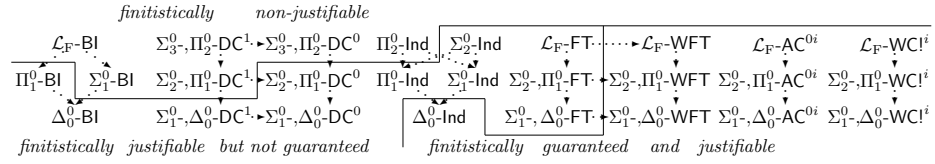


FIGURE 1. “Intuitionistic Situation” – over any base theory between  $\mathbf{EL}_0^-$  and  $\mathbf{EL}_0^- + \text{MP} + \Sigma_1^0\text{-GDM}$

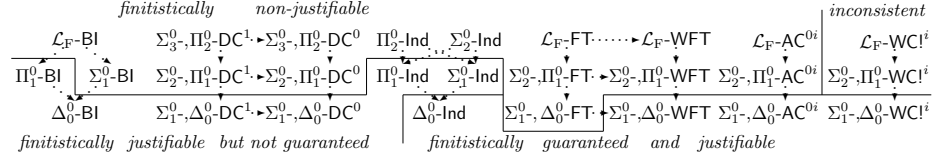


FIGURE 2. “Classical Situation” – over any base theory between  $\mathbf{EL}_0^- + \text{LPO}$  and  $\mathbf{EL}_0^- + \mathcal{L}_F\text{-LEM}$

**1.8. A marriage of Brouwer's Intuitionism and an ultrafinitism.** After Hilbert's Finitism in the early 20th century, ultrafinitisms, stricter kinds of finitism than Hilbert's, have been proposed. Some are motivated by the development of computational complexity theory in the latter half of the century: only functions of a certain complexity are admitted, in the same sense as Hilbert's (formalized as **PRA**) admits only primitive recursive ones. Which part of INT, with which semi-classical principle, is justifiable or guaranteed with respect to

<sup>10</sup>This seems plausible as far as the “antique” fields of mathematics (established until ca.1900) are concerned. Other fields may go beyond this perception (e.g., [46, 44] used BI not only FT in combinatorics), needless to say that of CLASS beyond  $\mathcal{L}_F$ .

<sup>11</sup>For this claim on LLPO, we need to keep continuity principle without replacing it by CC (so the axiom of function-number and function-function choice are excluded) as an axiom of INT. This might be supported by the fact that Brouwer talked about “assignments” rather than left-total binary relations and by the argument triggered by creative subject as will be in f.n.13.

them? An abundance of complexity classes (not yet proved to be identical), and hence of ultrafinitisms, makes this question too big to answer in one article.

Here we consider only the easiest kind, which admits only Kalmár's elementary functions.<sup>12</sup> This could be formalized as  $\mathbf{B}\Sigma_1\mathbf{ex}$ . All our finitistic guaranteedness results yield justifiability with respect to this kind of ultrafinitism, as they are proved via interpretability in  $\mathbf{B}\Sigma_1\mathbf{ex}$ . Recall that the notion of proof theoretic reducibility collapses the consistency of such weak theories but that of interpretability does not.

Theories for even stricter kinds of ultrafinitism require the distinction between large and small numbers (i.e.,  $x$ 's and  $|x|$ 's), and therefore, in such a context, the natural formulations of some axioms, e.g., fan theorem, are not clear. The authors hope that they could treat these topics somewhere in the near future.

**1.9. Outline and prerequisites.** Section 2 introduces our base theory  $\mathbf{EL}_0^-$  and some variants, as well as semi-classical principles and Brouwerian axioms whose strengths we will investigate, with basic properties. Section 3 gives upper bounds of the strengths of combinations of them, with Kleene's functional realizability and van Oosten's variant for Lifschitz-style, whose characterization by axioms will be generalized extensively. Folklore results from classical arithmetic, refined in Section 3.1, plays vital roles. Section 4 gives lower bounds, with Gödel–Gentzen negative interpretation and by generalizing Coquand–Hofmann forcing interpretation. Section 5 will present the results in final forms, with supplementary results, further problems and related works.

While Section 2 summarizes basic definitions and results on function-based second order arithmetic, the readers are assumed to be familiar with set-based counterpart from, e.g., [39]. They are supposed to know the systems  $\mathbf{RCA}_0^*$ ,  $\mathbf{WKL}_0^*$ ,  $\mathbf{RCA}_0$ ,  $\mathbf{WKL}_0$  and  $\mathbf{ACA}_0$  as well as the axiom schema  $\Pi_m^1\text{-TI}$ , which is known to be equivalent over  $\mathbf{ACA}_0$  to the transfinite induction along well-founded trees represented by sets. Comprehension axioms below are central in defining theories. By convention, *we always assume that there are no collisions of free variables with bound ones*. Thus below we implicitly assume that  $X$  is not free in  $A[x]$ .

(C-CA):  $\exists X\forall x(x \in X \leftrightarrow A[x])$  for  $A$  from  $\mathcal{C}$ .

## §2. Preliminaries.

### 2.1. The system $\mathbf{EL}_0^-$ of basic arithmetic.

- DEFINITION 2.1 (languages  $\mathcal{L}_1$  and  $\mathcal{L}_F$ ). (1) The language  $\mathcal{L}_1$  is a one-sorted first order language with equality = consisting of constants 0 and 1, binary function symbols +,  $\cdot$  and exp and a binary predicate <.
- (2) The language  $\mathcal{L}_F$  of elementary analysis is the two-sorted first order language, whose sorts are called *number* and *function*, which includes  $\mathcal{L}_1$  as the part of the number sort, and which, additionally, has two function symbols Ev and Rest of arity one function and one number and of value number.

<sup>12</sup>Such functions form the third level  $\mathcal{E}^3$  of *Grzegorzcyk hierarchy*. We can replace it by  $\mathcal{E}^n$  for any  $n \geq 3$  without changing the result, as ultrafinitistic non-justifiability is by the interpretability of  $\mathbf{I}\Sigma_1$  which proves the consistency of the theory for  $\mathcal{E}^n$ .

Notice that  $\mathcal{L}_F$  does not have the equality for the function sort. We call the systems on this language *function-based second order arithmetic*, in order to distinguish them from *set-based second order arithmetic*, systems on the language  $\mathcal{L}_S$  (called  $L_2$  in [39]), which has been common in classical reverse mathematics.

NOTATION 2.2. Variables of the number sort are denoted by lower-case Latin letters  $x, y, z, u, v$ , etc., and those of the function are by Greek ones  $\alpha, \beta$ , etc..

Let  $\alpha(x) := \text{Ev}(\alpha, x)$  and  $\alpha \upharpoonright x := \text{Rest}(\alpha, x)$ . Furthermore,  $(\exists x < t)A$  stands for  $\exists x(x < t \wedge A)$ ,  $(\forall x < t)A$  for  $\forall x(x < t \rightarrow A)$ ,  $\alpha < \beta$  for  $\forall x(\alpha(x) < \beta(x))$  and  $\alpha = \beta$  for  $\forall x(\alpha(x) = \beta(x))$ .

We let  $\exists! x A[x] := \exists x A[x] \wedge \forall y, z (A[y] \wedge A[z] \rightarrow y = z)$  and similarly we also let  $\exists! \alpha A[\alpha] := \exists \alpha A[\alpha] \wedge \forall \beta, \gamma (A[\beta] \wedge A[\gamma] \rightarrow \beta = \gamma)$ .

DEFINITION 2.3 ( $\mathcal{C} \wedge \mathcal{D}$ ,  $\mathcal{C} \vee \mathcal{D}$ ,  $\mathcal{C} \rightarrow \mathcal{D}$ ,  $\neg \mathcal{C}$ ,  $\text{B}\forall^i \mathcal{C}$ ,  $\text{B}\exists^i \mathcal{C}$ ,  $\forall^i \mathcal{C}$  and  $\exists^i \mathcal{C}$ ). Let  $\mathcal{C}$  and  $\mathcal{D}$  be classes of formulae.

$\mathcal{C} \square \mathcal{D}$  consists of all formulae of the form  $A \square B$  with  $A$  and  $B$  from  $\mathcal{C}$  and  $\mathcal{D}$ , respectively, for  $\square \equiv \wedge, \rightarrow, \vee$ .

Moreover  $\neg \mathcal{C}$ ,  $\text{B}\forall^0 \mathcal{C}$ ,  $\text{B}\exists^0 \mathcal{C}$ ,  $\forall^0 \mathcal{C}$ ,  $\exists^0 \mathcal{C}$ ,  $\text{B}\forall^1 \mathcal{C}$ ,  $\text{B}\exists^1 \mathcal{C}$ ,  $\forall^1 \mathcal{C}$  and  $\exists^1 \mathcal{C}$  consist of all those formulae of the forms  $\neg A$ ,  $(\forall x < t)A$ ,  $(\exists x < t)A$ ,  $\forall x A$ ,  $\exists x A$ ,  $(\forall \xi < \alpha)A$ ,  $(\exists \xi < \alpha)A$ ,  $\forall \xi A$  and  $\exists \xi A$ , respectively, with  $A$  from  $\mathcal{C}$ .

DEFINITION 2.4 ( $\Delta_0^0$ ,  $\text{B}\Pi_{n+1}^0$ ,  $\text{B}\Sigma_{n+1}^0$ ,  $\Pi_n^0$ ,  $\Sigma_n^0$ ,  $\Pi_\infty^0$ ,  $\Sigma_\infty^0$ ,  $\Delta_0^1$ ). A formula of  $\mathcal{L}_F$  is called  $\Delta_0^0$  (as well as  $\Sigma_0^0$  and  $\Pi_0^0$ ) if all the quantifiers in it are number and bounded, i.e., only in the forms  $\forall x < t$  and  $\exists x < t$ .

Let  $\text{B}\Pi_{n+1}^0 := \text{B}\forall^0 \Sigma_n^0$ ;  $\text{B}\Sigma_{n+1}^0 := \text{B}\exists^0 \Pi_n^0$ ;  $\Pi_{n+1}^0 := \forall^0 \Sigma_n^0$ ; and  $\Sigma_{n+1}^0 := \exists^0 \Pi_n^0$ . A formula is called *arithmetically prenex* ( $\Pi_\infty^0$  and  $\Sigma_\infty^0$ ) if it is  $\Pi_n^0$  or  $\Sigma_n^0$  for some  $n$ ; and called  $\Delta_0^1$  if it contains no function quantifiers.

DEFINITION 2.5 (**iQex**). The intuitionistic  $\mathcal{L}_1$ -theory **iQex** is generated by the equality axioms and

$$\begin{array}{ll}
 \text{(a0)} \ x + 0 = x; & \text{(a1)} \ x + (y + 1) = (x + y) + 1; \\
 \text{(m0)} \ x \cdot 0 = 0; & \text{(m1)} \ x \cdot (y + 1) = (x \cdot y) + x; \\
 \text{(e0)} \ \exp(x, 0) = 1; & \text{(e1)} \ \exp(x, y + 1) = \exp(x, y) \cdot x \\
 \text{(ir)} \ \neg(x < x) & \text{(tr)} \ x < y \wedge y < z \rightarrow x < z; \\
 \text{(s0)} \ x < x + 1; & \text{(s1)} \ x < y \rightarrow (x + 1 < y) \vee (x + 1 = y).
 \end{array}$$

DEFINITION 2.6 ( $\mathcal{C}$ -Ind,  $\mathcal{C}$ -Bdg,  $\mathcal{C}$ -LNP,  $\mathcal{C}$ -LEM and  $\mathcal{C}$ -DNE). For a class  $\mathcal{C}$  of  $\mathcal{L}_1$  or  $\mathcal{L}_F$  formulae, define the following axiom schemata:

$$\begin{array}{l}
 \text{(C-Ind): } A[0] \wedge (\forall x < n)(A[x] \rightarrow A[x+1]) \rightarrow A[n]; \\
 \text{(C-Bdg): } (\forall x < n) \exists y A[x, y, n] \rightarrow \exists u (\forall x < n) (\exists y < u) A[x, y, n]; \\
 \text{(C-LNP): } A[x] \rightarrow (\exists y \leq x) (A[y] \wedge (\forall z < y) \neg A[z]), \text{ where } y \leq x := y < x + 1; \\
 \text{(C-LEM): } A \vee \neg A; \\
 \text{(C-DNE): } \neg \neg A \rightarrow A,
 \end{array}$$

for any formula  $A$  from  $\mathcal{C}$ .

DEFINITION 2.7 ( $\mathbf{i}\Pi_{n+1}$ ,  $\mathbf{i}\Sigma_{n+1}$ ,  $\mathbf{B}\Sigma_1\mathbf{ex}$ ,  $\mathbf{I}\Sigma_{n+1}$ ). Define

$$\begin{aligned} \mathbf{i}\Pi_{n+1} &: \equiv \mathbf{iQex} + \Pi_{n+1}\text{-Ind}; & \mathbf{i}\Sigma_{n+1} &: \equiv \mathbf{iQex} + \Sigma_{n+1}\text{-Ind}; \\ \mathbf{I}\Delta_0\mathbf{ex} &: \equiv \mathbf{iQex} + \mathcal{L}_1\text{-LEM} + \Delta_0\text{-Ind}; & \mathbf{B}\Sigma_1\mathbf{ex} &: \equiv \mathbf{I}\Delta_0\mathbf{ex} + \Sigma_1\text{-Bdg}; \\ \mathbf{I}\Sigma_{n+1} &: \equiv \mathbf{i}\Sigma_{n+1} + \mathcal{L}_1\text{-LEM}. \end{aligned}$$

where  $\Delta_0 := \Delta_0^0 \cap \mathcal{L}_1$ ,  $\Sigma_n := \Sigma_n^0 \cap \mathcal{L}_1$  and  $\Pi_n := \Pi_n^0 \cap \mathcal{L}_1$ .

- PROPOSITION 2.8. (1) (i)  $0 < x+1$ ; (ii)  $x < y \vee x = y \vee y < x$ ; and (iii)  $\Delta_0\text{-LEM}$ , are provable in  $\mathbf{iQex} + \Delta_0\text{-Ind}$ .  
(2) (i)  $\mathbf{iQex} + \mathbf{B}\forall^0\text{-C-Ind} + \mathbf{B}\exists^0(\mathcal{C} \wedge \mathbf{B}\forall^0\text{-C})\text{-DNE} \vdash \mathcal{C}\text{-LNP}$ .  
In particular, (ii)  $\mathbf{iQex} + \Delta_0\text{-Ind} \vdash \Delta_0\text{-LNP}$ .  
(3) (i)  $\mathbf{B}\forall^0\Sigma_n \subseteq \Sigma_n$  up to equivalence over  $\mathbf{iQex} + \Sigma_n\text{-Bdg}$ ; and  
(ii)  $\mathbf{iQex} + \Sigma_n\text{-Ind} \vdash \Sigma_n\text{-Bdg}$ .

PROOF. (1) (i) is by  $\Delta_0\text{-Ind}$ , (s0) and (tr).

For (ii), let  $A[x, y] := (x < y \vee x = y \vee y < x)$ . Now  $A[0, 0]$  and, by (i),  $A[0, y] \rightarrow A[0, y+1]$ . Thus  $\Delta_0\text{-Ind}$  yields  $\forall y A[0, y]$ . Because of  $\Delta_0\text{-Ind}$  it remains to show  $A[x, y] \rightarrow A[x+1, y]$ .  $x < y \rightarrow A[x+1, y]$  is by (s1),  $x = y \rightarrow A[x+1, y]$  by (s0) and  $y < x \rightarrow A[x+1, y]$  by (s0) and (tr).

We see (iii) by induction on  $A$ . The atomic cases are by (ii), where (ir) implies  $x < y \vee y < x \rightarrow \neg(x = y)$  and (ir) and (tr) imply  $x < y \vee x = y \rightarrow \neg(y < x)$ . The cases of  $\wedge$  and  $\rightarrow$  logically follow from the induction hypothesis. For  $Q \equiv \exists, \forall$ , let  $B[n] := (Qx < n)A[x] \vee \neg(Qx < n)A[x]$ . By (s1), (i) and (tr), if  $x < 0$  then  $x+1 < 0 \vee x+1 = 0$  and  $x+1 < x+1$  contradicting (ir). Thus  $\neg(x < 0)$  and  $B[0]$ . Now  $x < n+1 \rightarrow x < n \vee x = n$  by (s1) and (ii).  $B[n] \wedge (A[n] \vee \neg A[n]) \rightarrow B[n+1]$  and  $B[n] \rightarrow B[n+1]$  by the hypothesis for  $A$ . Apply  $\Delta_0\text{-Ind}$ .

(2) Let  $A$  be  $\mathcal{C}$  and  $B[y] := (\forall z \leq y)\neg A[z]$ .  $\neg(\exists y \leq x)(A[y] \wedge (\forall z < y)\neg A[z])$ , i.e.,  $(\forall y \leq x)((\forall z < y)\neg A[z] \rightarrow \neg A[y])$  implies  $B[0] \wedge (\forall y < x)(B[y] \rightarrow B[y+1])$  and  $B[x]$  by  $\mathbf{B}\forall^0\text{-C-Ind}$ . So  $A[x] \rightarrow \neg\neg(\exists y \leq x)(A[y] \wedge (\forall z < y)\neg A[z])$ .

(3) (ii) Let  $A$  be  $\Pi_{n-1}$ . If  $(\forall x < m)\exists y, z A[x, y, z]$ , by  $\Sigma_n\text{-Ind}$  on  $k \leq m$ , we have  $\exists u(\forall x < k)(\exists y, z < u)A[x, y, z]$ .  $\dashv$

NOTATION 2.9. (1) While  $\mathcal{L}_F$  has no function symbols besides  $+$ ,  $\cdot$  and  $\text{exp}$ , we can treat a bounded  $\Delta_0^0$  definable function  $f$  (i.e., defined by  $A[\vec{x}, \vec{\alpha}, y]$  from  $\Delta_0^0$  and bounded by a term  $t[\vec{x}, \vec{\alpha}]$ ) as follows: for a formula  $B[y]$ , by  $B[f(\vec{x}, \vec{\alpha})]$  we mean  $(\exists y < t[\vec{x}, \vec{\alpha}])(A[\vec{x}, \vec{\alpha}, y] \wedge B[y])$ . If  $B[y]$  is  $\Delta_0^0$ , so is  $B[f(\vec{x}, \vec{\alpha})]$ . In this way, we can introduce fundamental operations on pairing and sequences of numbers without affecting the complexity: we fix, for each standard  $n$ , a bounded  $\Delta_0^0$  definable bijection  $(-, \dots, -) : \mathbb{N}^n \rightarrow \mathbb{N}$  and the associated projections  $(-)_i^n$  satisfying  $(x)_i^n \leq x$ ; and also a bijection  $\mathbb{N}^{<\omega} \rightarrow \mathbb{N}$  so that basic operations are bounded  $\Delta_0^0$  definable up to the identification, e.g., evaluation  $[u, x] \mapsto u(x)$ ; concatenation  $[u, v] \mapsto u * v$  and  $[u, x, \alpha] \mapsto (u * \alpha)(x)$ ; length-1 sequence  $x \mapsto \langle x \rangle$ ; length  $u \mapsto |u|$ ; and restriction  $[u, n] \mapsto u \upharpoonright n$ . Assume  $\max(u(x), |u|, u \upharpoonright n) \leq u$ .

(2) Define  $(\beta)_i^n = \lambda x.(\beta(x))_i^n$ ,  $(\beta, \gamma) = \lambda x.(\beta(x), \gamma(x))$ ,  $(\beta)_y = \lambda x.\beta((y, x))$ ,  $\beta \ominus y = \lambda x.\beta(y+x)$  and  $\underline{z} = \lambda x.z$ , which are all bounded  $\Delta_0^0$  definable. Alternatively, for example,  $A[(\beta)_i^n]$  is the result of replacing all the occurrences of  $\alpha(t)$  in  $A[\alpha]$  by  $(\beta(t))_i^n$  and those of  $\alpha \upharpoonright t$  by corresponding bounded  $\Delta_0^0$  definable terms.

(3) We assume that classes of formulae are closed under (i) conjunctions and disjunctions with  $\Delta_0^0$ , and (ii) substitutions of the expressions from (1) and (2). The operations in Definition 2.3 preserve these closure properties.

**DEFINITION 2.10 ( $\mathbf{EL}_0^-$ ).** The  $\mathcal{L}_F$ -theory  $\mathbf{EL}_0^-$  is generated over intuitionistic logic with equality for numbers, by (a) **iQex**, (b)  $\Delta_0^0$ -Ind, (c)  $\alpha \upharpoonright 0 = \langle \rangle$ ,  $\alpha \upharpoonright (x+1) = (\alpha \upharpoonright x) * \langle \alpha(x) \rangle$ ; and (d)  $\Delta_0^0$  bounded search defined below:

**(C bounded search):**  $\exists \beta \forall x ((\exists y < t[x]) A[x, y] \rightarrow \beta(x) < t[x] \wedge A[x, \beta(x)])$  for  $A$  from  $\mathcal{C}$  and a term  $t[x]$ .

$\mathbf{EL}_0^-$  is almost equivalent to  $\mathbf{ELELEM}$  from [18], which however has terms for all elementary functions by the help of functionals. Our  $\mathbf{EL}_0^-$  proves the existence of those functions by the axiom (d) but shares the important feature with  $\mathcal{L}_S$  from classical reverse mathematics that second order terms are only variables.

Since  $\Sigma_n^0$  is  $\Sigma_n$  with  $\mathcal{L}_F$ -terms substituted for  $x$ 's, 2.8 holds with  $\Delta_0$  and  $\Sigma_n$  replaced by  $\Delta_0^0$  and  $\Sigma_n^0$ .

**LEMMA 2.11.** For any  $A$  and  $B$ , in **iQex** or  $\mathbf{EL}_0^-$ ,  $A \vee B$  is equivalent to

$$(\exists i < 2)((i = 0 \rightarrow A) \wedge (i = 1 \rightarrow B)).$$

A key fact in second order arithmetic is a formal version of famous Kleene's normal form theorem. While in references (e.g., [39, Theorem II.2.7]) the proof is omitted or very sketchy, we give a little details.

**DEFINITION 2.12 ( $D_C, B_C$ ).** For a  $\Delta_0^0$  formula  $C[\vec{x}, \vec{\alpha}]$ , we define  $D_C$  and  $B_C$  as follows.

- (1)  $D_C[\vec{x}, \vec{u}]$  is the result of replacing  $\alpha_i(s)$  and  $\alpha_i \upharpoonright s$  by  $u_i(s)$  and  $u_i \upharpoonright s$ , respectively, in  $C$ .
- (2) (i) For atomic  $C$ , let  $B_C[\vec{x}, v, \vec{\alpha}] := \bigwedge_i (v > t_i[\vec{x}, \vec{\alpha}])$  where  $t_i[\vec{x}, \vec{\alpha}]$ 's are all subterms in  $C$ ;  
 (ii) for  $\square \equiv \wedge, \rightarrow, \vee$ , let  $B_{C_1 \square C_2}[\vec{x}, v, \vec{\alpha}] := \bigwedge_{i=1,2} B_{C_i}[\vec{x}, v, \vec{\alpha}]$ ;  
 (iii)  $B_{(Qz < t)C}[\vec{x}, v, \vec{\alpha}] := (\forall z < t[\vec{x}, \vec{\alpha}]) B_C[z, \vec{x}, v, \vec{\alpha}] \wedge B_{0 < t[\vec{x}, \vec{\alpha}]}[\vec{x}, v, \vec{\alpha}]$ .

$B_C[\vec{x}, v, \vec{\alpha}]$  means " $C[\vec{x}, \vec{\alpha}]$  refers  $\alpha$  only below  $v$ ". So we take ' $\bigwedge_{i=1,2}$ ' even for  $\rightarrow, \vee$  and ' $(\forall z < t[\vec{x}, \vec{\alpha}])$ ' for  $\exists$ . In  $\mathcal{L}_S$ ,  $v > t_C[\vec{x}]$  can play the role of  $B_C$  for a suitable  $t_C$  (cf. [25, Lemma 2.13], where  $t(i, \vec{k})$  on p.162, 1.9 is a typo of  $t''(i, \vec{k})$ ). Below  $\beta(x_0, \dots, x_n)$  stands for  $\beta((x_0, \dots, x_n))$  where the inner (...) is from 2.9(1).

**LEMMA 2.13.** For a  $\Delta_0^0$  formula  $C[\vec{x}, \vec{\alpha}]$ , the following are provable in  $\mathbf{EL}_0^-$ :

- (i)  $B_C[\vec{x}, u, \vec{\alpha}] \wedge u \leq v \rightarrow B_C[\vec{x}, v, \vec{\alpha}]$  (upward closure)
- (ii)  $\mathbf{EL}_0^- \vdash \exists \beta \forall \vec{x} B_C[\vec{x}, \beta(\vec{x}), \vec{\alpha}] \wedge \forall u, \vec{x} (B_C[\vec{x}, u, \vec{\alpha}] \rightarrow (C[\vec{x}, \vec{\alpha}] \leftrightarrow D_C[\vec{x}, \vec{\alpha} \upharpoonright u]))$ .

**PROOF.** As we can prove (i) by easy induction on  $C$ , we concentrate on (ii).

First let  $C$  be atomic, whose all subterms are  $t_i[\vec{x}, \vec{\alpha}]$ 's. By Axiom (d), take  $\beta(\vec{x}) = 1 + \sum_i t_i[\vec{x}, \vec{\alpha}]$ . Then  $B_C[\vec{x}, \beta(\vec{x}), \vec{\alpha}]$ . For the latter conjunct, assume  $B_C[\vec{x}, u, \vec{\alpha}]$ . Now  $t_i[\vec{x}, \vec{\alpha}] < u$  and so  $\alpha_j \upharpoonright (t_i[\vec{x}, \vec{\alpha}]) = (\alpha_j \upharpoonright u) \upharpoonright (t_i[\vec{x}, \vec{\alpha}])$ . Thus  $t_i[\vec{x}, \vec{\alpha}] = t_i[\vec{x}, \vec{\alpha} \upharpoonright u]$  by induction on  $t_i$  and hence  $C[\vec{x}, \vec{\alpha}] \leftrightarrow D_C[\vec{x}, \vec{\alpha} \upharpoonright u]$ .

In the quantifier case, the induction hypotheses for  $C$  and  $0 < t[\vec{x}, \vec{\alpha}]$  yield  $\gamma, \delta$  with  $\forall \vec{x}, z B_C[z, \vec{x}, \gamma(z, \vec{x}), \vec{\alpha}]$  and  $\forall \vec{x} B_{0 < t[\vec{x}, \vec{\alpha}]}[\vec{x}, \delta(\vec{x}), \vec{\alpha}]$ . Therefore, with  $\beta(\vec{x}) := \gamma \upharpoonright (t[\vec{x}, \vec{\alpha}], \vec{x}) + \delta(\vec{x})$  yielded by Axiom (c), we have  $\forall \vec{x} B_{(Qz < t)C}[\vec{x}, \beta(\vec{x}), \vec{\alpha}]$ .

For the latter conjunct, assume  $B_{(Qz < t)C}[\vec{x}, u, \vec{\alpha}]$ . Then  $(\forall z < t[\vec{x}, \vec{\alpha}])B_C[z, \vec{x}, u, \alpha]$  and, since  $C[z, \vec{x}, \vec{\alpha}] \leftrightarrow D_C[z, \vec{x}, \vec{\alpha}]u$  for each  $z < t[\vec{x}, \vec{\alpha}]$  by the induction hypothesis, we have  $(Qz < t[\vec{x}, \vec{\alpha}])C[z, \vec{x}, \vec{\alpha}] \leftrightarrow D_{(Qz < t)C}[z, \vec{x}, \vec{\alpha}]u$ .

The other cases are proved similarly.  $\dashv$

**THEOREM 2.14.** For any  $A[\vec{\alpha}]$  from  $\Sigma_1^0$  there is  $D[\vec{u}]$  from  $\Delta_0^0$  without  $\vec{\alpha}$  with  $\mathbf{EL}_0^- \vdash \forall \vec{\alpha}(A[\vec{\alpha}] \leftrightarrow \exists n D[\vec{u}]n)$ .

**PROOF.** For simplicity, let  $\vec{\alpha} = \alpha$ . Define

$$D[u] := (\exists x < |u|)(B_C[x, |u|, u*0] \wedge D_C[x, u])$$

for  $A[\alpha] \equiv \exists x C[x, \alpha]$ . Note  $B_C[x, n, \alpha] \rightarrow \forall \beta B_C[x, n, (\alpha|n)*\beta]$ . If  $\exists n D[\alpha|n]$ , say  $x < n \wedge B_C[x, n, (\alpha|n)*0] \wedge D_C[x, \alpha|n]$ , then, by 2.13,  $C[x, \alpha]$ . Conversely, if  $C[x, \alpha]$ , 2.13 yields  $n > x$  with  $B_C[x, n, \alpha]$  and so  $D_C[x, \alpha|n]$ .  $\dashv$

**2.2. Choice axioms along numbers.** Besides the existence of some specific functions and the closure conditions 2.10(d),  $\mathbf{EL}_0^-$  has no constraints on the second order domain. It seems common to use choice axioms to govern the domain in the function-based setting, while in the set-based one comprehension axioms are more common.

Among several variants of dependent choice, we decide to set the premise to be  $\text{Ran}(R) \subseteq \text{Dom}(R)$  for the relation  $R$ .

**DEFINITION 2.15** (choice schema). For a class  $\mathcal{C}$  of formulae, define the following axiom schemata.

$$(\mathcal{C}\text{-AC}^{00}): \forall x \exists y A[x, y] \rightarrow \exists \alpha \forall x A[x, \alpha(x)];$$

$$(\mathcal{C}\text{-AC}^{01}): \forall x \exists \beta A[x, \beta] \rightarrow \exists \alpha \forall x A[x, (\alpha)_x];$$

$$(\mathcal{C}\text{-DC}^0): \forall x, y (A[x, y] \rightarrow \exists z A[y, z])$$

$$\rightarrow \forall x, y (A[x, y] \rightarrow \exists \alpha (\alpha(0) = x \wedge \forall z A[\alpha(z), \alpha(z+1)]));$$

$$(\mathcal{C}\text{-DC}^1): \forall \beta, \gamma (A[\beta, \gamma] \rightarrow \exists \delta A[\gamma, \delta])$$

$$\rightarrow \forall \beta, \gamma (A[\beta, \gamma] \rightarrow \exists \alpha ((\alpha)_0 = \beta \wedge \forall z A[(\alpha)_z, (\alpha)_{z+1}]));$$

for any  $A$  from  $\mathcal{C}$ .

Moreover  $\mathcal{C}\text{-AC}^{0i}$  and  $\mathcal{C}\text{-DC}^i$  for  $i = 0, 1$  are defined with  $\exists$  replaced by  $\exists!$  in the premises.

**LEMMA 2.16.** (1) Over  $\mathbf{EL}_0^- + \mathcal{C}\text{-LNP}$ , (i)  $(\mathcal{C} \wedge B\forall^0\text{-}\mathcal{C})\text{-AC}^{!00}$  implies  $\mathcal{C}\text{-AC}^{00}$ ;

(ii)  $(\mathcal{C} \wedge B\forall^0\text{-}\mathcal{C})\text{-DC}^{!0}$  implies  $\mathcal{C}\text{-DC}^0$ .

(2) Over  $\mathbf{EL}_0^-$ , (i)  $\mathcal{C}\text{-DC}^i$  yields  $\exists^i \mathcal{C}\text{-DC}^j$ ; (ii)  $\mathcal{C}\text{-DC}^i$  yields  $\mathcal{C}\text{-AC}^{0j}$ ;

(iii)  $\mathcal{C}\text{-AC}^{0i}$  yields  $\exists^i \mathcal{C}\text{-AC}^{0j}$ , for  $j \leq i \in \{0, 1\}$ ; (iv)  $\mathcal{C}\text{-DC}^{!i}$  yields  $\mathcal{C}\text{-AC}^{!0i}$ ;

(v)  $\mathcal{C} \wedge \Pi_1^0\text{-DC}^{!1}$  yields  $\mathcal{C}\text{-DC}^{!0}$ ; (vi)  $\mathcal{C} \wedge \Pi_1^0\text{-AC}^{!01}$  yields  $\mathcal{C}\text{-AC}^{!00}$ .

(3) (i)  $\mathbf{EL}_0^- + \mathcal{C}\text{-DC}^{!0} \vdash \mathcal{C}\text{-Ind}$ ; (ii)  $\mathbf{EL}_0^- + \mathcal{C}\text{-AC}^{00} \vdash \mathcal{C}\text{-Bdg}$ .

(4)  $\mathbf{EL}_0^- + B\forall^0\mathcal{C}\text{-AC}^{!00} + \exists^0(B\forall^0\mathcal{C})\text{-Ind} \vdash \mathcal{C}\text{-DC}^{!0}$ .

(5)  $\mathbf{EL}_0^- + \forall^0(\mathcal{C} \wedge \text{-}\mathcal{C})\text{-DC}^{!1} + \mathcal{C}\text{-LNP} \vdash \forall^0 \exists^0 \mathcal{C}\text{-DC}^{!1}$ .

**PROOF.** In what follows, let  $A$  be  $\mathcal{C}$ .

(2)(i) ( $i=0$ ) If  $\forall x, y (\exists u A[x, y, u] \rightarrow \exists z, v A[y, z, v])$  then  $\forall x, y (B[x, y] \rightarrow \exists z B[y, z])$  where  $B[x, y] \equiv A[(x)_0^2, (y)_0^2, (y)_1^2]$ . For any  $x, y$  such that  $\exists u A[x, y, u]$ , since  $\exists y, u B[(x, 0), (y, u)]$ ,  $\mathcal{C}\text{-DC}^0$  yields  $\beta$  with  $\beta(0) = (x, 0)$  and  $\forall z B[\beta(z), \beta(z+1)]$ . Define  $\alpha$  by  $\alpha(x) = (\beta(x))_0^2$ . ( $i=1$ ) is similarly proved.

- (ii) ( $i=0$ ) If  $\forall x \exists y A[x, y]$  then  $\forall u \exists v ((v)_0^2 = (u)_0^2 + 1 \wedge A[(u)_0^2, (v)_1^2])$ , and  $\mathcal{C}\text{-DC}^0$  yields  $\alpha$  with  $\alpha(0) = (0, 0)$  and  $\forall x ((\alpha(x+1))_0^2 = (\alpha(x))_0^2 + 1 \wedge A[(\alpha(x))_0^2, (\alpha(x+1))_1^2])$ .  $\Delta_0^0\text{-Ind}$  shows  $(\alpha(x))_0^2 = x$  and so  $\forall x A[x, (\alpha(x+1))_1^2]$ .  
 ( $i=1$ ) If  $\forall x \exists \gamma A[x, \gamma]$ ,  $\mathcal{C}\text{-DC}^1$  yields  $\alpha$  with  $(\alpha)_0 = \underline{0}$  and

$$\forall x ((\alpha)_{x+1}(0) = (\alpha)_x(0) + 1 \wedge A[(\alpha)_x(0), (\alpha)_{x+1}\ominus 1]).$$

- (v)(vi) If  $\exists! z A[z]$  then  $\exists! \gamma (A[\gamma(0)] \wedge \gamma \ominus 1 = \underline{0})$  and vice versa, where  $\gamma \ominus 1 = \underline{0}$  is  $\Pi_1^0$ .

(3)(i) Let  $B[x, y] := y = x + 1 \wedge (y \leq n \rightarrow A[y])$ . If  $A[0] \wedge (\forall x < n)(A[x] \rightarrow A[x+1])$ , as  $\forall x, y (B[x, y] \rightarrow \exists! z B[y, z])$  and  $B[0, 1]$ ,  $\mathcal{C}\text{-DC}^0$  yields  $\alpha$  with  $\forall x B[\alpha(x), \alpha(x+1)]$  and  $\alpha(0) = 0$ . By  $\Delta_0^0\text{-Ind}$   $(\forall x \leq n)(x = \alpha(x))$  and  $A[n]$ .

(4) Let  $\forall x, y (A[x, y] \rightarrow \exists! z A[y, z])$  and  $A[x, y]$ .  $\exists^0(\mathcal{B}\forall^0\mathcal{C})\text{-Ind}$  shows  $\forall n \exists! u C[n, u]$  where

$$C[n, u] := |u| = n + 2 \wedge u(0) = x \wedge u(1) = y \wedge (\forall k < n + 1) A[u(k), u(k+1)].$$

$\mathcal{B}\forall^0\mathcal{C}\text{-AC}^{00}$  yields  $\beta$  with  $\forall n C[n, \beta(n)]$ . We can easily see  $\beta(n) \subset \beta(n+1)$  by  $\Delta_0^0\text{-Ind}$ . Thus  $\forall k A[\alpha(k), \alpha(k+1)]$  for  $\alpha(k) = \beta(k)(k)$ .

(5) Since  $\Pi_1^0 \wedge \forall^0(\mathcal{C} \wedge \neg \mathcal{C}) \subseteq \forall^0(\Delta_0^0 \wedge \mathcal{C} \wedge \neg \mathcal{C}) \subseteq \forall^0(\mathcal{C} \wedge \neg \mathcal{C})$ , (2)(iv)(v) and  $\mathcal{C}\text{-LNP}$  yield

$$\exists! \eta \forall x \exists y A[\xi, \eta, x, y] \leftrightarrow \exists! \eta B[\xi, \eta]$$

$$\text{where } B[\xi, \eta] := \forall x (\forall y < (\eta)_1^2(x)) (A[\xi, (\eta)_0^2, x, (\eta)_1^2(x)] \wedge \neg A[\xi, (\eta)_0^2, x, y]).$$

Assume  $\forall \beta, \gamma (\forall x \exists y A[\beta, \gamma, x, y] \rightarrow \exists! \delta \forall x \exists y A[\gamma, \delta, x, y])$ . Then, by the equivalence, we have  $\forall \beta, \gamma (B[(\beta)_0^2, \gamma] \rightarrow \exists! \delta B[(\gamma)_0^2, \delta])$ , and  $\forall^0(\mathcal{C} \wedge \neg \mathcal{C})\text{-DC}^1$  yields  $\gamma$  such that  $\forall z B[(\gamma)_z^2, (\gamma)_{z+1}^2]$  which implies  $\forall z, x \exists y A[(\gamma)_z^2, (\gamma)_{z+1}^2, x, y]$ .  $\dashv$

DEFINITION 2.17 ( $\mathbf{EL}_0^*$ ,  $\mathbf{EL}_0$  and  $\mathbf{EL}$ ).

$$\mathbf{EL}_0^* := \mathbf{EL}_0^- + \Delta_0^0\text{-AC}^{00}; \quad \mathbf{EL}_0 := \mathbf{EL}_0^* + \Sigma_1^0\text{-Ind}; \quad \mathbf{EL} := \mathbf{EL}_0 + \mathcal{L}_F\text{-Ind}.$$

By 2.8(2)(ii) and 2.16(1),  $\mathbf{EL}_0^- \vdash \Delta_0^0\text{-DC}^0 \leftrightarrow \Delta_0^0\text{-DC}^0$ . By 2.16(2)(i)(ii)(3)(i)(4),  $\mathbf{EL}_0 = \mathbf{EL}_0^- + \Delta_0^0\text{-DC}^0$ .

**2.3. Relation to set-based systems.** One might consider that the study of our function-based second order arithmetic is equivalent to that of the famous set-based one (extensively done, e.g., in [39]), since functions are coded by sets as graphs and sets are coded by functions as characteristic functions. This expectation is true if we consider only classical systems not sensitive to arithmetical complexity. Otherwise there are several delicate differences. We first clarify the correspondence between the two settings along which we consider similarity and dissimilarity.

DEFINITION 2.18 (characteristic function interpretation  $\text{ch}$ ). Assign injectively function variables  $\alpha_X$  of  $\mathcal{L}_F$  to set variables  $X$  of  $\mathcal{L}_S$ . For an  $\mathcal{L}_S$  formula  $A$ , define an  $\mathcal{L}_F$  formula  $A^{\text{ch}}$  by

$$\begin{aligned} \perp^{\text{ch}} &:= \perp; & (t \in X)^{\text{ch}} &:= \alpha_X(t) = 0; & (s \text{ R } t)^{\text{ch}} &:= s \text{ R } t \text{ for } \text{R} \equiv =, <; \\ (A \square B)^{\text{ch}} &:= A^{\text{ch}} \square B^{\text{ch}} \text{ for } \square \equiv \wedge, \rightarrow, \vee; & (Qx A)^{\text{ch}} &:= Qx A^{\text{ch}} \text{ for } Q \equiv \forall, \exists; \\ (\forall X A)^{\text{ch}} &:= \forall \alpha_X (\alpha_X < \underline{2} \rightarrow A^{\text{ch}}); & (\exists X A)^{\text{ch}} &:= \exists \alpha_X (\alpha_X < \underline{2} \wedge A^{\text{ch}}). \end{aligned}$$

DEFINITION 2.19 (graph interpretation  $\mathbf{g}$ ). Assign injectively variables  $X_\alpha$  of  $\mathcal{L}_S$  to variables  $\alpha$  of  $\mathcal{L}_F$ . For an  $\mathcal{L}_F$ -term  $t$ , define  $\llbracket t \rrbracket^{\mathbf{g}}(x)$ :

$$\begin{aligned} \llbracket x \rrbracket^{\mathbf{g}}(y) &\equiv x = y; \\ \llbracket c \rrbracket^{\mathbf{g}}(y) &\equiv c = y \text{ for } c = 0, 1; \\ \llbracket t \circ t' \rrbracket^{\mathbf{g}}(y) &\equiv \exists x, x' (\llbracket t \rrbracket^{\mathbf{g}}(x) \wedge \llbracket t' \rrbracket^{\mathbf{g}}(x') \wedge y = x \circ x') \text{ for } \circ \equiv +, \cdot, \exp; \\ \llbracket \alpha(t) \rrbracket^{\mathbf{g}}(y) &\equiv \exists z (\llbracket t \rrbracket^{\mathbf{g}}(z) \wedge (z, y) \in X_\alpha); \\ \llbracket \alpha \upharpoonright t \rrbracket^{\mathbf{g}}(u) &\equiv \llbracket t \rrbracket^{\mathbf{g}}(|u|) \wedge (\forall x < |u|) ((x, u(x)) \in X_\alpha). \end{aligned}$$

For  $A$  in  $\mathcal{L}_F$ , define  $A^{\mathbf{g}}$  in  $\mathcal{L}_S$  as follows, where  $\text{Func}[X] := \forall x \exists! y ((x, y) \in X)$ :

$$\begin{aligned} \perp^{\mathbf{g}} &\equiv \perp; & (s R t)^{\mathbf{g}} &\equiv \exists x, y (\llbracket s \rrbracket^{\mathbf{g}}(x) \wedge \llbracket t \rrbracket^{\mathbf{g}}(y) \wedge x R y) \text{ for } R \equiv =, <; \\ (A \square B)^{\mathbf{g}} &\equiv A^{\mathbf{g}} \square B^{\mathbf{g}} \text{ for } \square \equiv \wedge, \rightarrow, \vee; & (QxA)^{\mathbf{g}} &\equiv QxA^{\mathbf{g}} \text{ for } Q \equiv \forall, \exists; \\ (\forall \alpha A)^{\mathbf{g}} &\equiv \forall X_\alpha (\text{Func}[X_\alpha] \rightarrow A^{\mathbf{g}}); & (\exists \alpha A)^{\mathbf{g}} &\equiv \exists X_\alpha (\text{Func}[X_\alpha] \wedge A^{\mathbf{g}}). \end{aligned}$$

LEMMA 2.20.  $\mathbf{EL}_0^- + \Sigma_1^0\text{-Bdg} + \Delta_0^0\text{-AC}^{00} + \Sigma_n^0\text{-Ind}$  is interpreted by the graph interpretation  $\mathbf{g}$  in  $\mathbf{RCA}_0^* + \Sigma_n^0\text{-Ind}$ .

PROOF. As  $\mathbf{RCA}_0^*$  proves  $\Sigma_1^0\text{-Bdg}$ , we have, for any term  $t$ ,

$$\exists x \llbracket t \rrbracket^{\mathbf{g}}(x) \rightarrow \forall X_\alpha (\forall x \exists! y ((x, y) \in X_\alpha \rightarrow \exists v \llbracket \alpha \upharpoonright t \rrbracket^{\mathbf{g}}(v))$$

Thus we can show  $\exists! x \llbracket t \rrbracket^{\mathbf{g}}(x)$  by induction on  $t$ , and hence  $(s R t)^{\mathbf{g}}$  is equivalent to  $\forall x, y (\llbracket s \rrbracket^{\mathbf{g}}(x) \wedge \llbracket t \rrbracket^{\mathbf{g}}(y) \rightarrow x R y)$ . Thus, if  $A$  is  $\Delta_0^0$ , then  $A^{\mathbf{g}}$  is  $\Delta_1^0$  and  $\mathbf{RCA}_0^*$  yields  $X_\alpha = \{(x, y) : A[x, y]^{\mathbf{g}} \wedge (\forall z < y) \neg A[x, y]^{\mathbf{g}}\}$ .

If  $(\forall x \exists y A[x, y])^{\mathbf{g}}$ , then  $\forall x \exists! y ((x, y) \in X_\alpha)$  by  $\Delta_0^0\text{-LNP}$ , which is provable in  $\mathbf{RCA}_0^*$ . Now  $\forall x \exists y ((x, y) \in X_\alpha \wedge A[x, y]^{\mathbf{g}})$  i.e.,  $(\forall x A[x, \alpha(x)])^{\mathbf{g}}$ . Thus  $(\Delta_0^0\text{-AC}^{00})^{\mathbf{g}}$ . The interpretability of the remaining axioms by  $\mathbf{g}$  is obvious.  $\dashv$

Thus  $\mathbf{g}$  seems to require  $\Delta_1^0\text{-CA}$  in  $\mathcal{L}_S$ . To interpret it,  $\mathbf{ch}$  seems to require  $\Delta_0^0\text{-AC}^{00}$  and hence  $\mathbf{EL}_0^*$ .

The delicate differences are mainly caused by the clauses  $\forall x \exists! y ((x, y) \in X_\alpha)$  of the totality (which is known to be  $\Pi_2^0$  complete in recursion theory) and of  $\forall x (\alpha_X(x) < 2)$ . For example, the premise  $\forall x \exists \alpha A[x, \alpha]$  of the number-function choice  $\mathcal{C}\text{-AC}^{01}$  is interpreted by  $\mathbf{g}$  as  $\forall x \exists X_\alpha (\text{Func}[X_\alpha] \wedge A[x, \alpha]^{\mathbf{g}})$  and so we cannot apply the number-set choice, unless the class is closed under conjunctions with  $\Pi_2^0$  formulae. Conversely,  $(\forall x \exists X A[x, X])^{\mathbf{ch}}$  is  $\forall x (\exists \alpha_X < 2) A[x, X]^{\mathbf{ch}}$  and therefore we could say that the number-set choice is only a fragment of number-function choice, or bounded version of the latter. This motivates the following.

DEFINITION 2.21 (bounded choice schema). For a class  $\mathcal{C}$  of formulae, define the following axiom schemata:

$$\begin{aligned} (\mathcal{C}\text{-BAC}^{01}) &: \forall x (\exists \beta < (\gamma)_x) A[x, \beta] \rightarrow (\exists \alpha < \gamma) \forall x A[x, (\alpha)_x]; \\ (\mathcal{C}\text{-BAC}^{00}) &: \forall x (\exists y < \beta(x)) A[x, y] \rightarrow (\exists \alpha < \beta) \forall x A[x, \alpha(x)]; \\ (\mathcal{C}\text{-2AC}^{01}) &: \forall x (\exists \beta < \underline{2}) A[x, \beta] \rightarrow (\exists \alpha < \underline{2}) \forall x A[x, (\alpha)_x]; \\ (\mathcal{C}\text{-2AC}^{00}) &: \forall x (\exists y < 2) A[x, y] \rightarrow (\exists \alpha < \underline{2}) \forall x A[x, \alpha(x)], \end{aligned}$$

for any  $A$  from  $\mathcal{C}$ .



#### 2.4. Semi-classical or semi-constructive principles.

DEFINITION 2.22 (MP, LPO,  $\mathcal{C}$ -DM,  $\mathcal{C}$ -GDM and LLPO). MP and LPO denote  $\Sigma_1^0$ -DNE and  $\Sigma_1^0$ -LEM both from 2.6, respectively. LLPO denotes  $\Sigma_1^0$ -DM, where for a class  $\mathcal{C}$  of formulae, define the schemata:

$$(\mathcal{C}\text{-DM}): \neg(A \wedge B) \rightarrow \neg A \vee \neg B;$$

$$(\mathcal{C}\text{-GDM}): \neg(\forall x < y)A \rightarrow (\exists x < y)\neg A,$$

for  $A, B$  from  $\mathcal{C}$ .

LEMMA 2.23. (1)  $\mathcal{C}$ -LEM yields  $A \vee \neg A$  and  $\neg\neg A \rightarrow A$  for any  $A$  built from  $\mathcal{C}$  formulae by  $\wedge, \vee, \rightarrow$  and  $\neg$ .

- (2) (i)  $\mathbf{B}\exists^0(\forall^0\text{-}\mathcal{C}) \subseteq \neg\exists^0\mathbf{B}\forall^0\mathbf{B}\exists^0\mathcal{C}$  over  $\mathbf{EL}_0^- + \exists^0\mathcal{C}\text{-GDM} + \mathcal{C}\text{-Bdg}$ ;  
 (ii)  $\mathbf{EL}_0^- \vdash (\neg\mathcal{C} \vee \neg\mathcal{C})\text{-DNE} \leftrightarrow \mathcal{C}\text{-DM}$ .
- (3)  $\mathbf{EL}_0^- + \mathcal{C}\text{-GDM} \vdash \mathbf{B}\exists^0(\neg\mathcal{C})\text{-DNE}$  and  $\mathbf{EL}_0^- + \mathcal{C}\text{-DNE} + \mathbf{B}\exists^0(\neg\mathcal{C})\text{-DNE} \vdash \mathcal{C}\text{-GDM}$ .
- (4)  $\mathbf{EL}_0^- + \mathcal{C}\text{-GDM} \vdash \mathcal{C}\text{-DM}$ .

PROOF. Let  $A$  and  $B$  be  $\mathcal{C}$ .

(2) (i)  $\neg\exists u(\forall x < t)(\exists y < u)A[x, y]$  is equivalent to  $\neg(\forall x < t)\exists yA[x, y]$  by  $\mathcal{C}\text{-Bdg}$  and to  $(\exists x < t)\forall y\neg A[x, y]$  by  $\exists^0\mathcal{C}\text{-GDM}$ . (ii)  $\neg\neg(\neg A \vee \neg B), (\neg\neg A \wedge \neg\neg B) \rightarrow \perp$  and  $\neg(A \wedge B)$  are equivalent.

(3)  $\neg\neg(\exists x < y)\neg A$  is equivalent to  $\neg(\forall x < y)\neg\neg A$  and implies  $\neg(\forall x < y)A$ . Thus  $\mathcal{C}\text{-DNE}$  yields the converse.  $\dashv$

LEMMA 2.24. (1) Over  $\mathbf{EL}_0^- + \Sigma_n^0\text{-DNE}$ , (i)  $\neg\Pi_n^0 = \Sigma_n^0$ ; (ii)  $\neg\Sigma_{n+1}^0 = \Pi_{n+1}^0$ ; and so (iii)  $\Pi_{n+1}^0\text{-DNE}$  holds.

- (2) Over  $\mathbf{EL}_0^-$ , the following hold.
  - (i)  $\Sigma_{n+1}^0\text{-DNE}$  yields  $\Sigma_n^0\text{-GDM}$ ;
  - (ii)  $\Sigma_n^0\text{-GDM} \wedge \Sigma_{n-1}^0\text{-DNE}$  yields  $\mathbf{B}\Sigma_{n+1}^0\text{-DNE}$ ;
  - (iii)  $\mathbf{B}\Sigma_{n+1}^0\text{-DNE}$  yields  $\Pi_n^0 \vee \Pi_n^0\text{-DNE}$ ;
  - (iv) both  $\Sigma_{n+1}^0\text{-DNE}$  and  $\Pi_{n+1}^0 \vee \Pi_{n+1}^0\text{-DNE}$  yield  $\Sigma_n^0 \vee \Pi_n^0\text{-DNE}$ ;
  - (v)  $\Sigma_n^0 \vee \Pi_n^0\text{-DNE}$  is equivalent to  $\Sigma_n^0\text{-LEM}$ ;
  - (vi)  $\Sigma_n^0\text{-LEM}$  yields  $\Sigma_n^0\text{-DNE}$  and  $\Pi_n^0 \vee \Pi_n^0\text{-DNE}$ .

PROOF. (1) By induction,  $\neg\Pi_n^0 = \neg\forall^0\neg\neg\Sigma_{n-1}^0 = \neg\neg\exists^0\neg\Sigma_{n-1}^0 = \neg\neg\exists^0\Pi_{n-1}^0 = \Sigma_n^0$ , and  $\neg\Sigma_{n+1}^0 = \forall^0\neg\Pi_n^0 = \forall^0\Sigma_n^0$ .

(2) (i) and (ii) are by 2.23(3), since  $\Sigma_{n-1}^0\text{-DNE}$  implies  $\neg\Sigma_n^0 = \Pi_n^0$  and since  $\mathbf{B}\exists^0(\neg\Sigma_n^0) = \mathbf{B}\Sigma_{n+1}^0 \subseteq \Sigma_{n+1}^0$ . (iii) and (iv) are by 2.11. For (v), for  $A$  from  $\Sigma_{n-1}^0$ ,  $\Sigma_{n-1}^0\text{-DNE}$  applied to  $\neg((\forall x)A) \wedge \neg\forall xA$  yields  $\neg((\forall x\neg\neg A) \wedge \neg\forall xA)$  and  $\neg\neg(\exists x\neg A \vee \forall xA)$  where  $\neg\Sigma_{n-1}^0 = \Pi_{n-1}^0$ . The rest of (v) and (vi) are by 2.23(1).  $\dashv$

We thus obtain the diagram in Section 1.5. [1] showed the independence of  $\Pi_n^0 \vee \Pi_n^0\text{-DNE}$  and  $\Sigma_n^0\text{-DNE}$  and the non-reversibility of (2) (i), (iv) and (vi) for  $n > 0$ . While (ii) and (iii) are reversible with  $\Delta_0^1\text{-Ind}$ , we do not know over  $\mathbf{EL}_0^-$  if they are nor if  $\Pi_{n+1}^0 \vee \Pi_{n+1}^0\text{-DNE}$  or  $\Sigma_n^0\text{-LEM}$  implies  $\mathbf{B}\Sigma_{n+1}^0\text{-DNE}$  or  $\Sigma_n^0\text{-GDM}$ .

## 2.5. Brouwerian axioms.

### 2.5.1. bar induction.

DEFINITION 2.25 (Bar). Let  $\text{Bar}[\gamma, \{u: B[u]\}] := \forall \alpha (\forall k (\gamma(\alpha \upharpoonright k) = 0) \rightarrow \exists n B[\alpha \upharpoonright n])$ .

DEFINITION 2.26 ( $\mathcal{C}$ -BI $_D$ ,  $(\mathcal{C}, \mathcal{D})$ -BI $_M$ ,  $\mathcal{C}$ -BI). Define the following axiom schemata:

$$\begin{aligned} (\mathcal{C}\text{-BI}_D): & \text{Bar}[\underline{0}, \{u: \alpha(u) = 0\}] \wedge \wedge \forall u (\alpha(u) = 0 \rightarrow A[u]) \\ & \rightarrow (\forall u (\forall x A[u * \langle x \rangle] \rightarrow A[u]) \rightarrow A[\langle \rangle]); \\ ((\mathcal{C}, \mathcal{D})\text{-BI}_M): & \text{Bar}[\underline{0}, \{u: B[u]\}] \wedge \forall u, v (B[u] \rightarrow B[u * v]) \wedge \forall u (B[u] \rightarrow A[u]) \\ & \rightarrow (\forall u (\forall x A[u * \langle x \rangle] \rightarrow A[u]) \rightarrow A[\langle \rangle]); \\ (\mathcal{C}\text{-BI}): & \text{Bar}[\underline{0}, \{u: A[u]\}] \wedge \forall u (\forall x A[u * \langle x \rangle] \rightarrow A[u]) \rightarrow A[\langle \rangle], \end{aligned}$$

for any  $A$  from  $\mathcal{C}$  and  $B$  from  $\mathcal{D}$ .

Note that, in  $\mathcal{C}$ -BI we do not distinguish  $B$  from  $A$ , since  $\text{Bar}[\underline{0}, \{u: B[u]\}]$  and  $\forall u (B[u] \rightarrow A[u])$  imply  $\text{Bar}[\underline{0}, \{u: A[u]\}]$ .

As LPO is absolutely against Brouwer's philosophy, 2.27 below shows that  $\mathcal{L}_F$ -BI cannot be a Brouwerian axiom though Brouwer's original texts look to accept it. Whereas Kleene presumed that Brouwer had meant  $\mathcal{L}_F$ -BI $_D$ , it seems more common to consider  $(\mathcal{L}_F, \mathcal{L}_F)$ -BI $_M$  (see, e.g., [45]), which are, as will be shown in 2.28(1)(iii) and 2.39(4), equivalent to  $\mathcal{L}_F$ -BI $_D$  under another Brouwerian axiom. Yet, there seems to be no positive argument for this presumption in the literature (for, monotonicity was not mentioned explicitly in the original texts and there might be other ways to restrict bar induction consistently with other Brouwerian axioms) and  $\mathcal{C}$ -BI for  $\mathcal{C} \not\geq \Sigma_1^0 \vee \Pi_1^0$  still survives. However we do not need to enter into such discussion, since our result will be same for  $\mathcal{C}$ -BI and  $\mathcal{C}$ -BI $_D$ , and hence for any variant inbetween, including  $(\mathcal{C}, \mathcal{D})$ -BI $_M$ . Actually below we see:  $\Pi_1^0$ -BI is finitistically justifiable and this is optimal in the sense that  $\Sigma_1^0$ -BI $_D$  is not.

LEMMA 2.27.  $\mathbf{EL}_0^- + \mathcal{C}\text{-LEM} + (\exists^0 \mathcal{C} \vee \forall^0 \neg \mathcal{C})\text{-BI} \vdash \exists^0 \mathcal{C}\text{-LEM}$ .

In particular  $\mathbf{EL}_0^- + (\Sigma_1^0 \vee \Pi_1^0)\text{-BI} \vdash \text{LPO}$ .

PROOF. Let  $C[x]$  be  $\mathcal{C}$  and

$$B[u] := (|u| = 1 \wedge \neg C[u(0)]) \vee (|u| = 0 \wedge (\exists x C[x] \vee \forall x \neg C[x])).$$

If  $\forall x B[u * \langle x \rangle]$  then  $|u| = 0 \wedge \forall x \neg C[x]$  and  $B[u]$ .  $\mathcal{C}$ -LEM yields  $\text{Bar}[\underline{0}, \{u: B[u]\}]$  by  $C[\alpha(0)] \rightarrow B[\alpha \upharpoonright 0]$  and  $\neg C[\alpha(0)] \rightarrow B[\alpha \upharpoonright 1]$ .  $\dashv$

LEMMA 2.28. (1) (i)  $\mathbf{EL}_0^- + \mathcal{C}\text{-BI} \vdash (\mathcal{C}, \mathcal{L}_F)\text{-BI}_M$ ;

(ii)  $\mathbf{EL}_0^- + \mathcal{C}\text{-BI}_D \vdash (\mathcal{C}, \Delta_0^0)\text{-BI}_M$ ;

(iii)  $\mathbf{EL}_0^- + (\mathcal{C}, \Delta_0^0)\text{-BI}_M \vdash \mathcal{C}\text{-BI}_D$ .

(2)  $\mathbf{EL}_0^- + \mathcal{C}\text{-BI}_D \vdash \mathcal{C}\text{-Ind}$ .

(3)  $\mathbf{EL}_0^- + \exists^0 \mathcal{C}\text{-DNE} + \mathcal{C}\text{-DC}^0 \vdash \neg \mathcal{C}\text{-BI}$ .

(4)  $\mathbf{EL}_0^- + (\mathcal{D}, \mathbb{B}\exists^0 \mathcal{C})\text{-BI}_M \vdash (\mathcal{D}, \exists^0 \mathcal{C})\text{-BI}_M$ .

(5) (i)  $\mathbf{EL}_0^- + \mathcal{C}\text{-BI}_D \vdash \forall^0 \mathcal{C}\text{-BI}_D$ ;

(ii)  $\mathbf{EL}_0^- + (\mathcal{C}, \mathcal{D})\text{-BI}_M \vdash (\forall^0 \mathcal{C}, \mathcal{D})\text{-BI}_M$ ; and

(iii)  $\mathbf{EL}_0^- + \mathcal{C}\text{-BI} \vdash \forall^0 \mathcal{C}\text{-BI}$ .

PROOF. (1) (i) Trivial. (ii) Easy by 2.10(d). (iii) Let

$$B[u] := (\exists x \leq |u|)(\alpha(u \upharpoonright x) = 0).$$

Then  $\text{Bar}[0, \{u: \alpha(u) = 0\}]$  implies  $\text{Bar}[0, \{u: B[u]\}]$ , and also  $B[u^*(x)]$  implies  $B[u] \vee \alpha(u^*(x)) = 0$  and  $B[u] \vee A[u^*(x)]$  if  $\forall u(\alpha(u) = 0 \rightarrow A[u])$ . Thus we can see that  $\forall x(B[u^*(x)] \vee A[u^*(x)])$  implies  $B[u] \vee \forall x A[u^*(x)]$  and  $B[u] \vee A[u]$  if  $\forall x A[u^*(x)] \rightarrow A[u]$ .

In what follows, let  $C$  be  $\mathcal{C}$ .

(2) Assume  $C[0]$  and  $(\forall x < n)(C[x] \rightarrow C[x+1])$ . Take

$$\alpha(u) = |u| \dot{-} n \text{ and } A[u] := C[n - |u|].$$

(3) Assume (a)  $\text{Bar}[0, \{u: \neg C[u]\}]$  and (b)  $\forall u(\forall x \neg C[u^*(x)] \rightarrow \neg C[u])$ . Let

$$B[u, v] := C[v] \wedge u \subset v \wedge |v| = |u| + 1.$$

By  $\exists^0\mathcal{C}$ -DNE with (b),  $\forall u, v(B[u, v] \rightarrow \exists w B[v, w])$ . If  $C[\langle \rangle]$ , as  $\exists v B[\langle \rangle, v]$ ,  $\mathcal{C}$ -DC<sup>0</sup> yields  $\alpha$  with  $\forall n B[\alpha(n), \alpha(n+1)]$  and  $\alpha(0) = \langle \rangle$  and, for  $\beta(n) := (\alpha(n+1))(n)$ ,  $\Delta_0^0$ -Ind shows  $\alpha(n) = \beta \upharpoonright n$  and so  $\forall n C[\beta \upharpoonright n]$  contradicting (a).

(4) Let  $B[u] := (\exists x, y < |u|)C[u \upharpoonright y, x]$ . Obviously  $B[u] \rightarrow B[u^*v]$ .

$\text{Bar}[0, \{u: \exists x C[u, x]\}]$  implies  $\text{Bar}[0, \{u: B[u]\}]$ , and  $B[u]$  implies  $\exists x C[u, x]$ , if  $\forall u, v(\exists x C[u, x] \rightarrow \exists x C[u^*v, x])$ .

(5) (i) Let  $[v]_0^2 := \langle (v(0))_0^2, \dots, (v(|v|-1))_0^2 \rangle$  and  $A[y, u] := C[[u]_0^2, (\langle \langle y \rangle * u \rangle(|u|))_1^2]$ . If  $\text{Bar}[0, \{u: \alpha(u) = 0\}]$  and  $\forall u(\alpha(u) = 0 \rightarrow \forall z C[u, z])$  then  $\text{Bar}[0, \{u: \alpha([u]_0^2) = 0\}]$  and  $\forall u(\alpha([u]_0^2) = 0 \rightarrow A[y, u])$ .

If  $\forall u(\forall x, z C[u^*(x), z] \rightarrow \forall z C[u, z])$ , then  $\forall x A[y, u^*(x)]$ , i.e.,  $\forall x C[[u]_0^2 * \langle (x)_0^2, (x)_1^2 \rangle]$  yields  $\forall z C[[u]_0^2, z]$ , and so  $A[y, u]$ .

Thus  $A[y, \langle \rangle]$  by  $\mathcal{C}$ -Bl<sub>D</sub> for any  $y$ . Hence  $\forall z C[\langle \rangle, z]$ . (ii) (iii) Similar.  $\dashv$

**COROLLARY 2.29.** (1)  $\mathbf{EL}_0 + \mathbf{MP} \vdash \Pi_1^0\text{-Bl}$ .

(2)  $\mathbf{EL}_0^- + \Sigma_n^0\text{-Bl}_D \vdash \Pi_{n+1}^0\text{-Ind}$ .

(3)  $\mathbf{EL}_0^- \vdash \mathcal{C}\text{-Bl}_D \leftrightarrow (\mathcal{C}, \Sigma_1^0)\text{-Bl}_M$ .

### 2.5.2. fan theorem.

**DEFINITION 2.30 (Fan).** Let  $u < \beta := (\forall k < |u|)(u(k) < \beta(k))$  and

$$\text{Fan}[\gamma] := \forall u(\gamma(u) = 0 \rightarrow \exists x(\gamma(u^*(x)) = 0) \wedge \exists n \forall x(\gamma(u^*(x)) = 0 \rightarrow x < n)).$$

**DEFINITION 2.31 ( $\mathcal{C}$ -FT,  $\mathcal{C}$ -BFT,  $\mathcal{C}$ -WFT).** For a class  $\mathcal{C}$  of formulae, define the following axiom schemata.

$$\begin{aligned} (\mathcal{C}\text{-FT}): \text{Fan}[\gamma] \wedge \text{Bar}[\gamma, \{u: B[u]\}] &\rightarrow \exists m \forall \alpha (\forall k (\gamma(\alpha \upharpoonright k) = 0) \\ &\rightarrow (\exists n < m) B[\alpha \upharpoonright n]); \end{aligned}$$

$$\begin{aligned} (\mathcal{C}\text{-BFT}): \text{Fan}[\gamma] \wedge \forall u(\gamma(u) = 0 \rightarrow u < \beta) \wedge \text{Bar}[\gamma, \{u: B[u]\}] \\ \rightarrow \exists m \forall \alpha (\forall k (\gamma(\alpha \upharpoonright k) = 0) \rightarrow (\exists n < m) B[\alpha \upharpoonright n]); \end{aligned}$$

$$(\mathcal{C}\text{-WFT}): (\forall \alpha < \underline{2}) \exists n B[\alpha \upharpoonright n] \rightarrow \exists m (\forall \alpha < \underline{2}) (\exists n < m) B[\alpha \upharpoonright n],$$

for any  $B$  from  $\mathcal{C}$ .

$\mathcal{C}$ -WFT consists of the instances of  $\mathcal{C}$ -FT with  $\gamma$  defined by  $\gamma(u) = 0$  iff  $u < \underline{2}$ . This is a classical contrapositive of weak König's lemma. 2.20 is enhanced as (1) in the following (cf. [39, X.4 and IV.1.4]).

**LEMMA 2.32.** (1)  $\mathbf{EL}_0^- + \mathcal{L}_F\text{-LEM} + \Sigma_1^0\text{-Bdg} + \Delta_0^0\text{-AC}^{00} + \Delta_0^0\text{-BFT}$  is interpreted by  $\mathbf{g}$  in  $\mathbf{WKL}_0^*$ .

- (2) (i)  $\mathbf{EL}_0^- + (\exists^0 \forall^0 \mathbf{B} \exists^0 \mathcal{C}, \mathbf{B} \exists^0 \mathcal{C})\text{-BI}_M \vdash \mathcal{C}\text{-FT}$ ; and  
(ii)  $\mathbf{EL}_0^- + (\exists^0 \mathbf{B} \forall^0 \mathbf{B} \exists^0 \mathcal{C}, \mathbf{B} \exists^0 \mathcal{C})\text{-BI}_M \vdash \mathcal{C}\text{-WFT}$ .  
(3) (i)  $\mathbf{EL}_0^- + \mathbf{B} \exists^0 \mathcal{C}\text{-FT} \vdash \exists^0 \mathcal{C}\text{-FT}$  and (ii)  $\mathbf{EL}_0^- + \mathbf{B} \exists^0 \mathcal{C}\text{-BFT} \vdash \exists^0 \mathcal{C}\text{-BFT}$ .  
(4)  $\mathbf{EL}_0^- + \mathbf{B} \forall^0 \mathcal{C}\text{-WFT} \vdash \mathcal{C}\text{-Bdg}$ .

PROOF. In what follows, let  $\mathcal{C}$  be from  $\mathcal{C}$ .

- (2) (i) Define  $A$  as follows, which is in from  $\exists^0 \forall^0 \mathbf{B} \exists^0 \mathcal{C}$ :

$$A[u, \gamma] := \exists n \forall v ((\forall k \leq |v|)(\gamma(u*(v|k)) = 0) \wedge |v| = n \rightarrow (\exists k < |u*v|)C[(u*v)|k]).$$

If  $\text{Fan}[\gamma]$  then  $\forall^0 \mathbf{B} \exists^0 \mathcal{C}\text{-Bdg}$ , which is by 2.28(2), yields  $\forall x A[u*(x)] \rightarrow A[u]$ . (ii) Similar.

- (3) Let  $B[u] := (\exists x, k < |u|)C[u|k, x]$ . As  $\exists k, xC[\alpha|k, x]$  implies  $\exists n B[\alpha|n]$ , if  $\text{Bar}[\gamma, \{u: \exists x C[u, x]\}]$  then  $\text{Bar}[\gamma, \{u: B[u]\}]$ .

- (4) Let  $B[u, m] := |u| \geq m \wedge (\forall x < m)(u \upharpoonright x \wedge u(x) > 0 \rightarrow C[x, |u| - m])$ . Then  $(\forall x < m) \exists y C[x, y]$  implies  $(\forall \alpha < \underline{2}) \exists k B[\alpha|k, m]$  and, by  $\mathbf{B} \forall^0 \mathcal{C}\text{-WFT}$ , it also implies  $\exists n (\forall \alpha < \underline{2})(\exists k < n) B[\alpha|k, m]$ , i.e.,  $\exists n (\forall x < m)(\exists y < n) C[x, y]$ .  $\dashv$

Thus, classically  $\Sigma_1^0\text{-BFT}$  is finitistically justifiable. This is optimal in the sense that  $(\mathbf{ACA}_0)^{\text{cl}}$  classically follows from  $\Pi_1^0\text{-WFT}$  as shown in [7] (cf. 4.8(1)); and from  $\Delta_0^0\text{-FT}$  as in [39, Theorem III.7.2] (cf. 4.9(1)). Though [39, Theorem III.7.2] relies on  $\Sigma_1^0\text{-Ind}$ , it does not matter as seen in the next proposition.

PROPOSITION 2.33.  $\mathbf{EL}_0^- + \Delta_0^0\text{-FT}$  proves  $\Sigma_1^0\text{-Ind}$ .

PROOF. Let  $\mathcal{C}$  be  $\Delta_0^0$ . Assume  $\exists y C[0, y]$  and  $(\forall x < n)(\exists y C[x, y] \rightarrow \exists y C[x+1, y])$ . With  $\Delta_0^0\text{-LNP}$ , by replacing  $C[x, y]$  with  $C[x, y] \wedge (\forall z < y) \neg C[x, z]$  we may assume  $(C[x, y] \wedge C[x, z]) \rightarrow y = z$ . Define  $\gamma$  and  $B[x, u]$  by

$$\begin{aligned} \gamma(u) &= 0 \leftrightarrow (\forall k < |u|)(u(k) \neq 0 \rightarrow k \leq n \wedge (\forall l \leq k)(u(l) \neq 0 \wedge C[l, u(l)-1])); \\ B[x, u] &:= |u| > u \upharpoonright (x+1). \end{aligned}$$

Assume  $\gamma(u) = 0$ . We prove  $\text{Fan}[\gamma]$  by case-distinction:

- if  $(\forall k < |u|)(u(k) \neq 0) \wedge |u| \leq n$ , then  $\forall x (\gamma(u*(x)) = 0 \leftrightarrow x = 0 \vee x = y+1)$  for  $y$  with  $C[|u|, y]$ , yielded by  $C[|u|-1, u(|u|-1)-1]$  if  $|u| > 0$ ;
- otherwise  $\forall x (\gamma(u*(x)) = 0 \leftrightarrow x = 0)$ .

As  $\forall \alpha \exists m B[n, \alpha|n]$ ,  $\Delta_0^0\text{-FT}$  yields  $m$  with  $\forall \alpha (\forall k (\gamma(\alpha|k) = 0) \rightarrow (\exists k < m) B[n, \alpha|k])$ . By  $\Delta_0^0\text{-Ind}$  on  $k \leq n+1$  we prove  $(\exists u < m) D[k, u]$  for

$$D[k, u] := |u| = k \wedge (k \neq 0 \rightarrow u(k-1) \neq 0) \wedge \gamma(u) = 0.$$

If  $D[k, v]$ , the assumption yields  $y$  with  $C[k, y]$ ; then  $D[k+1, u]$  for  $u := v*(y+1)$ , and  $(\exists k < m) B[n, (u*\underline{0})|k]$  which implies  $u \leq (u*\underline{0}) \upharpoonright (n+1) < k < m$ .  $\dashv$

### 2.5.3. (weak) continuity principles.

DEFINITION 2.34 ( $\mathcal{C}\text{-WC}^i$ ,  $\mathcal{C}\text{-WC}!^i$ ). For a class  $\mathcal{C}$  of formulae and  $i = 0, 1$ ,  $\mathcal{C}\text{-WC}^i$  is defined as follows, and  $\mathcal{C}\text{-WC}!^i$  is defined with  $\exists$  replaced by  $\exists!$  in the premises.

$$(\mathcal{C}\text{-WC}^0): \forall \alpha \exists x A[\alpha, x] \rightarrow \forall \alpha \exists x, m \forall \beta A[(\alpha|_m)*\beta, x];$$

( $\mathcal{C}$ -WC<sup>1</sup>):  $\forall\alpha\exists\gamma A[\alpha, \gamma] \rightarrow \forall\alpha\exists\gamma(A[\alpha, \gamma] \wedge \forall n\exists m\forall\beta\exists\delta A[(\alpha \upharpoonright m)*\beta, (\gamma \upharpoonright n)*\delta])$ ,<sup>13</sup>  
for  $A$  from  $\mathcal{C}$ .

We can see that  $(\exists^1\mathcal{C})$ -WC!<sup>0</sup> implies  $(\exists^1\mathcal{C})$ -WC!<sup>1</sup>, by considering

$$A[\alpha, x, n] := \exists\gamma(B[\alpha, \gamma] \wedge \gamma \upharpoonright n = x).$$

Thus, with 2.35(1)(iii) below,  $\mathcal{L}_F$ -WC!<sup>1</sup> and  $\mathcal{L}_F$ -WC!<sup>0</sup> are equivalent.<sup>14</sup> Informally this is an easy consequence of the universality (in the sense of category theory) of the product topology with which Baire space is equipped.

$\mathcal{C}$ -WC<sup>i</sup> asserts the existence of a continuous *branch cut*, not the continuity of all branch cuts. We cannot show the equivalence between  $\mathcal{L}_F$ -WC<sup>1</sup> and  $\mathcal{L}_F$ -WC<sup>0</sup>, because of the results mentioned in f.n.14.

By 2.14,  $\Sigma_1^0$ -WC!<sup>1</sup> is vacuous and  $\mathbf{EL}_0^- \vdash \Sigma_1^0$ -WC!<sup>1</sup>. Classically this is optimal by 2.35(2)(ii) below.

- LEMMA 2.35. (1) Over  $\mathbf{EL}_0^-$ , (i)  $\Sigma_1^0$ -WC!<sup>1</sup> holds;  
 (ii)  $\mathcal{C}$ -WC<sup>1</sup> implies  $\mathcal{C}$ -WC<sup>0</sup>; and  
 (iii)  $(\mathcal{C} \wedge \Pi_1^0)$ -WC!<sup>1</sup> implies  $\mathcal{C}$ -WC!<sup>0</sup>.  
 (2) (i)  $\mathbf{EL}_0^- + \Pi_1^0$ -WC<sup>0</sup> + LLPO is inconsistent; and  
 (ii)  $\mathbf{EL}_0^- + \Pi_1^0$ -WC!<sup>0</sup> + LPO is inconsistent.

PROOF. (1) As (ii) is easier, we prove (iii). For  $A$  from  $\mathcal{C}$ , let

$$B[\alpha, \gamma] := A[\alpha, \gamma(0)] \wedge \gamma \oplus 1 = \underline{0}.$$

Then  $\forall\alpha\exists!x A[\alpha, x]$  implies  $\forall\alpha\exists!\gamma B[\alpha, \gamma]$ . By applying  $(\mathcal{C} \wedge \Pi_1^0)$ -WC!<sup>1</sup> to the latter, we have  $\forall\alpha\exists\gamma, m(B[\alpha, \gamma] \wedge \forall\beta\exists\delta B[(\alpha \upharpoonright m)*\beta, (\gamma \upharpoonright 1)*\delta])$ .

(2)(i) Let  $A[\alpha, i] := \exists n(\alpha \upharpoonright n = \underline{0} \upharpoonright n \wedge \alpha(n) > 0 \wedge n = 2 \cdot \lfloor n/2 \rfloor + i)$ . Since  $\neg(A[\alpha, 0] \wedge A[\alpha, 1])$ , by applying LLPO, we have  $\forall\alpha\exists i \neg A[\alpha, i]$ .  $\Pi_1^0$ -WC<sup>0</sup> yields  $i$  and  $n$  with  $\forall\beta \neg A[(\underline{0} \upharpoonright n)*\beta, i]$ . Thus  $\neg A[(\underline{0} \upharpoonright n)*\underline{1}, i] \wedge \neg A[(\underline{0} \upharpoonright (n+1))*\underline{1}, i]$ , a contradiction.

(ii) Let  $A[\alpha, n] := (n = 0 \rightarrow \alpha = \underline{0}) \wedge (n > 0 \rightarrow \alpha(n-1) > 0 \wedge \alpha \upharpoonright (n-1) = \underline{0} \upharpoonright (n-1))$ . LPO and  $\Delta_0^0$ -LNP imply  $\forall\alpha\exists!n A[\alpha, n]$ .  $\Pi_1^0$ -WC!<sup>0</sup>, applied to  $\underline{0}$ , leads a contradiction similarly.  $\dashv$

<sup>13</sup> As  $\mathcal{L}_F$ -WC<sup>1</sup> has turned out to be refuted by Kripke's schema (KS) (see, e.g., [14, p.246]), a formalization of creative subject (CS), its status as an axiom of INT is questionable. Though Vesley [47] proposed an alternative formalization consistent with  $\mathcal{L}_F$ -WC<sup>1</sup>, it does not seem to represent any informal idea of CS but just a technical substitute for KS in a similar way as WFT is a substitute for BI. (Namely, it follows from KS and suffices for concrete uses of CS by Brouwer.) Once  $\mathcal{L}_F$ -WC<sup>1</sup> thus becomes doubtful, we can no longer fully trust  $\mathcal{L}_F$ -WC<sup>0</sup>, because any argument for the latter, basically appealing to the meaning of  $\exists$  in Intuitionism, cannot avoid the former. This is one reason why we take only  $\mathcal{C}$ -WC!<sup>i</sup> in Figures 1 and 2 (see also f.n.11). However, for us it matters only when we discuss which axioms characterize INT (to be weakened for our purpose), and we can use models (or interpretations) satisfying  $\mathcal{L}_F$ -WC<sup>i</sup>: as declared in f.n.5 we confine our study to "objective Intuitionism".

<sup>14</sup>Hence the consistency of  $\mathcal{L}_F$ -WC!<sup>1</sup> with Kripke's schema follows from that of  $\mathcal{L}_F$ -WC<sup>0</sup>, which is known.

**2.5.4.** *summary: maximal fragments in the classical setting.*

- PROPOSITION 2.36. (1)  $\mathbf{EL}_0^- + \mathcal{L}_F\text{-LEM} + \Sigma_1^0\{\text{-Bdg, -BFT, -AC}^{00}, \text{-AC}^{01}, \text{-WC}^0, \text{-WC}^1\}$   
is interpreted by  $\mathfrak{g}$  in  $\mathbf{WKL}_0^*$ .  
(2)  $\mathbf{EL}_0 + \mathcal{L}_F\text{-LEM} + \Pi_1^0\{\text{-BI, -Ind}\} + \Sigma_1^0\{\text{-DC}^1, \text{-DC}^0, \text{-Ind, -BFT, -AC}^{00}, \text{-AC}^{01}, \text{-WC}^0, \text{-WC}^1\}$   
is interpreted by  $\mathfrak{g}$  in  $\mathbf{WKL}_0$ .

PROOF.  $\Sigma_1^0\text{-AC}^{00}, \text{-DC}^0$  yield  $\Sigma_1^0\text{-AC}^{01}, \text{-DC}^1$  by 2.14. The rest is by 2.32(1)(3), 2.16(2)(i)(4), 2.29(1), 2.35(1).  $\dashv$

These fragments are optimal (in the classical setting) in the following sense:  $\Delta_0^0\text{-DC}^i$  yields  $\Sigma_1^0\text{-Ind}$  by 2.16(2)(i)(3)(i);  $\Sigma_1^0\text{-DC}^1$  is vacuous by 2.14;  $\Pi_1^0\text{-AC}^{!00}$ ,  $\Pi_1^0\text{-BFT}$  and  $\Delta_0^0\text{-FT}$  imply  $(\mathbf{ACA}_0)^{cb}$  where all  $\Pi_1^0\text{-DC}^1$ ,  $\Pi_1^0\text{-DC}^0$  and  $\Pi_1^0\text{-AC}^{!01}$  imply  $\Pi_1^0\text{-AC}^{!00}$  by 2.16(2)(v)(vi); and  $\Pi_1^0\text{-WC}^0$  is inconsistent by 2.35(2)(ii).

One of our main results is that for this optimality LPO suffices instead of the full classical logic or  $\mathcal{L}_F\text{-LEM}$ .

**2.5.5.** *continuous choice and remarks on choice axioms along functions.*

NOTATION 2.37.  $\alpha = \beta|\gamma$  denotes a  $\Pi_2^0$  formula

$$\forall x \exists y (\beta(\langle x \rangle * (\gamma \upharpoonright y)) = \alpha(x) + 1 \wedge (\forall z < y) (\beta(\langle x \rangle * (\gamma \upharpoonright z)) = 0)).$$

DEFINITION 2.38 (generalized continuous choice/bounding;  $\mathcal{C}\text{-CC}^i$ ,  $\mathcal{C}\text{-CB}^i$  and  $\mathcal{C}\text{-CC}^{!i}$ ).  
For classes  $\mathcal{C}$  and  $\mathcal{D}$  of formulae, define the following axiom schemata:

$$\begin{aligned} ((\mathcal{C}, \mathcal{D})\text{-GCC}^0): & \forall \alpha (B[\alpha] \rightarrow \exists x A[\alpha, x]) \\ & \rightarrow \exists \gamma \forall \alpha (B[\alpha] \rightarrow \exists \delta (\delta = \gamma|\alpha \wedge A[\alpha, \delta(0)])); \\ ((\mathcal{C}, \mathcal{D})\text{-GCB}^0): & \forall \alpha (B[\alpha] \rightarrow \exists x A[\alpha, x]) \\ & \rightarrow \exists \gamma \forall \alpha (B[\alpha] \rightarrow \exists \delta (\delta = \gamma|\alpha \wedge (\exists y < \delta(0)) A[\alpha, y])); \\ ((\mathcal{C}, \mathcal{D})\text{-GCC}^1): & \forall \alpha (B[\alpha] \rightarrow \exists \beta A[\alpha, \beta]) \\ & \rightarrow \exists \gamma \forall \alpha (B[\alpha] \rightarrow \exists \delta (\delta = \gamma|\alpha \wedge A[\alpha, \delta])); \\ ((\mathcal{C}, \mathcal{D})\text{-GCB}^1): & \forall \alpha (B[\alpha] \rightarrow \exists \beta A[\alpha, \beta]) \\ & \rightarrow \exists \gamma \forall \alpha (B[\alpha] \rightarrow \exists \delta (\delta = \gamma|\alpha \wedge (\exists \beta < \delta) A[\alpha, \beta])). \end{aligned}$$

for any  $A$  from  $\mathcal{C}$  and  $B$  from  $\mathcal{D}$ .

$(\mathcal{C}, \mathcal{D})\text{-GCC}^{!i}$  is defined with  $\exists$  replaced by  $\exists!$  in the premise;  $\mathcal{C}\text{-CC}^i$ ,  $\mathcal{C}\text{-CB}^i$  and  $\mathcal{C}\text{-CC}^{!i}$  are by setting  $B \equiv \top$ .

$\mathcal{C}\text{-CC}^1$  could be seen as the conjunction of  $\mathcal{C}\text{-AC}^{11}$  the axiom of function-function choice for  $\mathcal{C}$  properties and  $\mathcal{C}\text{-CC}^{!1}$  asserting that any  $\mathcal{C}$ -definable functional is represented as  $\alpha \mapsto \gamma|\alpha$  for some  $\gamma$ .

Even while  $\mathcal{C}\text{-AC}^{1i}$ 's are not formalizable in our  $\mathcal{L}_F$ , it is plausible to think: (1)  $\mathcal{C}\text{-AC}^{!1i}$  implies  $\mathcal{C}\text{-AC}^{!0i}$ ; and (2)  $\mathcal{C}\text{-AC}^{1i}$ 's follow from  $\mathcal{C}\text{-CC}^i$  and  $\mathcal{C}\text{-AC}^{!1i}$ 's from  $\mathcal{C}\text{-CC}^{!i}$  if all the classes in the axioms of the system are closed under  $\Sigma_1^0$  definable total functions. For, ‘‘imaginary’’ choice functionals would be of the base complexity but, for (2), be coded by  $\alpha|\beta$ , which is  $\Sigma_1^0$  definable as far as  $(\alpha|\beta)\downarrow$ . As  $\Sigma_1^0\text{-AC}^{00}$  makes  $\mathbf{EL}_0^-$  satisfy this condition by overwriting 2.10(d), we can ‘‘imaginarily’’ evaluate the strength of  $\mathcal{C}\text{-AC}^{1i}$ , by that of  $\mathcal{C}\text{-CC}^i + \Sigma_1^0\text{-AC}^{00}$  from above and  $\mathcal{C}\text{-AC}^{!0i}$  from below. We *could* thus add  $\mathcal{L}_F\text{-AC}^{1i}$ 's (as we can add  $\mathcal{L}_F\text{-CC}^i$ ) in Section 1.4;  $\Sigma_1^0\text{-AC}^{1i}$ 's in Section 2.5.4 by 2.39(1); and claim that  $\text{LPO} + \Pi_1^0\text{-AC}^{!1i}$ 's are non-justifiable by 4.9(iii) and 2.16(vi).

Similarly, we could consider that  $\mathcal{C}\text{-AC}^{10}$  (and so  $\mathcal{C}\text{-AC}^{11}$ ) makes  $\mathcal{C}\text{-WC}^0$  and  $\mathcal{C}\text{-WC}^0$  be equivalent. From 2.35(2)(i) we *could* claim that neither  $\Pi_1^0\text{-AC}^{11}$  nor  $\Pi_1^0\text{-AC}^{10}$  can be added to the combination of Brouwerian axioms finitistically justifiable or guaranteed jointly with LLPO, while  $\mathcal{L}_F\text{-AC}^{1i}$  can with  $\Sigma_1^0\text{-GDM}$  and MP.

- LEMMA 2.39. (1)  $\mathbf{EL}_0^- \vdash \Sigma_1^0\text{-CC}^1$ .  
 (2) Over  $\mathbf{EL}_0^-$ , (i)  $\mathcal{C}\text{-CC}^1$  implies  $\mathcal{C}\text{-WC}^0$ ; (ii)  $(\mathcal{C} \wedge \Pi_1^0)\text{-CC}^1$  implies  $\mathcal{C}\text{-WC}^0$ .  
 (3) Over  $\mathbf{EL}_0^- + \Sigma_1^0\text{-Bdg}$ , (i)  $\mathcal{C}\text{-CC}^1$  yields  $\mathcal{C}\text{-WC}^1$ ; (ii)  $\mathcal{C}\text{-CC}^1$  yields  $\mathcal{C}\text{-WC}^1$ .  
 (4)  $\mathbf{EL}_0^- + \mathcal{D}\text{-CB}^0 + \mathcal{C}\text{-Bl}_D \vdash (\mathcal{C}, \mathcal{D})\text{-Bl}_M$ .

PROOF. (1) For  $A$  from  $\Sigma_1^0$ , let  $\forall\alpha\exists\beta A[\alpha, \beta]$ . Take  $D$  by 2.14 and  $\gamma$  as follows. Then  $\forall\alpha\exists\beta(\beta = \gamma|\alpha \wedge A[\alpha, \beta])$ .

$$\gamma(y) = \begin{cases} (v*0)(z)+1 & \text{if } y = \langle z \rangle * u \text{ and if } v := |u| \text{ satisfies } D[|u||v|, v] \\ 0 & \text{otherwise.} \end{cases}$$

(2) Easy.

(3) Let  $C[x, y] := \gamma(\langle x \rangle * (\alpha|y)) > 0 \wedge (\forall z < y)(\gamma(\langle x \rangle * (\alpha|y)) = 0)$ . If  $\exists\delta(\delta = \gamma|\alpha)$ , then  $(\forall x < n)\exists y C[x, y]$  and  $\Sigma_1^0\text{-Bdg}$  yields  $m$  with  $(\forall x < n)(\exists y < m)C[x, y]$ . Then  $\forall\beta(\beta \upharpoonright m = \alpha \upharpoonright m \rightarrow (\gamma|\beta) \upharpoonright n = (\gamma|\alpha) \upharpoonright n)$ .

(4) Let  $B$  from  $\mathcal{D}$  and assume  $\mathbf{Bar}[0, \{u: B[u]\}] \equiv \forall\alpha\exists n B[\alpha \upharpoonright n]$ .  $\mathcal{D}\text{-CB}^0$  yields  $\gamma$  with  $\forall\alpha(\exists k < (\gamma|\alpha)(0))B[\alpha \upharpoonright k]$ . Define  $\beta$  by

$$\beta(u) = 0 \leftrightarrow (\exists k \leq |u|)(\gamma(\langle 0 \rangle * (u \upharpoonright k)) \neq 0 \wedge |u| \geq \gamma(\langle 0 \rangle * (u \upharpoonright k)) - 1).$$

Then  $\mathbf{Bar}[0, \{u: \beta(u) = 0\}]$ . For any  $\alpha$ , there is  $n$  with  $\beta(\alpha \upharpoonright n) = 0$ , which implies  $n \geq (\gamma|\alpha)(0)$  and so  $B[\alpha \upharpoonright n]$ , if  $\forall u, v(B[u] \rightarrow B[u*v])$  holds.  $\dashv$

**2.5.6. remarks on axiom schemata for decidable properties.** In the context of Intuitionism, one of the most important constraints on properties is decidability:  $A$  is called *decidable* or *detachable* if  $\forall x(A[x] \vee \neg A[x])$ . In other words, we can decide, for any  $x$ , if  $A[x]$  holds or not.

This is not syntactical and so inadequate for our way of defining axiom schemata, similarly to the non-syntactical constraints  $\Delta_{n+1}^0$  in classical arithmetic. For, it might be the case that  $\forall x(A[x, y] \vee \neg A[x, y])$  holds for some  $y$  but, for another  $z$ ,  $\forall x(A[x, z] \vee \neg A[x, z])$  does not. Thus the constraint is on the abstract  $\{x: A[x, y]\}$  rather than on the formula  $A$ , as the constraint  $\mathbf{Bar}$  (Definition 2.25), where an abstract  $\{\vec{x}: B[\vec{x}, \vec{y}]\}$  is a formula  $B[\vec{x}, \vec{y}]$  with designated free variables  $\vec{x}$ . By 2.8(1),  $\Delta_0^0$  abstracts are decidable, but not vice versa.

Below are some related schemata, where D, E and U stand for ‘decidable’, ‘existential’ and ‘universal’, respectively. In some literature MP and LLPO refer to E-DNE and E-GDM (restricted to  $z = 2$ ), respectively.

DEFINITION 2.40.  $A[\vec{x}, \vec{y}]$  is called *decidable in  $\vec{x}$*  if

$$D[\{\vec{x}: A[\vec{x}, \vec{y}]\}] := \forall\vec{x}(A[\vec{x}, \vec{y}] \vee \neg A[\vec{x}, \vec{y}]).$$

Define the following axiom schemata:

$$(\mathbf{E}\text{-DNE}): D[\{x: A[x]\}] \rightarrow (\neg\neg\exists x A[x] \rightarrow \exists x A[x]);$$

$$\begin{aligned}
(\text{E-GDM}): & \text{D}\{\{x, y: A[x, y, z]\}\} \\
& \rightarrow (\neg(\forall x < z)\exists y A[x, y, z] \rightarrow (\exists x < z)\forall y \neg A[x, y, z]); \\
(\text{EU-Ind}): & \text{D}\{\{x, y, z: A[x, y, z]\} \wedge \exists y \forall z A[0, y, z] \\
& \rightarrow ((\forall x < n)(\exists y \forall z A[x, y, z] \rightarrow \exists y \forall z A[x+1, y, z]) \rightarrow \exists y \forall z A[n, y, z]); \\
(\text{U-BI}): & \text{D}\{\{u, y: B[u, y]\}\} \wedge \text{Bar}[0, \{u: \forall y B[u, y]\}] \\
& \rightarrow (\forall u(\forall x, y B[u * \langle x \rangle, y] \rightarrow \forall y B[u, y]) \rightarrow \forall y B[\langle \cdot \rangle, y]).
\end{aligned}$$

In what follows, however, we will not consider these for the following reason. In the upper bound proofs, we always have full choice  $\mathcal{L}_F\text{-AC}^{00}$ , with which decidable properties are equivalently  $\Delta_0^0$ , in other words,  $\text{D}(\{x: A[x, \vec{y}]\})$  implies  $\exists \alpha \forall x (\alpha(x) = 0 \leftrightarrow A[x, \vec{y}])$ . For lower bounds, we can obtain all the expected results for the corresponding weaker syntactical classes (e.g.,  $\Delta_0^0$  instead of  $\text{D}$ ,  $\Sigma_1^0$  instead of  $\text{E}$ ). Thus our results for syntactic classes can automatically be enhanced for these schemata. So the schemata listed above (as well as  $\text{EU-DC}^0$  and  $\text{E-DC}^1$  defined similarly) are all finitistically justifiable jointly with  $\mathcal{L}_F\text{-AC}^{0i}$  ( $i = 0, 1$ ),  $\mathcal{L}_F\text{-FT}$  and  $\mathcal{L}_F\text{-CC}^1$ .

### §3. Upper Bounds: Functional Realizability.

**3.1. Preliminaries for upper bound proofs.** We will need two equivalences, which are among the folklore in classical second order arithmetic. We here sharpen these in the intuitionistic context (Corollaries 3.3 and 3.9) with some related fundamental results.

**3.1.1. bounded comprehension.** The first equivalence to be sharpen is between induction and bounded comprehension. This was mentioned in [39, Exercise II.3.13]. For this equivalence, we need a semi-classical principle. For the equivalence in the purely intuitionistic setting, we need to replace the induction  $\mathcal{C}\text{-Ind}$  by the least number principle  $\mathcal{C}\text{-LNP}$ .

**DEFINITION 3.1** ( $\mathcal{C}\text{-BCA}$ ,  $\Delta_0^0(\mathcal{C})$ ,  $\Sigma_1^0(\mathcal{C})$ ,  $\Pi_1^0(\mathcal{C})$ ). For a class  $\mathcal{C}$  of formulae,

**( $\mathcal{C}\text{-BCA}$ ):**  $\exists u(|u| = n \wedge (\forall k < n)(u(k) = 0 \leftrightarrow A[k]))$  for any  $A$  from  $\mathcal{C}$ .

$\Delta_0^0(\mathcal{C})$  denotes the smallest class  $\mathcal{D} \supseteq \mathcal{C}$  closed under  $\wedge, \vee, \rightarrow, \text{B}\exists^0, \text{B}\forall^0$ . Analogously  $\Sigma_1^0(\mathcal{C}) \equiv \exists^0 \Delta_0^0(\mathcal{C})$  and  $\Pi_1^0(\mathcal{C}) \equiv \forall^0 \Delta_0^0(\mathcal{C})$ .

**LEMMA 3.2.** (1)  $\mathbf{EL}_0^- + \text{B}\forall^0 \mathcal{C}\text{-LNP}$  proves  $\mathcal{C}\text{-BCA}$ .

(2)  $\mathbf{EL}_0^- + \mathcal{C}\text{-BCA}$  proves  $\mathcal{C}\text{-Ind}$ ,  $\mathcal{C}\text{-LEM}$  and  $\mathcal{C}\text{-LNP}$ .

(3)  $\mathbf{EL}_0^- + \mathcal{C}\text{-BCA}$  proves  $\Delta_0^0(\mathcal{C})\text{-BCA}$ .

(4) Hence  $\mathcal{C}\text{-BCA}$  and  $\text{B}\forall^0 \mathcal{C}\text{-LNP}$  are equivalent over  $\mathbf{EL}_0^-$ .

**PROOF.** In this proof, let  $A$  be from  $\mathcal{C}$ .

(1) We may assume  $|u| \leq |v| \wedge (\forall k < |u|)(u(k) \leq v(k)) \rightarrow u \leq v$  by changing way of coding if necessary. Let  $B[u] := |u| = n \wedge (\forall k < n)(u(k) = 0 \rightarrow A[k])$  which is  $\text{B}\forall^0 \mathcal{C}$  (cf. Notation 2.9(3)).  $\text{B}\forall^0 \mathcal{C}\text{-LNP}$  yields  $v$  with  $B[v] \wedge (\forall u < v) \neg B[u]$ . It remains to show  $(\forall k < n)(A[k] \rightarrow v(k) = 0)$ . For  $k < n$  with  $A[k]$ , if  $v(k) \neq 0$ , then  $u$  defined by  $u(k) = 0$  and  $u(l) = v(l)$  for  $l \neq k$  satisfies  $u < v$  and  $B[u]$ , a contradiction.

(2) By  $\mathcal{C}\text{-BCA}$  we can take  $u$  such that  $(\forall x \leq n)(u(x) = 0 \leftrightarrow A[x])$ . If  $A[0]$  and  $(\forall x < n)(A[x] \rightarrow A[x+1])$ , then  $u(0) = 0$  and  $(\forall x < n)(u(x) = 0 \rightarrow u(x+1) = 0)$  which, with  $\Delta_0^0\text{-Ind}$ , yields  $u(n) = 0$  and so  $A[n]$ . The others are similar.



(3) We show  $\exists u(|u| = n \wedge (\forall k < n)(u(x) = 0 \leftrightarrow A[(x)_0^k, \dots, (x)_{k-1}^k]))$  by induction on  $A$ . Consider the case of  $A[\vec{x}] \equiv (Qy < t[\vec{x}])B[\vec{x}, y]$ . The induction hypothesis yields  $v$  with  $(\forall z < |v|)(v(z) = 0 \leftrightarrow B[(z)_0^{k+1}, \dots, (z)_{k-1}^{k+1}])$  and  $|v| = (n, t[(n)_0^k, \dots, (n)_{k-1}^k])$ . Then  $(\forall x < n)(\forall y < (|v|_1^2))(v((x)_0^k, \dots, (x)_{k-1}^k, y) = 0 \leftrightarrow B[(x)_0^k, \dots, (x)_{k-1}^k, y])$ . Take  $u$  with  $(\forall x < n)(u(x) = 0 \leftrightarrow (Qy < t[(x)_0^k, \dots, (x)_{k-1}^k])v((x)_0^k, \dots, (x)_{k-1}^k, y) = 0)$ . This is what we need.  $\dashv$

- COROLLARY 3.3.** (1)  $\mathbf{EL}_0^- \vdash \Pi_n^0\text{-BCA} \leftrightarrow \Pi_n^0\text{-LNP}$ .  
 (2)  $\mathbf{EL}_0^- + \Sigma_n^0\text{-Ind} + \Sigma_{n+1}^0\text{-DNE} \vdash \Sigma_n^0\text{-BCA} \wedge \Delta_0^0(\Sigma_n^0)\text{-Ind}$ .  
 (3)  $\mathbf{EL}_0^- + \Sigma_n^0\text{-Ind} + \Sigma_n^0\text{-LEM} \subseteq \mathbf{EL}_0^- + \Sigma_n^0\text{-BCA} \subseteq \mathbf{EL}_0^- + \Sigma_n^0\text{-Ind} + \Sigma_{n+1}^0\text{-DNE}$ .

**PROOF.** (1) This is by 3.2(1)(2). (2) We have  $\mathbf{B}\forall^0\text{-}\Pi_n^0 \subseteq \Sigma_n^0$  by 2.8(3) and 2.24(1)(i), and  $\mathbf{B}\exists^0(\Pi_n^0 \wedge \mathbf{B}\forall^0\text{-}\Pi_n^0) \subseteq \Sigma_{n+1}^0$ . By 2.8(2)(i),  $\mathbf{EL}_0^- + \Sigma_n^0\text{-Ind} + \Sigma_{n+1}^0\text{-DNE}$  proves  $\Pi_n^0\text{-LNP}$  and so  $\Pi_n^0\text{-BCA}$  which with  $\Sigma_n^0\text{-DNE}$  implies  $\Sigma_n^0\text{-BCA}$ .  $\dashv$

The statements (2) and (3) refine the corresponding classical results:  $\Sigma_n^0\text{-Ind}$  implies  $\Delta_0^0(\Sigma_n^0)\text{-Ind}$  (e.g., [17, Chapter I, 2.14 Lemma]); and  $\Sigma_n^0\text{-Ind}$  is equivalent to  $\Sigma_n^0\text{-BCA}$ . Since  $\Sigma_n^0\text{-BCA}$  easily follows from  $\mathcal{L}_F\text{-Ind} + \Sigma_n^0\text{-LEM}$ , in the usual intuitionistic context with full induction,  $\Sigma_n^0\text{-BCA}$  is equivalent to  $\Sigma_n^0\text{-LEM}$ . In our context however we need some trick to adjust the proof above to  $\Sigma_n^0$  to show this (cf. [27, Lemma 37]) while we saw that it is equivalent to  $\mathbf{B}\Pi_{n+1}^0\text{-LNP}$ , to  $\Delta_0^0(\Sigma_n^0)\text{-LNP}$  and to  $\Pi_n^0\text{-LNP} + \Sigma_n^0\text{-DNE}$ . As  $\mathcal{L}_F\text{-Ind} + \Sigma_n^0\text{-LEM}$  is known not to imply  $\Sigma_{n+1}^0\text{-DNE}$  (by [1]), the second  $\subseteq$  in (3) is proper. We do not know if so is the first.

Our proof refines [17, Chapter I, 2.13 Lemma] and differs from that suggested in [39]. The latter proof is based on *pigeon-hole principle* (PHP), and does not solve the question above either. Whereas we applied the least number principle to sequence  $u$ 's or large numbers in the sense of Section 1.8, in the proof by PHP the induction is applied to  $k$ 's with  $k < |u|$  or small numbers.<sup>15</sup> Thus the difference between these two proofs could be essential in the further studies mentioned in Section 1.8,<sup>16</sup> but not so essential for the purpose of the present article.

**3.1.2. bounded König's lemma.** The other equivalence is between weak König's lemma (WKL) and  $\Pi_1^0$  axiom of choice (for sets). The implication from the former to the latter was in [25, Lemma 3.6], and the converse is a consequence of the equivalence known in constructive reverse mathematics (e.g., [18, Proposition 16.18 and Theorem 16.21]).

**DEFINITION 3.4** ( $u < \alpha$ ,  $\mathcal{C}\text{-BKL}$ ,  $\mathcal{C}\text{-WKL}$ ). Let  $u < \alpha \equiv (\forall k < |u|)(u(k) < \alpha(k))$ . For a class  $\mathcal{C}$  of formulae, define the following axiom schemata:

**( $\mathcal{C}\text{-BKL}$ ):**  $\forall n(\exists u < \alpha)(|u| = n \wedge (\forall k \leq n)A[u \upharpoonright k]) \rightarrow (\exists \gamma < \alpha)\forall nA[\gamma \upharpoonright n]$ ;

**( $\mathcal{C}\text{-WKL}$ ):**  $\forall n(\exists u < \underline{2})(|u| = n \wedge (\forall k \leq n)A[u \upharpoonright k]) \rightarrow (\exists \gamma < \underline{2})\forall nA[\gamma \upharpoonright n]$ ,

for any  $A$  from  $\mathcal{C}$ .

**LEMMA 3.5.** (1) For  $A$  from  $\forall^0\mathcal{C}$  there is a formula  $B$  from  $\mathbf{B}\forall^0\mathcal{C}$  such that

<sup>15</sup>Actually bounded comprehension in [39] is the existence of set with the condition to which only finite segment is relevant.

<sup>16</sup>Also, the dissolution of the distinction between large and small numbers is essential for the proof of 2.39(1).

- (a)  $\forall n B[\beta \uparrow n] \rightarrow \forall n A[\beta \uparrow n]$  and
- (b)  $\forall n (\exists u < \alpha)(|u| = n \wedge (\forall k \leq n) A[u \uparrow k]) \rightarrow \forall n (\exists u < \alpha)(|u| = n \wedge (\forall k \leq n) B[u \uparrow k])$ .
- (2) Over  $\mathbf{EL}_0^- + \mathbf{B}\forall^0\mathcal{C}\text{-BKL}$ , (i)  $\forall^0\mathcal{C}\text{-BKL}$  holds; (ii)  $(\exists \beta < \alpha)\forall n A[\beta \uparrow n]$  is  $\forall^0(\mathbf{B}\exists^0\mathbf{B}\forall^0\mathcal{C})$  if  $A$  is  $\forall^0\mathcal{C}$ .
- (3)  $\mathbf{EL}_0^- + \mathcal{D}\text{-BKL} + \mathbf{B}\exists^0\mathcal{D}\text{-Ind} + \mathbf{B}\exists^0\mathbf{B}\forall^0\text{-}\mathcal{C}\text{-LEM} + \mathbf{B}\exists^0\mathcal{C}\text{-DNE} \vdash \mathcal{C}\text{-BFT}$ ,  
where  $\mathcal{D} \equiv \mathbf{B}\forall^0(\mathcal{C} \rightarrow \mathbf{B}\exists^0\mathcal{C})$ .

PROOF. Let  $C$  be  $\mathcal{C}$ .

- (1) Say  $A[u] \equiv \forall x C[u, x]$ . Define  $B[u] := (\forall x, k < |u|) C[u \uparrow k, x]$ .  
For (a), if  $\forall n B[\beta \uparrow n]$ , then, for  $n$  and  $x$ ,  $B[\beta \uparrow (n+x+1)]$  implies  $C[\beta \uparrow n, x]$ .  
As  $\forall u ((\forall k \leq |u|) A[u \uparrow k]) \rightarrow (\forall k \leq |u|) B[u \uparrow k]$ , (b) holds.
- (2) This follows from (1).
- (3) Define the following, where  $B$  is in  $\mathcal{D}$ .

$$D[v] := (\exists k \leq |v|) C[v \uparrow k]$$

$$B[u] := \gamma(u) = 0 \wedge (\forall v < \beta)(\gamma(v) = 0 \wedge |v| = |u| \wedge D[u] \rightarrow D[v]).$$

Assume  $\mathbf{Fan}[\gamma]$ ,  $\mathbf{Bar}[\gamma, C]$  and  $\forall u(\gamma(u) = 0 \rightarrow u < \beta)$ .

We show  $\exists u(\gamma(u) = 0 \wedge |u| = n \wedge (\forall k \leq n) B[u \uparrow k])$  by  $\mathbf{B}\exists^0\mathcal{D}\text{-Ind}$  on  $n$ . If  $n = 0$  this is trivial. Assume  $|v| = n \wedge (\forall k \leq n) B[v \uparrow k]$ .  $\mathbf{B}\exists^0\mathbf{B}\forall^0\text{-}\mathcal{C}\text{-LEM}$  gives two cases: if  $\gamma(w) = 0 \wedge |w| = n+1 \wedge \neg D[w]$  then  $(\forall k \leq n+1) \neg D[w \uparrow k]$  and  $(\forall k \leq n+1) B[w \uparrow k]$ ; if no such  $w$  exists, as  $\forall w(\gamma(w) = 0 \wedge |w| = n+1 \rightarrow D[w])$  by  $\mathbf{B}\exists^0\mathcal{C}\text{-DNE}$ ,  $\mathbf{Fan}[\gamma]$  yields  $x$  with  $\gamma(v * \langle x \rangle) = 0 \wedge B[v * \langle x \rangle]$ .

Now  $\mathcal{D}\text{-WKL}$  yields  $\beta$  with  $\forall k B[\beta \uparrow k]$ . By  $\mathbf{Bar}[\gamma, C]$  we have  $n$  with  $C[\beta \uparrow n]$ . Then  $\forall v(\gamma(v) = 0 \wedge |v| = n \rightarrow (\exists k \leq n) C[v \uparrow k])$  by  $B[\beta \uparrow n]$ .  $\dashv$

Compare (2)(i) with 2.32(3)(ii). A similar argument was also used for 2.28(4) (and will be in 3.56(2)).

As an instance of (3) with  $\mathcal{C} \equiv \Delta_0^0$ ,  $\mathbf{EL}_0^- + \Delta_0^0\text{-BKL} \vdash \Delta_0^0\text{-BFT}$ . This was shown in [20], but the essentially same proof had been given: e.g., the proof of [23, 4.7 Proposition 2] “ $\rightarrow$ ” with  $g$  instantiated with the particular  $g$  defined just below (++) on p.1263 is exactly the same proof, and there might be earlier proofs.

- LEMMA 3.6. (1)  $\mathbf{EL}_0^- + \text{-}\mathcal{C}\text{-BKL} + \mathbf{B}\exists^0\mathcal{C}\text{-GDM} \vdash \exists^0\mathcal{C}\text{-GDM}$ ;  
(2)  $\mathbf{EL}_0^- + \mathbf{B}\forall^0\mathcal{C}\text{-BKL} + \mathbf{B}\exists^0(\mathbf{B}\forall^0\mathcal{C})\text{-Ind} \vdash \forall^0\mathcal{C}\text{-BAC}^{00}$ ;  
(3)  $\mathbf{EL}_0^- + \mathcal{D}\text{-DNE} + \mathcal{D}\text{-Ind} + \forall^0\text{-}\mathcal{E}\text{-2AC}^{00} + \exists^0\mathcal{E}\text{-DM} \vdash \mathcal{C}\text{-WKL}$  for  $\mathcal{D} \equiv \mathbf{B}\exists^0\mathbf{B}\forall^0\mathcal{C}$   
and  $\mathcal{E} \equiv \mathcal{D} \wedge \neg \mathcal{D}$ .

PROOF. Let  $A$  be  $\mathcal{C}$ .

- (1) Let  $C[u] := |u| > 0 \rightarrow \neg A[u(0), |u|-1]$ . Assume  $\neg(\forall x < m)\exists y A[x, y]$ . For any  $n$ , by  $(\mathbf{B}\exists^0\mathcal{C})\text{-GDM}$ ,  $\neg(\forall x < m)(\exists y < n) A[x, y]$  implies  $(\exists x < m)(\forall y < n) \neg A[x, y]$ . For such  $x < m$ ,  $\langle x \rangle * (\underline{0} \uparrow n-1)$  witnesses  $\exists u(u < \underline{m} \wedge |u| = n \wedge (\forall k \leq n) C[u \uparrow k])$ .  $\text{-}\mathcal{C}\text{-BKL}$  yields  $\beta < \underline{m}$  with  $\forall n C[\beta \uparrow n]$ , and  $\forall y \neg A[\beta(0), y]$ .
- (2) Assume  $\forall x(\exists y < \alpha(x))\forall z A[x, y, z]$ . Let  $B[u] := (\forall x, z < |u|) A[x, u(x), z]$ . For  $n$ ,  $\mathbf{B}\exists^0(\mathbf{B}\forall^0\mathcal{C})\text{-Ind}$  on  $k \leq n$  shows  $(\exists u < \alpha)(|u| = k \wedge (\forall x < k)(\forall z < n) A[x, u(x), z])$ .  $\mathbf{B}\forall^0\mathcal{C}\text{-BKL}$  yields  $\beta$  with  $\forall x B[\beta \uparrow x]$ . So  $\forall x, z A[x, \beta(x), z]$ .

(3) Assume  $\forall n(\exists u < \underline{2})(|u| = n \wedge (\forall k \leq n)A[u \upharpoonright k])$ . Define a  $\mathcal{D}$  formula  $B$  and an  $\mathcal{E}$  formula  $C$  by

$$\begin{aligned} B[k, u] &::= (\exists v < \underline{2})(|v| = k \wedge (\forall l \leq |u| + k)A[(u * v) \upharpoonright l]); \\ C[n, u, x] &::= B[n, u * \langle 1 - x \rangle] \wedge \neg B[n, u * \langle x \rangle]. \end{aligned}$$

Suppose  $\exists n C[n, u, 0] \wedge \exists n C[n, u, 1]$ , say  $C[n, u, 0] \wedge C[m, u, 1]$ . We may assume  $n \geq m$ .  $C[n, u, 0]$  implies  $B[n, u * \langle 1 \rangle]$  and so  $B[m, u * \langle 1 \rangle]$  contradicting  $C[m, u, 1]$ . Thus  $\exists^0 \mathcal{E}\text{-DM}$  yields  $\forall n \neg C[n, u, 0] \vee \forall n \neg C[n, u, 1]$ .

$\forall^0 \neg \mathcal{E}\text{-}2\text{AC}^{00}$  yields  $\gamma < \underline{2}$  with  $\forall u, n \neg C[n, u, \gamma(u)]$ . By induction on  $n$ , we can show  $(\exists v < \underline{2} \upharpoonright n)(\forall k < n)(v(k) = \gamma(v \upharpoonright k))$ . Thus  $\Delta_0^0\text{-}2\text{AC}^{00}$  yields  $\beta < \underline{2}$  with  $\forall k(\beta(k) = \gamma(\beta \upharpoonright k))$  and so  $\forall n, k \neg C[n, \beta \upharpoonright k, \beta(k)]$ .

We prove  $B[n - k, \beta \upharpoonright k]$  by  $\mathcal{D}\text{-Ind}$  on  $k \leq n$ . For  $k = 0$ , this is by assumption. For  $k < n$ , if  $B[n - k, \beta \upharpoonright k]$ , say  $|v| = n - k \wedge (\forall l \leq n)A[(\beta \upharpoonright k * v) \upharpoonright l]$  then  $B[n - k - 1, (\beta \upharpoonright k) * \langle v(0) \rangle]$ . We may assume  $v(0) = 1 - \beta(k)$ . By  $\neg C[n - k - 1, \beta \upharpoonright k, \beta(k)]$  we have  $\neg B[n - k - 1, (\beta \upharpoonright k) * \langle \beta(k) \rangle]$ . Apply  $\mathcal{D}\text{-DNE}$ . Thus  $B[0, \beta \upharpoonright n]$ , and  $A[\beta \upharpoonright n]$ .  $\dashv$

Via  $\mathfrak{g}$  and  $\mathfrak{ch}$  from Section 2.3,  $\Pi_1^0\text{-}2\text{AC}^{01}$  corresponds to  $\Pi_1^0\text{-AC}$  and  $\Pi_1^0\text{-}2\text{AC}^{00}$  to  $\Sigma_1^0$  separation. Hence (iii) with  $\mathcal{C} \equiv \Delta_0^0$  refines the classical fact that  $\Sigma_1^0$  separation implies WKL (cf. [39, Lemma IV.4.4]).

Replacing  $\forall^0 \neg \mathcal{E}\text{-}2\text{AC}^{00}$  and  $\exists^0 \mathcal{E}\text{-DM}$  by  $\forall^0 \neg \mathcal{E}\text{-BAC}^{00}$  and  $\exists^0 \mathcal{E}\text{-GDM}$  in (iii), we can prove  $\mathcal{C}\text{-BKL}$ . However, in a straightforward manner (or as in [39, Lemma IV.1.4]) we can show  $\mathbf{EL}_0^- + \mathcal{C}\text{-WKL} \vdash \mathcal{C}\text{-BKL}$ .

**COROLLARY 3.7.** Over  $\mathbf{EL}_0^- + \Delta_0^0(\mathcal{C})\{-\text{DNE}, -\text{GDM}, -\text{Ind}\}$ , the following are equivalent:

- (a)  $\Pi_1^0(\mathcal{C})\text{-BKL}$ ;
- (b)  $\Delta_0^0(\mathcal{C})\text{-BKL}$ ;
- (c)  $\Sigma_1^0(\mathcal{C})\text{-GDM} + \Pi_1^0(\mathcal{C})\text{-BAC}^{00}$ ;
- (d)  $\Sigma_1^0(\mathcal{C})\text{-DM} + \Pi_1^0(\mathcal{C})\text{-}2\text{AC}^{00}$ ;
- (e)  $\Delta_0^0(\mathcal{C})\text{-WKL}$ .

**LEMMA 3.8.**  $\mathbf{EL}_0^- + \Delta_0^0\text{-BKL}$  proves  $\Pi_1^0\text{-BAC}^{01}$ .

**PROOF.** Let  $A$  be  $\Pi_1^0$ . By 2.14, we may assume  $A[x, \beta] \equiv \forall y C[x, \beta \upharpoonright y]$  where  $C$  is  $\Delta_0^0$ . Let  $(u)_x(y) = u((x, y))$  for  $(x, y) < |u|$  and define

$$\begin{aligned} B[u] &::= (\forall x < |u|)(\forall y < |(u)_x|)C[x, (u)_x \upharpoonright y]; \\ D[x, n, v] &::= v < (\gamma)_x \wedge |v| = n \wedge (\forall y < n)C[x, v \upharpoonright y] \end{aligned}$$

Assume  $\forall x(\exists \beta < (\gamma)_x)A[x, \beta]$ .

By assumption,  $(\forall x < n)(\exists v)D[x, n, v]$ . By induction on  $m \leq n$ , we can show  $(\exists w < \gamma \upharpoonright (m, n))(w < \gamma \wedge (\forall x < m)D[x, n, (w)_x])$ . We have  $(\exists u < \gamma)(|u| = n \wedge B[u])$  by setting  $m = n$ .  $\Delta_0^0\text{-BKL}$  yields  $\beta < \gamma$  with  $\forall n B[\beta \upharpoonright n]$ , and  $\forall x, y C[x, (\beta)_x \upharpoonright y]$ , i.e.,  $\forall x A[x, (\beta)_x]$ .  $\dashv$

**COROLLARY 3.9.**  $\Pi_1^0\text{-BKL}$ ;  $\Pi_1^0\text{-BAC}^{01} + \Sigma_1^0\text{-GDM}$ ;  $\Pi_1^0\text{-}2\text{AC}^{00} + \text{LLPO}$ ; and  $\Delta_0^0\text{-WKL}$  are equivalent over  $\mathbf{EL}_0^-$ .

*Remark 3.10.* If we define  $\mathcal{C}\text{-BDC}^i$ , bounded dependence choice, similarly to  $\Pi_1^0\text{-BAC}^1$ , 3.8 can be enhanced to  $\Pi_1^0\text{-BDC}^1$  with the essentially same proof (see

also the proof of 3.56(2)), and  $\Pi_1^0\text{-BDC}^{01} + \Sigma_1^0\text{-GDM}$  can be added to 3.9. This will play an essential role in the second author's next work [36].

### 3.2. Functional realizability.

**3.2.1. general theory of Lifschitz's realizability.** A general and abstract machinery for Lifschitz's realizability is provided by a theory **CDL** of combinators and  $\in_L$ . This could be seen as a subsystem of *explicit mathematics* with classes<sup>17</sup> from [16]: all individuals are also classes and comprehension is much more restricted than elementary, with some modification on case distinction. Since the use of undefined terms is essential, we have to modify the first order logic as follows.

DEFINITION 3.11 (logic of partial terms (cf. [5, VI.1])). The first order logic of partial terms is formulated by the usual axioms and inference rules of the first order (intuitionistic or classical) logic, but

- (i) a new unary predicate (treated as a logical symbol)  $\downarrow$ , called *definedness predicate*, is added;
- (ii) the usual  $\forall$ - and  $\exists$ -axioms (if formulated in Hilbert-style) are replaced by  $\forall xA[x] \wedge t\downarrow \rightarrow A[t]$  and  $A[t] \wedge t\downarrow \rightarrow \exists xA[x]$ , respectively;
- (iii) the equality axioms are formulated only with free variables and only for atomic formulae;
- (iv) so-called strictness axiom:  $A[t] \rightarrow t\downarrow$  for any *atomic* formula  $A[x]$  in which  $x$  actually occurs (which includes  $t[s]\downarrow \rightarrow s\downarrow$  for any term  $t[x]$  in which  $x$  actually occurs).

Notice that (iii) includes  $x = x$  and so (iv) yields  $x\downarrow$ . Thus free variables vary only over "defined" objects. This logic is called  $E^+$ -logic with equality in [42, Chapter 1, 2.4], where  $\downarrow$  is called the existence predicate.

DEFINITION 3.12 ( $\mathcal{L}_{\text{Cb}}$ ,  $\mathcal{L}_{\text{CD}}$ ,  $\mathcal{L}_{\text{CDL}}$ ). (1) The language  $\mathcal{L}_{\text{Cb}}$  has  $=$  as the only predicate symbol; one binary function symbol  $|$ ; constant symbols  $\mathbf{k}$ ,  $\mathbf{s}$ ,  $\mathbf{p}$ ,  $\mathbf{p}_0$  and  $\mathbf{p}_1$ .  $\mathcal{L}_{\text{CD}}$  is the expansion with constants  $\mathbf{z}$ ,  $\mathbf{o}$  and  $\mathbf{d}$ ; and a unary relation symbol  $\text{Bo}$ .  $\mathcal{L}_{\text{CDL}}$  expands  $\mathcal{L}_{\text{CD}}$  with a binary predicate symbol  $\in_L$  and constant symbols  $\mathbf{g}$ ,  $\mathbf{u}$ ,  $\mathbf{r}$ ,  $\mathbf{f}$  and  $\mathbf{c}$ . Variables of these languages are denoted by  $\alpha, \beta, \gamma, \dots, \xi, \eta, \dots$  (except  $\lambda$ ) possibly with subscripts.

- (2) (i)  $st \equiv s|t$ ;  $st_0 \dots t_n \equiv \dots(st_0) \dots t_n$ ;  $\langle s, t \rangle := \mathbf{p}st$  and  $\langle s, t, t' \rangle := \mathbf{p}s(\mathbf{p}tt')$ .  
(ii)  $s \simeq t \equiv (s\downarrow) \vee (t\downarrow) \rightarrow s = t$ .
- (3) (i) For a term  $t$  and a variable  $\xi$ , another term  $\lambda\xi.t$ , without occurrences of  $\xi$ , is defined inductively:
  - (a)  $\lambda\xi.\eta \equiv \mathbf{k}\eta$  if  $\xi \neq \eta$ ; (b)  $\lambda\xi.\xi \equiv \mathbf{s}\mathbf{k}\mathbf{k}$ ; (c)  $\lambda\xi.c \equiv \mathbf{k}c$  for a constant  $c$ ;
  - (d)  $\lambda\xi.st \equiv \mathbf{s}(\lambda\xi.s)(\lambda\xi.t)$ ;
- (4) (i)  $\lambda\eta_0 \dots \eta_n.t \equiv \lambda\eta_0.(\dots(\lambda\eta_n.t)\dots)$ ; (ii)  $\text{fix} := \lambda\zeta.(\lambda\xi\eta.\zeta(\xi\xi)\eta)(\lambda\xi\eta.\zeta(\xi\xi)\eta)$ .

DEFINITION 3.13 (**Cb**, **CD**, **CDL**). The theory **Cb** of  $\mathcal{L}_{\text{Cb}}$  is generated over intuitionistic logic of partial terms by axioms (k), (s), (p). **CD** is **Cb**+(zo)+(d)

<sup>17</sup>The notion of class in explicit mathematics has been called *type* in the later references of explicit mathematics.

in  $\mathcal{L}_{\text{CD}}$ , and **CDL** is **Cb**+(g)+(u)+(r) in  $\mathcal{L}_{\text{CDL}}$ .<sup>18</sup>

- (k)  $k\alpha\beta = \alpha$ ; (s)  $s\alpha\beta\downarrow \wedge s\alpha\beta\gamma \simeq \alpha\gamma(\beta\gamma)$ ;  
 (p)  $p_0(p\alpha\beta) = \alpha \wedge p_1(p\alpha\beta) = \beta \wedge p_0\alpha\downarrow \wedge p_1\alpha\downarrow$ ;  
 (zo)  $\text{Bo}[\alpha] \leftrightarrow (\alpha = z \vee \alpha = o)$ ; (d)  $d\beta\gamma z = \beta \wedge d\beta\gamma o = \gamma$ ;  
 (g)  $g\alpha\downarrow \wedge (\xi \in_L g\alpha \leftrightarrow \xi = \alpha)$ ; (u)  $u\alpha\downarrow \wedge (\xi \in_L u\alpha \leftrightarrow (\exists \beta \in_L \alpha)(\xi \in_L \beta))$ ;  
 (r)  $(\forall \eta \in_L \alpha)(\beta\eta\downarrow) \rightarrow r\alpha\beta\downarrow \wedge \forall \xi(\xi \in_L r\alpha\beta \leftrightarrow (\exists \eta \in_L \alpha)(\xi = \beta\eta))$ .

In **CDL** we can consider an object as a code of sets of objects with  $\in_L$ , and **g**, **u** and **r** give the codes of singletons, unions and direct images under operations. The constants **f** and **c** are used only in the extensions.

- DEFINITION 3.14 (**CDLc**, **CDLf**). (1) **CDLc** is an extension of **CDL** by the additional axiom  $\exists!\xi(\xi \in_L \alpha) \rightarrow (c\alpha\downarrow \wedge c\alpha \in_L \alpha)$ .  
 (2) **CDLf** is an extension of **CDL** by

$$(\exists \xi \in_L \alpha)(p_0\xi = \eta) \rightarrow f\alpha\eta\downarrow \wedge \forall \xi(\xi \in_L f\alpha\eta \leftrightarrow \xi \in_L \alpha \wedge p_0\xi = \eta).$$

Thus **c** “chooses” an element if the set is a singleton and **f** gives the code of inverse images along projection if inhabited. While these were not needed in the definition nor in the proofs of basic properties below, they will be essential to generalize the “featured” properties of Lifschitz’s realizability (**c** in 3.32 and **f** in 3.34).

- LEMMA 3.15. (1) For any  $\mathcal{L}_{\text{Cb}}$  term  $t[\xi]$ , **Cb**  $\vdash (\lambda\xi.t[\xi])\downarrow \wedge (s\downarrow \rightarrow (\lambda\xi.t[\xi])s \simeq t[s])$ .  
 (2) **Cb**  $\vdash \text{fix } \zeta\downarrow \wedge \text{fix } \zeta\eta \simeq \zeta(\text{fix } \zeta)\eta$ .

$\mathbb{N}$  with Kleene bracket  $nm \simeq \{n\}(m)$  is a model of **CD**. We can trivially extend it to **CDL** by interpreting  $\in_L$  as  $=$  (only singletons are codable), but also by interpreting  $n \in_L m$  as  $n < (m)_1^2 \wedge \pi[(m)_0^2, n]$  where  $\pi$  is universal  $\Pi_1$  (the codable are bounded  $\Pi_1^0$ ), and we can interpret **g**, **u** and **r** accordingly, as well as **c** and **f**.

In  $\mathbf{r}_L$ -realizability defined below, a realizer of existence statement is a (code of) inhabited sets of pairs of witnesses and realizers of the instantiated statements. Within the trivial model of **CDL**,  $\mathbf{r}_L$ -realizability is the usual number-realizability; and in the other aforementioned model it is Lifschitz’s (number) realizability.

Below let  $\mathcal{L}$  and  $\mathcal{L}'$  be first order languages sharing the set of variables, and let  $\mathcal{L}'$  expand  $\mathcal{L}_{\text{CDL}}$ .

DEFINITION 3.16 ( $\alpha \mathbf{r}_L A$ ,  $\mathbf{r}_L$ -realizable). For atomic  $\mathcal{L}$  formulae  $A$ , fix  $\mathcal{L}'$  formulae  $\alpha \mathbf{r}_L A$  whose free variables are  $\alpha$  and those in  $A$ , where  $\alpha \mathbf{r}_L \perp \equiv \perp$ .

<sup>18</sup>With the totality  $\forall\alpha, \beta(\alpha|\beta\downarrow)$ , we can define **p** and **p<sub>i</sub>** by **d**, **z** and **o**. However, without it we cannot obtain  $p_0\alpha\downarrow \wedge p_1\alpha\downarrow$ .

Extend  $\alpha \mathbf{r}_L A$  for an arbitrary  $\mathcal{L}$  formula  $A$  by

$$\begin{aligned} \alpha \mathbf{r}_L (A \wedge B) &::= (\mathbf{p}_0 \alpha \mathbf{r}_L A) \wedge (\mathbf{p}_1 \alpha \mathbf{r}_L B); \\ \alpha \mathbf{r}_L (A \rightarrow B) &::= \forall \beta (\beta \mathbf{r}_L A \rightarrow \alpha \beta \downarrow \wedge \alpha \beta \mathbf{r}_L B); \\ \alpha \mathbf{r}_L (A \vee B) &::= \exists \eta (\eta \in_L \alpha) \wedge \\ &\quad (\forall \xi \in_L \alpha) (\text{Bo}[\mathbf{p}_0 \xi] \wedge (\mathbf{p}_0 \xi = \mathbf{z} \rightarrow \mathbf{p}_1 \xi \mathbf{r}_L A) \wedge (\mathbf{p}_0 \xi = \mathbf{o} \rightarrow \mathbf{p}_1 \xi \mathbf{r}_L B)); \\ \alpha \mathbf{r}_L \forall \xi A[\xi] &::= \forall \xi (\alpha \xi \downarrow \wedge \alpha \xi \mathbf{r}_L A[\xi]); \\ \alpha \mathbf{r}_L \exists \xi A[\xi] &::= \exists \eta (\eta \in_L \alpha) \wedge (\forall \xi \in_L \alpha) (\mathbf{p}_1 \xi \mathbf{r}_L A[\mathbf{p}_0 \xi]). \end{aligned}$$

An  $\mathcal{L}$  theory  $T$  is called  $\mathbf{r}_L$ -realizable in an  $\mathcal{L}'$  theory  $T'$  if, for any  $A$  in  $T$ ,  $T' \vdash \exists \alpha (\alpha \mathbf{r}_L A)$ .

DEFINITION 3.17 (operator  $\mathbf{b}_A$ ). Fix  $\mathcal{L}_{\text{CDL}}$  terms  $\mathbf{b}_{A[\vec{\eta}]}$  for atomic  $A[\vec{\eta}]$ 's. Extend  $\mathbf{b}_A$  to arbitrary  $A$  by

$$\begin{aligned} \mathbf{b}_{A \wedge B} &::= \lambda \vec{\eta} \alpha. \mathbf{p}(\mathbf{b}_A \vec{\eta}(\mathbf{r} \alpha \mathbf{p}_0))(\mathbf{b}_B \vec{\eta}(\mathbf{r} \alpha \mathbf{p}_1)); \\ \mathbf{b}_{B \rightarrow A} &::= \lambda \vec{\eta} \alpha \beta. \mathbf{b}_A \vec{\eta}(\mathbf{r} \alpha(\lambda \zeta. \zeta \beta)); \\ \mathbf{b}_{\forall \xi A[\vec{\eta}, \xi]} &::= \lambda \vec{\eta} \alpha \xi. \mathbf{b}_{A[\vec{\eta}, \xi]} \vec{\eta}(\mathbf{r} \alpha(\lambda \zeta. \zeta \xi)); \\ \mathbf{b}_{\exists \xi A[\vec{\eta}, \xi]}, \mathbf{b}_{A \vee B} &::= \lambda \vec{\eta} \alpha. u \alpha. \end{aligned}$$

Strictly,  $\mathbf{b}_A$  is defined for abstracts  $A$  rather than formulae. We write  $\mathbf{b}_{C[\vec{\alpha}]}$  also for  $\mathbf{b}_{C[\vec{\alpha}]} \vec{\eta}$  with the free variables  $\vec{\eta}$  implicit (i.e., other than  $\vec{\alpha}$ 's) in  $C[\vec{\alpha}]$ . We will not need the definition of  $\mathbf{b}_A$  but the following.

LEMMA 3.18. For an  $\mathcal{L}'$  theory  $T'$ , if

$$\mathbf{CDL} + T' \vdash \exists \xi (\xi \in_L \alpha) \wedge (\forall \xi \in_L \alpha) (\xi \mathbf{r}_L A[\vec{\eta}]) \rightarrow (\mathbf{b}_A \vec{\eta} \alpha) \downarrow \wedge \mathbf{b}_A \vec{\eta} \alpha \mathbf{r}_L A[\vec{\eta}]$$

for any atomic  $\mathcal{L}$  formula  $A$ , then it holds for an arbitrary  $\mathcal{L}$  formula  $A$ .

PROPOSITION 3.19. Assume the premise of 3.18. If  $A[\vec{\eta}]$  follows from sentences  $B_1, \dots, B_n$  intuitionistically, then there is a closed  $\mathcal{L}_{\text{CDL}}$ -term  $t$  such that

$$\mathbf{CDL} \vdash \forall \beta_1, \dots, \beta_n (\beta_1 \mathbf{r}_L B_1 \wedge \dots \wedge \beta_n \mathbf{r}_L B_n \rightarrow t \beta_1 \dots \beta_n \downarrow \wedge t \beta_1 \dots \beta_n \mathbf{r}_L \forall \vec{\eta} A[\vec{\eta}])$$

PROOF. Consider a Hilbert-style calculus. The axioms in the negative parts are realizable as follows.  $\lambda \vec{\eta}. \mathbf{k}$ ,  $\lambda \vec{\eta}. \mathbf{s}$ ,  $\lambda \vec{\eta}. \mathbf{p}_i$ ,  $\lambda \vec{\eta}. \mathbf{p}$  and  $\lambda \vec{\eta} \xi \alpha. \alpha \xi$  realize the universal closures of the axioms  $\forall \vec{\eta} (A \rightarrow B \rightarrow A)$ ,  $\forall \vec{\eta} ((A \rightarrow (B \rightarrow C)) \rightarrow (A \rightarrow B) \rightarrow (A \rightarrow C))$ ,  $\forall \vec{\eta} (A_0 \wedge A_1 \rightarrow A_i)$ ,  $\forall \vec{\eta} (A_0 \rightarrow A_1 \rightarrow A_0 \wedge A_1)$  and  $\forall \vec{\eta}, \xi (\forall \zeta A[\zeta] \rightarrow A[\xi])$ , respectively. For the inference rules for the negative part, If  $s \mathbf{r}_L \forall \vec{\eta} (C \rightarrow A)$  and  $t \mathbf{r}_L \forall \vec{\eta} C$  then  $\lambda \vec{\eta}. s \vec{\eta} (t \vec{\eta}) \mathbf{r}_L \forall \vec{\eta} A$ , and if  $t \mathbf{r}_L \forall \vec{\eta}, \zeta (C \rightarrow A[\zeta])$  then  $\lambda \vec{\eta} \alpha \zeta. t \vec{\eta} \zeta \alpha \mathbf{r}_L \forall \vec{\eta} (C \rightarrow \forall \zeta A[\zeta])$ .

For the  $\exists$ -axiom, it is easy to see  $\lambda \vec{\eta} \xi \gamma. \mathbf{g}(\langle \xi, \gamma \rangle) \mathbf{r}_L \forall \vec{\eta}, \xi (A[\xi] \rightarrow \exists \zeta A[\zeta])$ . For the  $\exists$ -rule, we show that if  $t \mathbf{r}_L \forall \vec{\eta}, \zeta (A[\zeta] \rightarrow C)$  then  $\lambda \vec{\eta} \gamma. \mathbf{b}_C \vec{\eta}(\mathbf{r} \gamma(\lambda \xi. t \vec{\eta}(\mathbf{p}_0 \xi)(\mathbf{p}_1 \xi)))$  realizes  $\forall \vec{\eta} (\exists \zeta A[\zeta] \rightarrow C)$  as follows. Take  $\gamma$  such that  $\gamma \mathbf{r}_L \exists \zeta A[\zeta]$ . Then we have  $(\forall \xi \in_L \gamma) (\mathbf{p}_1 \xi \mathbf{r}_L A[\mathbf{p}_0 \xi])$  and  $(\forall \xi \in_L \gamma) (t \vec{\eta}(\mathbf{p}_0 \xi)(\mathbf{p}_1 \xi) \downarrow \wedge t \vec{\eta}(\mathbf{p}_0 \xi)(\mathbf{p}_1 \xi) \mathbf{r}_L C)$ , i.e.,  $(\forall \xi' \in_L \mathbf{r} \gamma(\lambda \xi. t \vec{\eta}(\mathbf{p}_0 \xi)(\mathbf{p}_1 \xi)))(\xi' \mathbf{r}_L C)$ . Similarly  $\exists \xi' (\xi' \in_L \mathbf{r} \gamma(\lambda \xi. \beta \vec{\eta}(\mathbf{p}_0 \xi)(\mathbf{p}_1 \xi)))$ . Now we can apply 3.18.

For the  $\vee$ -axioms, it is easy to see  $\lambda \vec{\eta} \gamma. \mathbf{g}(\langle \mathbf{z}, \gamma \rangle) \mathbf{r}_L \forall \vec{\eta} (A \rightarrow A \vee B)$  and also  $\lambda \vec{\eta} \gamma. \mathbf{g}(\langle \mathbf{o}, \gamma \rangle) \mathbf{r}_L \forall \vec{\eta} (B \rightarrow A \vee B)$ . For the  $\vee$ -rule, if  $s \mathbf{r}_L \forall \vec{\eta} (A \rightarrow C)$  and  $t \mathbf{r}_L \forall \vec{\eta} (B \rightarrow C)$  then, similarly we can show that  $\lambda \vec{\eta} \alpha. \mathbf{b}_C \vec{\eta}(\mathbf{r} \alpha(\lambda \xi. \mathbf{d}(s \vec{\eta}(\mathbf{p}_1 \xi))(t \vec{\eta}(\mathbf{p}_1 \xi))(\mathbf{p}_0 \xi)))$  realizes  $\forall \vec{\eta} (A \vee B \rightarrow C)$ .  $\dashv$

Therefore  $A \mapsto \exists\alpha(\alpha \mathbf{r}_L A)$  can be considered as an interpretation of intuitionistic logic (i.e., the theory axiomatized by  $\emptyset$ ) over  $\mathcal{L}$  to extensions of **CDL** in the sense of Section 1.2. The theme of this section is to clarify: with which axioms in  $\mathcal{L}'$ , which axioms in  $\mathcal{L}$  can be interpreted in this way.

**3.2.2. Kleene's second model  $\mathfrak{k}$ .** We will need functional realizability and so a functional model of **CD**, called Kleene's second model. Though [43, Chapter 9, 4.1] gave a construction in an abstract way, it seems easier for us to give an explicit definition, in order to check if the construction is possible in our context of weak induction.

NOTATION 3.20 ( $u|v$ ).  $(u|v)(x)$  is  $u(\langle x \rangle * (v|y)) - 1$  if  $y = \min\{z : u(\langle x \rangle * (v|z)) > 0\}$ , and is undefined if there is no such  $y$ . “ $(u|v)(x)$  is defined” is  $\Delta_0^0$ . If  $u \subseteq u'$ ,  $v \subseteq v'$  and  $(u|v)(k)$  is defined, then  $(u|v)(k) = (u'|v')(k)$ .

DEFINITION 3.21 ( $A^\mathfrak{k}$ ). For an  $\mathcal{L}_{\text{Cb}}$  term  $t$  and  $\mathcal{L}_{\text{Cb}}$  formula  $A$ , define  $\mathcal{L}_F$  formulae  $\llbracket t \rrbracket^\mathfrak{k}(\xi)$  and  $A^\mathfrak{k}$  by

$$\begin{aligned} \llbracket \alpha \rrbracket^\mathfrak{k}(\xi) &::= \xi = \alpha; & \llbracket c \rrbracket^\mathfrak{k}(\xi) &::= \xi = c^\mathfrak{k} \text{ for a constant } c; \\ \llbracket st \rrbracket^\mathfrak{k}(\xi) &::= \exists \eta, \zeta (\llbracket s \rrbracket^\mathfrak{k}(\eta) \wedge \llbracket t \rrbracket^\mathfrak{k}(\zeta) \wedge \xi = \eta|\zeta); \end{aligned}$$

and by

$$\begin{aligned} (s \downarrow)^\mathfrak{k} &::= \exists \xi (\llbracket s \rrbracket^\mathfrak{k}(\xi)); & (s = t)^\mathfrak{k} &::= \exists \xi (\llbracket s \rrbracket^\mathfrak{k}(\xi) \wedge \llbracket t \rrbracket^\mathfrak{k}(\xi)); & \perp^\mathfrak{k} &::= \perp; \\ (A \square B)^\mathfrak{k} &::= A^\mathfrak{k} \square B^\mathfrak{k} \ (\square \equiv \wedge, \rightarrow, \vee); & (Q\xi A)^\mathfrak{k} &::= Q\xi A^\mathfrak{k} \ (Q \equiv \forall, \exists). \end{aligned}$$

where  $\xi = \eta|\zeta$  is from 2.37 and where  $c^\mathfrak{k}$ 's are defined as follows by  $\Delta_0^0$  bounded search in  $\mathbf{EL}_0^-$  from 2.10:

$$\begin{aligned} \mathbf{p}_i^\mathfrak{k}(x) &= \begin{cases} (w(y))_i^2 + 1 & \text{if } x = \langle y \rangle * w \\ & \text{and } |w| = y + 1; \\ 0 & \text{otherwise.} \end{cases} \\ \mathbf{p}^\mathfrak{k}(x) &= \begin{cases} (u(y), v(y)) + 2 & \text{if } x = \langle \langle y \rangle * v \rangle * u \text{ and } |u| = |v| = y + 1; \\ 0 & \text{if } x = \langle \langle y \rangle * v \rangle * u \text{ and } |u| \neq |v| = y + 1; \\ 1 & \text{otherwise.} \end{cases} \\ \mathbf{k}^\mathfrak{k}(x) &= \begin{cases} u(y) + 2 & \text{if } x = \langle \langle y \rangle \rangle * u \text{ and } |u| = y + 1; \\ 1 & \text{if } x = \langle v \rangle \text{ and } |v| \neq 1; \\ 0 & \text{otherwise.} \end{cases} \\ \mathbf{s}^\mathfrak{k}(x) &= \begin{cases} ((u|w)|(v|w))(y) + 3 & \text{if } x = \langle \langle \langle y \rangle * w \rangle * v \rangle * u \text{ and } |u| = |v| = |w| \\ & \text{and } (\forall z \leq y) \left( \begin{array}{l} (u|w)(z), (v|w)(z) \text{ and} \\ ((u|w)|(v|w))(z) \text{ are defined} \end{array} \right); \\ 2 & \text{if } x = \langle \langle \langle y \rangle * w \rangle * v \rangle * u \text{ and } |u| = |v| = |w| \text{ but otherwise;} \\ 1 & \text{if } x = \langle \langle \langle y \rangle * w \rangle * v \rangle, 0 < |w| \text{ and } |v| \neq |w|; \\ 2 & \text{if } x = \langle \langle \langle y \rangle \rangle * v \rangle \text{ with } |v| > 0 \text{ or } x = \langle \langle \langle \rangle \rangle * v \rangle \text{ or } x = \langle \langle \rangle \rangle; \\ 0 & \text{otherwise.} \end{cases} \end{aligned}$$

PROPOSITION 3.22.  $\mathbf{EL}_0^- + \Delta_0^0\text{-AC}^{00} \vdash (\mathbf{Cb})^\mathfrak{k} \wedge ((\mathbf{p}\alpha\beta)^\mathfrak{k} = (\alpha, \beta))$ .

PROOF. Let  $\bar{\alpha}n$  denote  $\alpha \upharpoonright n$ . We can easily see  $(\mathbf{p}_i \alpha)^{\mathfrak{e}}(x) = (\alpha(x))_i^2$ , and using the following we can show  $(\mathbf{k}\alpha\beta)^{\mathfrak{e}}(x) = \alpha(x)$  and  $(\mathbf{p}\alpha\beta)^{\mathfrak{e}}(x) = (\alpha(x), \beta(x))$  and the first conjunct of (s).

$$\begin{aligned} (\mathbf{p}\alpha)^{\mathfrak{e}}(x) &= \begin{cases} (\alpha(y), v(y)) + 1 & \text{if } x = \langle y \rangle * v \wedge |v| = y + 1; \\ 0 & \text{otherwise.} \end{cases} \\ (\mathbf{k}\alpha)^{\mathfrak{e}}(x) &= \begin{cases} \alpha(y) + 1 & \text{if } x = \langle y \rangle; \\ 0 & \text{otherwise.} \end{cases}; \\ (\mathbf{s}\alpha)^{\mathfrak{e}}(x) &= \begin{cases} ((\bar{\alpha}k|w)|(v|w))(y) + 2 & \text{if } x = \langle \langle y \rangle * w \rangle * v \text{ and, for } k := |v| = |w|, \\ & (\forall z \leq y) \left( \begin{array}{l} (\bar{\alpha}k|w)(z), (v|w)(z) \text{ and} \\ ((\bar{\alpha}k|w)|(v|w))(z) \text{ are defined} \end{array} \right); \\ 1 & \text{if } x = \langle \langle y \rangle * w \rangle * v \text{ and } |v| = |w| \text{ but otherwise;} \\ 0 & \text{if } x = \langle \langle y \rangle * w \rangle * v, 0 < |w| \text{ and } |v| \neq |w|; \\ 1 & \text{if } x = \langle \langle y \rangle \rangle * v \text{ with } |v| > 0 \text{ or } x = \langle \langle \rangle \rangle * v \text{ or } x = \langle \rangle. \end{cases} \\ (\mathbf{s}\alpha\beta)^{\mathfrak{e}}(x) &= \begin{cases} ((\bar{\alpha}k|w)|(\bar{\beta}k|w))(y) + 1 & \text{if } x = \langle y \rangle * w \text{ and, for } k := |w|, \\ & (\forall z \leq y) \left( \begin{array}{l} (\bar{\alpha}k|w)(z), (\bar{\beta}k|w)(z) \text{ and} \\ ((\bar{\alpha}k|w)|(\bar{\beta}k|w))(z) \text{ are defined} \end{array} \right); \\ 0 & \text{otherwise.} \end{cases} \end{aligned}$$

Let  $(\mathbf{s}\alpha\beta\gamma)^{\mathfrak{e}} \downarrow$ . Then  $(\mathbf{s}\alpha\beta\gamma)^{\mathfrak{e}}(y) = ((\bar{\alpha}k|\bar{\gamma}k)|(\bar{\beta}k|\bar{\gamma}k))(y)$ , where  $k$  is a least such that  $(\bar{\alpha}k|\bar{\gamma}k)(z)$ ,  $(\bar{\beta}k|\bar{\gamma}k)(z)$  and  $((\bar{\alpha}k|\bar{\gamma}k)|(\bar{\beta}k|\bar{\gamma}k))(z)$  are defined for all  $z \leq y$ . By 3.20,  $((\alpha|\gamma)|(\beta|\gamma))(y)$  is defined and is  $((\bar{\alpha}k|\bar{\gamma}k)|(\bar{\beta}k|\bar{\gamma}k))(y)$ .  $\Sigma_1^0\text{-AC}^{00}$  yields  $(\alpha|\gamma) \downarrow$ ,  $(\beta|\gamma) \downarrow$ ,  $((\alpha|\gamma)|(\beta|\gamma)) \downarrow$  and  $(\mathbf{s}\alpha\beta\gamma)^{\mathfrak{e}} = ((\alpha|\gamma)|(\beta|\gamma))$ . Conversely let  $((\alpha|\gamma)|(\beta|\gamma)) \downarrow$ , which implies  $(\alpha|\gamma) \downarrow$  and  $(\beta|\gamma) \downarrow$ . For  $x$ , by 2.16(3)(ii)  $\Delta_0^0\text{-AC}^{00}$  yields  $k$  with  $(\bar{\alpha}k|\bar{\gamma}k)(y)$ ,  $(\bar{\beta}k|\bar{\gamma}k)(y)$  and  $((\bar{\alpha}k|\bar{\gamma}k)|(\bar{\beta}k|\bar{\gamma}k))(y)$  are defined for all  $y \leq x$ . Then  $(\mathbf{s}\alpha\beta\gamma)^{\mathfrak{e}}(x) = ((\bar{\alpha}k|\bar{\gamma}k)|(\bar{\beta}k|\bar{\gamma}k))(x)$ . Thus  $(\mathbf{s}\alpha\beta\gamma)^{\mathfrak{e}} \downarrow$ .  $\dashv$

LEMMA 3.23. (1) (i) For a  $\Sigma_1^0$  formula  $A$ ,  $\mathbf{EL}_0^-$  proves that:

if  $\forall x, y, z, \alpha (A[x, y, \alpha] \wedge A[x, z, \alpha] \rightarrow y = z)$   
then there is  $\gamma_A$  such that (a)  $\forall \alpha ((\gamma_A|\alpha) \downarrow \leftrightarrow \exists \beta \forall x A[x, \beta(x), \alpha])$   
and that (b)  $\forall \alpha ((\gamma_A|\alpha) \downarrow \rightarrow \forall x A[x, (\gamma_A|\alpha)(x), \alpha])$ ;

and (ii) for a  $\Sigma_1^0$  formula  $A$ ,  $\mathbf{EL}_0^- + \Delta_0^0\text{-AC}^{00}$  proves that there is  $\gamma_A$  with (b) and  $\forall \alpha ((\gamma_A|\alpha) \downarrow \leftrightarrow \forall x \exists y A[x, y, \alpha])$ .

(2) For a  $\Pi_1^0$  formula  $B[\xi, \eta, \gamma]$ ,  $\mathbf{EL}_0^- + \Delta_0^0\text{-BKL}$  proves that there is  $\chi_B$  such that, for any  $\alpha, \beta, \xi$ ,

$$(\chi_B|\alpha|\beta) \downarrow \wedge \forall \xi ((\exists \eta < \alpha) B[\xi, \eta, \beta] \leftrightarrow \forall n ((\chi_B|\alpha|\beta)(\xi \upharpoonright n) = 0)).$$

PROOF. (1)(ii) follows from (i) and  $\Delta_0^0\text{-LNP}$ . (i) By 2.14, take  $C$  from  $\Delta_0^0$  with  $A[x, y, \alpha] \leftrightarrow \exists k C[x, y, \alpha \upharpoonright k]$ . Let

$$\gamma_A(w) = \begin{cases} y+1 & \text{if } w = \langle x \rangle * v \text{ and } y < |v| \wedge (\exists k < |v|) C[x, y, v \upharpoonright k]; \\ 0 & \text{if there are no such } x, v, y. \end{cases}$$

(2) By 3.5(2)(ii) and 2.14, let  $\forall \xi, \alpha, \beta ((\exists \eta < \alpha) B[\xi, \eta, \beta] \leftrightarrow \neg \exists n C[\xi \upharpoonright n, (\alpha, \beta)])$  where  $C$  is  $\Delta_0^0$ . By (1)(i) with 2.10(d) we can take  $\gamma$  with  $(\gamma|(\alpha, \beta)) \downarrow$  and  $\forall u ((\gamma|(\alpha, \beta))(u) = 0 \leftrightarrow \neg C[u, (\alpha, \beta)])$ . Set  $\chi_B := \lambda \alpha \beta. \gamma|(\mathbf{p}|\alpha|\beta)$ .  $\dashv$



Here (1) formalizes the famous fact: any continuous functional can be represented by an operation in Kleene's second model (cf. [22, Section 5.2]). (2) is a preliminary for van Oosten's model treated in 3.2.3.

**DEFINITION 3.24** ( $\mathfrak{k}$ ). Expand  $\mathfrak{k}$  to  $\mathcal{L}_{\text{CDL}}$  by  $\text{Bo}[\alpha]^\mathfrak{k} := \alpha < 2 \wedge \forall x, y(\alpha(x) = \alpha(y))$  and  $\xi \in_{\mathbb{L}}^\mathfrak{k} \alpha := \alpha = \xi$  with  $\mathbf{z}^\mathfrak{k} := \mathbf{0}$ ;  $\mathbf{o}^\mathfrak{k} := \mathbf{1}$ ;  $\mathbf{d}^\mathfrak{k} := \lambda \xi \eta \zeta. \gamma_A(\mathbf{p}\xi(\mathbf{p}\eta\zeta))$ ;  $\mathbf{g}^\mathfrak{k}, \mathbf{u}^\mathfrak{k}, \mathbf{c}^\mathfrak{k} := \lambda \xi. \xi$ ;  $\mathbf{f}^\mathfrak{k} := \mathbf{k}$ ; and  $\mathbf{r}^\mathfrak{k} := \lambda \xi \eta. \eta | \xi$ , where  $\gamma_A$  is as in 3.23(1)(i) above applied to  $A$  from  $\Delta_0^0$  such that  $A[x, y, \mathbf{p}^\mathfrak{k}\xi(\mathbf{p}^\mathfrak{k}\eta\zeta)] \leftrightarrow ((\zeta(0) = 0 \rightarrow y = \xi(x)) \wedge (\zeta(0) \neq 0 \rightarrow y = \eta(x)))$ .

**PROPOSITION 3.25.**  $\mathbf{EL}_0^- + \Delta_0^0\text{-AC}^{00} \vdash (\mathbf{CDLc})^\mathfrak{k} + (\mathbf{CDLf})^\mathfrak{k}$ .

**3.2.3. van Oosten's model  $\mathfrak{o}$ .** Under  $\mathfrak{k}$ , only singletons are codable and so  $\mathbf{r}_{\mathbb{L}}$ -realizability is the usual function realizability. On the other hand, under  $\mathfrak{o}$  due to van Oosten [29, Section 5],  $\alpha$  codes the sets of infinite paths through the "bounded" tree  $\{u < (\alpha)_1^2 : \forall n((\alpha)_0^2(u \upharpoonright n) = 0)\}$  so that bounded König's lemma could be  $\mathbf{r}_{\mathbb{L}}$ -realizable. We have to check if it works in our context of weak induction. This is not easy. Indeed Dorais [13, Remark 4.10] tried to weaken induction in van Oosten's argument but required  $\Pi_1^0\text{-Bdg}$ . We show that it is not needed and  $\Delta_0^0\text{-Ind}$  suffices.

**DEFINITION 3.26** ( $\mathfrak{o}$  and  $\pi_A$ ). (1) Let  $\mathfrak{o}$  coincide with  $\mathfrak{k}$  on  $\mathcal{L}_{\text{CD}}$ , and

$$\xi \in_{\mathbb{L}}^\mathfrak{o} \alpha := \xi < (\alpha)_1^2 \wedge \forall n((\alpha)_0^2(\xi \upharpoonright n) = 0).$$

(2) For any  $\Pi_1^0$  formula  $A[\xi, \eta, \gamma]$ , define  $\pi_A := \lambda \alpha \beta \gamma. \mathbf{p} | (\chi_A | \beta | \gamma) | \alpha$  where  $\chi_A$  is from 3.23(2).

Then  $\pi_A | \alpha | \beta | \gamma$  codes the bounded  $\Pi_1^0$  set  $\{\xi < \alpha : (\exists \eta < \beta) A[\xi, \eta, \gamma]\}$ , as stated in the next lemma (2), whereas (1) gives us the necessary bound to make the arguments (for 3.28) work only with  $\Delta_0^0\text{-Ind}$ . This will be essential to define the interpretation of  $\mathbf{r}$  in 3.28, and, in later parts,  $\mathbf{r}$  will give the necessary bounds.

**LEMMA 3.27.** (1)  $\mathbf{EL}_0^- + \text{MP} + \Delta_0^0\text{-AC}^{00} + \Delta_0^0\text{-BKL}$  proves that there is  $\zeta$  such that, for any  $\alpha$  and  $\beta$ ,

$$\begin{aligned} & (\forall \eta \in_{\mathbb{L}}^\mathfrak{o} \alpha)((\beta | \eta) \downarrow) \\ \rightarrow & \zeta | (\alpha, \beta) \downarrow \wedge (\forall \eta \in_{\mathbb{L}}^\mathfrak{o} \alpha)((\beta | \eta) < \zeta | (\alpha, \beta) \wedge \forall k(\exists n < (\zeta | (\alpha, \beta))(k))(\beta(\langle k \rangle * (\eta \upharpoonright n)) > 0)). \end{aligned}$$

(2) For  $A$  from  $\Pi_1^0$ ,  $\mathbf{EL}_0^- + \Delta_0^0\text{-BKL}$  proves

$$\forall \alpha, \beta, \gamma((\pi_A | \alpha | \beta | \gamma) \downarrow \wedge \forall \xi(\xi \in_{\mathbb{L}}^\mathfrak{o} \pi_A | \alpha | \beta | \gamma \leftrightarrow \xi < \alpha \wedge (\exists \eta < \beta) A[\xi, \eta, \gamma])).$$

**PROOF.** Since (2) is immediate, we prove (1). Let

$$C[u, k, \alpha, \beta] := (\exists x, w < |u|) \neg ((\alpha)_0^2(u \upharpoonright x) = 0 \wedge \beta(\langle k \rangle * (u \upharpoonright w)) = 0)$$

and  $D[k, y, \alpha, \beta] := (\forall u < (\alpha)_1^2)(|u| = y \rightarrow (\exists l \leq |u|)C[u \upharpoonright l, k, \alpha, \beta])$ , where  $u < \gamma$  is defined in 3.4. Now we have

$$\begin{aligned}
& (\forall \eta \in \mathbb{L}^{\circ} \alpha)((\beta \upharpoonright \eta) \downarrow) \\
& \leftrightarrow \forall k (\forall \eta < (\alpha)_1^2) (\forall x ((\alpha)_0^2(\eta \upharpoonright x) = 0) \rightarrow \exists w (\beta(\langle k \rangle * (\eta \upharpoonright w)) > 0)) \\
& \hspace{25em} (\text{by } \Delta_0^0\text{-AC}^{00}) \\
& \leftrightarrow \forall k (\forall \eta < (\alpha)_1^2) \neg (\forall x ((\alpha)_0^2(\eta \upharpoonright x) = 0) \wedge \neg \exists w (\beta(\langle k \rangle * (\eta \upharpoonright w)) > 0)) \\
& \hspace{25em} (\text{by MP}) \\
& \leftrightarrow \forall k (\forall \eta < (\alpha)_1^2) \exists x, w \neg ((\alpha)_0^2(\eta \upharpoonright x) = 0 \wedge \beta(\langle k \rangle * (\eta \upharpoonright w)) = 0) \\
& \hspace{25em} (\text{by MP}) \\
& \leftrightarrow \forall k (\forall \eta < (\alpha)_1^2) \exists l C[\eta \upharpoonright l, k, \alpha, \beta] \leftrightarrow \forall k \neg (\exists \eta < (\alpha)_1^2) \forall l \neg C[\eta \upharpoonright l, k, \alpha, \beta] \\
& \leftrightarrow \forall k \neg \forall y (\exists u < (\alpha)_1^2) (|u| = y \wedge (\forall l \leq y) \neg C[u \upharpoonright l, k, \alpha, \beta]) \leftrightarrow \forall k \exists y D[k, y, \alpha, \beta] \\
& \hspace{25em} (\text{by } \Delta_0^0\text{-BKL, MP}).
\end{aligned}$$

3.23(1)(ii) yields  $\gamma$  with  $\forall k D[k, (\gamma | (\alpha, \beta))(k), \alpha, \beta]$ . Then

$$\forall k (\forall \eta \in \mathbb{L}^{\circ} \alpha) (\exists n < (\gamma | (\alpha, \beta))(k)) (\beta(\langle k \rangle * (\eta \upharpoonright n)) > 0).$$

Thus  $\zeta$  with  $(\zeta | (\alpha, \beta))(k) = \max((\gamma | (\alpha, \beta))(k), \beta \upharpoonright (\langle k \rangle * ((\alpha)_1^2 \upharpoonright (\gamma | (\alpha, \beta))(k)))) + 1$  is what we need.  $\dashv$

**PROPOSITION 3.28.**  $\mathbf{EL}_0^- + \mathbf{MP} + \Delta_0^0\text{-AC}^{00} + \Delta_0^0\text{-BKL} \vdash (\mathbf{CDLc} + \mathbf{CDLf})^{\circ}$  with suitable  $\mathbf{g}^{\circ}$ ,  $\mathbf{u}^{\circ}$ ,  $\mathbf{r}^{\circ}$ ,  $\mathbf{c}^{\circ}$  and  $\mathbf{f}^{\circ}$ .

**PROOF.** First  $\alpha = \xi$  is  $\Pi_1^0$ . Next  $(\exists \beta \in \mathbb{L}^{\circ} \alpha)(\xi \in \mathbb{L}^{\circ} \beta)$ ,  $(\exists \eta \in \mathbb{L}^{\circ} \alpha)(\xi = \beta \upharpoonright \eta)$  and  $\xi \in \mathbb{L}^{\circ} \alpha \wedge \mathbf{p}_0 \xi = \eta$  are equivalent, respectively, to  $\xi < \alpha \wedge (\exists \beta < \alpha)((\beta \in \mathbb{L}^{\circ} \alpha) \wedge (\xi \in \mathbb{L}^{\circ} \beta))$ ,  $\xi < \zeta | (\alpha, \beta) \wedge (\exists \eta \in \mathbb{L}^{\circ} \alpha)(\xi = \beta \upharpoonright \eta)$  and  $\xi < \alpha \wedge \xi \in \mathbb{L}^{\circ} \alpha \wedge (\xi)_0^2 = \eta$ , where  $\zeta$  is from 3.27(1) and  $\xi = \beta \upharpoonright \eta$  is equivalently  $\Pi_1^0$  with the bound  $\zeta | (\alpha, \beta)$ . 3.27(2) yields  $\mathbf{g}^{\circ}$ ,  $\mathbf{u}^{\circ}$ ,  $\mathbf{r}^{\circ}$  and  $\mathbf{f}^{\circ}$ .

Let  $u \perp \xi := (\exists k < |u|)(u(k) \neq \xi(k))$ ; recall  $u < \beta := (\forall k < |u|)(u(k) < \beta(k))$  and  $(\beta \ominus n)(k) = \beta(k+n)$ .

Assume  $\exists! \xi (\xi \in \mathbb{L}^{\circ} \alpha)$  and  $\xi \in \mathbb{L}^{\circ} \alpha$ . Then

$$(\forall u < (\alpha)_1^2)(u \perp \xi \rightarrow \neg (\exists \eta < (\alpha)_1^2 \ominus |u|) \forall n ((\alpha)_0^2((u * \eta) \upharpoonright n) = 0)).$$

By  $\Delta_0^0\text{-BKL}$ , we have

$$(\forall u < (\alpha)_1^2)(u \perp \xi \rightarrow \neg \forall m (\exists v < (\alpha)_1^2 \ominus |u|) (|v| = m \wedge (\forall n < m + |u|) ((\alpha)_0^2((u * v) \upharpoonright n) = 0))),$$

and, by MP,  $(\forall u < (\alpha)_1^2)(u \perp \xi \rightarrow B[u, \alpha])$  where

$$B[u, \alpha] := \exists m (\forall v < (\alpha)_1^2 \ominus |u|) (|v| = m \rightarrow (\exists n < m + |u|) ((\alpha)_0^2((u * v) \upharpoonright n) > 0)).$$

Thus  $\xi \upharpoonright n$  is the only  $w$  with

$$C[n, w, \alpha] := w < (\alpha)_1^2 \wedge |w| = n \wedge (\forall u < (\alpha)_1^2) (|u| = n \wedge u \neq w \rightarrow B[u, \alpha])$$

since  $\forall n \neg B[\xi \upharpoonright n, \alpha]$ .  $C$  is equivalently  $\Sigma_1^0$  with  $\Sigma_1^0\text{-Bdg}$  which is by  $\Delta_0^0\text{-AC}^{00}$  with 2.16(3)(ii). Apply 3.23(1)(ii) to  $D[n, y, \alpha] := \exists w (C[n+1, w, \alpha] \wedge w(n) = y)$ ; then  $\forall n D[n, (\gamma_D | \alpha)(n), \alpha]$ , i.e.,  $(\gamma_D | \alpha)(n) = \xi(n)$ . Set  $\mathbf{c}^{\circ} = \gamma_D$ .  $\dashv$

**3.2.4. characterizing axioms of realizability.** As in Section 3.2.1 let  $\mathcal{L}'$  expand  $\mathcal{L}_{\text{CDL}}$  via some interpretation, but atomic  $\mathcal{L}_{\text{CDL}}$  formulae may be non-atomic in  $\mathcal{L}'$ , as in  $\mathfrak{k}$  or  $\mathfrak{o}$ . As  $\Delta_0^0$  is non-sense, 2.9(3) is not applicable here. General treatment here will help us in [28].

DEFINITION 3.29 ( $A^{\mathfrak{r}_L}$ , canonicalized,  $N(\mathcal{C})$ ,  $RH(\mathcal{C})$ ,  $\mathcal{R}$ ). (1) To an  $\mathcal{L}$  formula  $A$ , assign an  $\mathcal{L}'$  formula  $A^{\mathfrak{r}_L}$  by

$$\begin{aligned} A^{\mathfrak{r}_L} &::= \exists \alpha (\alpha \mathfrak{r}_L A) \text{ for atomic } A; \\ (A \square B)^{\mathfrak{r}_L} &::= A^{\mathfrak{r}_L} \square B^{\mathfrak{r}_L} \text{ for } \square \equiv \wedge, \rightarrow, \vee; \\ (Qx A)^{\mathfrak{r}_L} &::= Qx A^{\mathfrak{r}_L} \text{ for } Q \equiv \forall, \exists. \end{aligned}$$

- (2)  $A[\bar{\eta}]$ , without other parameters, is called  $\mathfrak{r}_L$ -canonicalized by  $c_A$  (in a theory) if  $\forall \bar{\eta}, \alpha (\alpha \mathfrak{r}_L A[\bar{\eta}] \rightarrow c_A \bar{\eta} \downarrow \wedge c_A \bar{\eta} \mathfrak{r}_L A[\bar{\eta}])$  (is provable in the theory).  
 (3) A formula is called (i)  $N(\mathcal{C})$  or *negative in  $\mathcal{C}$*  if it is built up from  $\mathcal{C}$  formulae by  $\wedge, \rightarrow$  and  $\forall$ ; and  
 (ii) *Rasiowa–Harrop in  $\mathcal{C}$*  or  $RH(\mathcal{C})$  if it is built up from  $\mathcal{C}$  by  $\wedge, \forall$  and  $A \rightarrow -$  with arbitrary formulae  $A$ .  
 (4)  $\mathcal{R}$  is the class of  $\mathcal{L}'$  formulae negative in

$$\{\exists \xi (\xi \in_L \alpha), \xi \in_L \alpha, \alpha \beta \downarrow, \gamma = \alpha \beta, \text{Bo}[\alpha]\} \cup \{\alpha \mathfrak{r}_L A \mid A \text{ is } \mathcal{L}\text{-atomic}\}.$$

DEFINITION 3.30 (Generalized choice schemata  $(\mathcal{C}, \mathcal{D})\text{-GC}_L$  and  $(\mathcal{C}, \mathcal{D})\text{-GC!}$ ). For classes  $\mathcal{C}$  and  $\mathcal{D}$  of  $\mathcal{L}'$  formulae, define the following axiom schemata:

$$\begin{aligned} ((\mathcal{C}, \mathcal{D})\text{-GC}_L): & \forall \alpha (D[\alpha] \rightarrow \exists \beta C[\alpha, \beta]) \\ & \rightarrow \exists \gamma \forall \alpha (D[\alpha] \rightarrow \gamma \alpha \downarrow \wedge \exists \xi (\xi \in_L \gamma \alpha) \wedge (\forall \xi \in_L \gamma \alpha) C[\alpha, \xi]); \\ ((\mathcal{C}, \mathcal{D})\text{-GC!}): & \forall \alpha (D[\alpha] \rightarrow \exists ! \beta C[\alpha, \beta]) \rightarrow \exists \gamma \forall \alpha (D[\alpha] \rightarrow \gamma \alpha \downarrow \wedge C[\alpha, \gamma \alpha]), \end{aligned}$$

for any  $C$  from  $\mathcal{C}$  and  $D$  from  $\mathcal{D}$ .

LEMMA 3.31. Assume the premise of 3.18.

- (1) If  $\mathcal{C}$  formulae are  $\mathfrak{r}_L$ -canonicalized, then so are  $RH(\mathcal{C})$  ones.  
 (2) (i)  $\alpha \mathfrak{r}_L A$  is in  $\mathcal{R}$ ; and (ii)  $\mathbf{CDL}+(\mathcal{R}, \mathcal{R})\text{-GC}_L \vdash A^{\mathfrak{r}_L} \leftrightarrow \exists \alpha (\alpha \mathfrak{r}_L A)$ , for an  $\mathcal{L}$  formula  $A$ .

PROOF. It is easy to see (1) and (2)(i). We prove (2)(ii) by induction on  $A$ . The atomic,  $\wedge, \vee$  cases are obvious.

By induction hypothesis,  $(B \rightarrow C)^{\mathfrak{r}_L}$  is equivalent to  $\exists \beta (\beta \mathfrak{r}_L B) \rightarrow \exists \gamma (\gamma \mathfrak{r}_L C)$ , i.e.,  $\forall \beta ((\beta \mathfrak{r}_L B) \rightarrow \exists \gamma (\gamma \mathfrak{r}_L C))$ . Obviously  $\alpha \mathfrak{r}_L (B \rightarrow C)$  implies this. Conversely, by (2)(i), the above with  $(\mathcal{R}, \mathcal{R})\text{-GC}_L$  yields  $\alpha$  such that

$$\forall \beta (\beta \mathfrak{r}_L B \rightarrow (\alpha \beta) \downarrow \wedge \exists \xi (\xi \in_L \alpha \beta) \wedge (\forall \xi \in_L \alpha \beta) (\xi \mathfrak{r}_L C)).$$

Thus  $\lambda \beta. \mathbf{b}_C(\alpha \beta) \mathfrak{r}_L (B \rightarrow C)$ .

If  $\alpha \mathfrak{r}_L \forall \xi A[\xi]$  then  $\forall \xi (\alpha \xi \mathfrak{r}_L A[\xi])$  and so  $\forall \xi A[\xi]^{\mathfrak{r}_L}$  by induction hypothesis. If  $\forall \xi A[\xi]^{\mathfrak{r}_L}$  then  $\forall \xi \exists \gamma (\gamma \mathfrak{r}_L A[\xi])$  and so  $(\mathcal{R}, \mathcal{R})\text{-GC}_L$  yields  $\alpha$  with

$$\forall \xi (\alpha \xi \downarrow \wedge \exists \eta (\eta \in_L \alpha \xi) \wedge (\forall \eta \in_L \alpha \xi) (\eta \mathfrak{r}_L A[\xi])).$$

Thus  $\lambda \xi. \mathbf{b}_A \xi(\alpha \xi) \mathfrak{r}_L \forall \xi A[\xi]$ .

If  $\alpha \mathfrak{r}_L \exists \xi A[\xi]$ , then  $(\exists \xi \in_L \alpha) (\mathbf{p}_1 \xi \mathfrak{r}_L A[\mathbf{p}_0 \xi])$  and by induction hypothesis  $A[\mathbf{p}_0 \xi]^{\mathfrak{r}_L}$  and so  $\exists \eta A[\eta]^{\mathfrak{r}_L}$ . Conversely, if  $A[\eta]^{\mathfrak{r}_L}$ , the induction hypothesis yields  $\alpha$  with  $\alpha \mathfrak{r}_L A[\eta]$  and so  $\mathbf{g}(\mathbf{p} \eta \alpha) \mathfrak{r}_L \exists \xi A[\xi]$ .  $\dashv$

LEMMA 3.32. In **CDLc**, if  $(\xi = \eta)^{\mathbf{r}_L} \rightarrow \xi = \eta$  and  $\mathcal{D}$  formulae are canonicalized, then  $(\mathcal{L}, \mathcal{D})\text{-GC!}$  is realizable.

PROOF. Assume  $\zeta \mathbf{r}_L \forall \alpha (D[\alpha] \rightarrow \exists! \beta C[\alpha, \beta])$ . For  $\alpha$  with  $\zeta' \mathbf{r}_L D[\alpha]$ ,

- (a)  $\zeta \alpha (c_D \alpha) \downarrow$ ,
- (b)  $\mathbf{p}_0(\zeta \alpha (c_D \alpha)) \mathbf{r}_L \exists \beta C[\alpha, \beta]$  and
- (c)  $\mathbf{p}_1(\zeta \alpha (c_D \alpha)) \mathbf{r}_L \forall \beta, \beta' (C[\alpha, \beta] \wedge C[\alpha, \beta'] \rightarrow \beta = \beta')$ .

Let  $\gamma := \lambda \alpha. \mathbf{c}(\mathbf{r}(\mathbf{p}_0(\zeta \alpha (c_D \alpha)))) \mathbf{p}_0$ .

If  $\eta, \eta' \in_L \mathbf{p}_0(\zeta \alpha (c_D \alpha))$ , by (b)(c),  $(\mathbf{p}_0 \eta = \mathbf{p}_0 \eta')^{\mathbf{r}_L}$ . By the assumption, we have  $\exists! \eta (\eta \in_L \mathbf{r}(\mathbf{p}_0(\zeta \alpha (c_D \alpha)))) \mathbf{p}_0$  and  $\gamma \alpha \downarrow$ . For  $\xi \in_L \mathbf{p}_0(\zeta \alpha (c_D \alpha))$ , by  $\mathbf{p}_0 \xi = \gamma \alpha$  and (b), we have  $\mathbf{p}_1 \xi \mathbf{r}_L C[\alpha, \gamma \alpha]$ . So  $\mathbf{b}_C \alpha (\gamma \alpha) (\mathbf{r}(\mathbf{p}_0(\zeta \alpha (c_D \alpha)))) \mathbf{p}_1 \mathbf{r}_L C[\alpha, \gamma \alpha]$ .

Thus  $\zeta \mathbf{r}_L \forall \alpha (D[\alpha] \rightarrow \exists! \beta C[\alpha, \beta])$  implies

$$\lambda \alpha \zeta'. \mathbf{b}_C \alpha (\gamma \alpha) (\mathbf{r}(\mathbf{p}_0(\zeta \alpha (c_D \alpha)))) \mathbf{p}_1 \mathbf{r}_L \forall \alpha (D[\alpha] \rightarrow C[\alpha, \gamma \alpha]).$$

⊣

Below we additionally assume  $\mathcal{L} \equiv \mathcal{L}'$ . The notions of canonicalizedness, actualizedness and completedness defined below are, although *not* implying “being realized”, called “having a canonical realizer” in the literature, where the three notions do not seem to be distinguished clearly. The last two make sense only when the formula belongs to both the realized and realizing languages (i.e.,  $A \in \mathcal{L} \cap \mathcal{L}'$ ), while the first is free from such an assumption. By definition,  $A^{\mathbf{r}_L} \leftrightarrow A$  if all the atomic are  $\mathbf{r}_L$ -completed.

DEFINITION 3.33 (actualized, completed).  $A[\vec{\eta}]$  is (i)  $\mathbf{r}_L$ -actualized by  $d_A$  if  $\forall \vec{\eta} (A[\vec{\eta}] \leftrightarrow (d_A \vec{\eta} \downarrow \wedge d_A \vec{\eta} \mathbf{r}_L A[\vec{\eta}]))$ ; (ii)  $\mathbf{r}_L$ -completed by  $c_A$  if it is  $\mathbf{r}_L$ -canonicalized and  $\mathbf{r}_L$ -actualized by the same  $c_A$ .

- LEMMA 3.34. (1) If  $\in_L$  is completed, so is  $\exists \xi (\xi \in_L -)$ .  
(2) If  $\mathcal{C}$  formulae are completed, so are  $N(\mathcal{C})$  ones.  
(3)  $(\mathcal{L}, \mathcal{D})\text{-GC}_L$  is  $\mathbf{r}_L$ -realizable in **CDLf** if  $\in_L$  is completed,  $\downarrow$  actualized, and  $\mathcal{D}$  formulae canonicalized.

PROOF. (1) For  $\xi \in_L \alpha$ , we have  $c_{\in_L} \xi \alpha \downarrow$  and  $\langle \xi, c_{\in_L} \xi \alpha \rangle \downarrow$ . Therefore  $\exists \xi (\xi \in_L \alpha)$  iff  $\mathbf{r} \alpha (\lambda \xi. \langle \xi, c_{\in_L} \xi \alpha \rangle) \mathbf{r}_L \exists \xi (\xi \in_L \alpha)$ .

(2) By induction on  $N(\mathcal{C})$  formulae. Consider  $\rightarrow$  only. If  $\alpha \mathbf{r}_L (A \rightarrow B)$ ,  $A$  implies  $\alpha c_A \mathbf{r}_L B$ ,  $c_B \mathbf{r}_L B$  and  $B$ . If  $A \rightarrow B$  then  $\zeta \mathbf{r}_L A$  implies  $c_A \mathbf{r}_L A$  and  $A$  whence  $B$ , which means  $\lambda \xi. c_B \mathbf{r}_L (A \rightarrow B)$ .

(3) Assume  $\zeta \mathbf{r}_L \forall \alpha (D[\alpha] \rightarrow \exists \beta C[\alpha, \beta])$ . Then, for  $\alpha$  with  $\zeta' \mathbf{r}_L D[\alpha]$ , we have  $\zeta \alpha (c_D \alpha) \downarrow \wedge (\zeta \alpha (c_D \alpha) \mathbf{r}_L \exists \beta C[\alpha, \beta])$ . Let

$$\delta := \lambda \zeta \alpha. \mathbf{r}(\zeta \alpha (c_D \alpha)) \mathbf{p}_0.$$

For  $\xi \in_L \delta \zeta \alpha$ , by  $(\forall \eta \in_L \mathbf{f}(\zeta \alpha (c_D \alpha)) \xi) (\mathbf{p}_1 \eta \mathbf{r}_L C[\alpha, \xi])$ , and 3.18 we can imply that  $\mathbf{b}_C \alpha \xi (\mathbf{r}(\mathbf{f}(\zeta \alpha (c_D \alpha)) \xi) \mathbf{p}_1)$  realizes  $C[\alpha, \xi]$ . Since  $\in_L$  is completed,

$$(*) \quad \lambda \xi \xi'. \mathbf{b}_C \alpha \xi (\mathbf{r}(\mathbf{f}(\zeta \alpha (c_D \alpha)) \xi) \mathbf{p}_1)$$

realizes  $(\forall \xi \in_L \delta \zeta \alpha) C[\alpha, \xi]$ . As  $\exists \xi (\xi \in_L \delta \zeta \alpha)$ , (1) yields  $d_{\exists \xi (\xi \in_L -)} (\delta \zeta \alpha) \mathbf{r}_L \exists \xi (\xi \in_L \delta \zeta \alpha)$ . The triple of  $d_{\downarrow} (\delta \zeta \alpha)$ ,  $d_{\exists \xi (\xi \in_L -)} (\delta \zeta \alpha)$  and  $(*)$  realizes  $\delta \zeta \alpha \downarrow \wedge \exists \xi (\xi \in_L \delta \zeta \alpha) \wedge (\forall \xi \in_L \delta \zeta \alpha) C[\alpha, \xi]$ . Thus  $\exists \gamma \forall \alpha (D[\alpha] \rightarrow \gamma \alpha \downarrow \wedge \exists \xi (\xi \in_L \gamma \alpha) \wedge (\forall \xi \in_L \gamma \alpha) C[\alpha, \xi])$  is

realized by  $\mathbf{g}(\langle \delta\zeta, \lambda\alpha\zeta' \cdot \langle d_\downarrow(\delta\zeta)\alpha, d_{\exists\xi(\xi \in \mathbf{L}^-)}(\delta\zeta)\alpha, \lambda\xi\xi' \cdot \mathbf{b}_C\alpha\xi(r(\mathbf{f}(\zeta\alpha(c_D\alpha))\xi)\mathbf{p}_1) \rangle \rangle)$ .  
Take  $\lambda\zeta$ . of this term.  $\dashv$

**COROLLARY 3.35.** If  $\xi \in \mathbf{L} \alpha$ ,  $\alpha\beta\downarrow$ ,  $\gamma = \alpha\beta$ ,  $\text{Bo}[\alpha]$  and atomic formulae are  $\mathbf{r}_\mathbf{L}$ -completed in  $\mathbf{CDL}\mathbf{f}+T$ ;  $T$  is  $\mathbf{r}_\mathbf{L}$ -realizable in  $\mathbf{CDL}\mathbf{f}+T$ ;  $RH(\mathcal{R}) \supseteq \mathcal{D} \supseteq \mathcal{R}$ ; and  $\mathcal{C} \supseteq \mathcal{R}$ , then  $\mathbf{CDL}\mathbf{f}+T \vdash \exists\alpha(\alpha \mathbf{r}_\mathbf{L} A)$  iff  $\mathbf{CDL}\mathbf{f}+T+(\mathcal{C}, \mathcal{D})\text{-GC}_\mathbf{L} \vdash A$ .

This generalizes the characterizations of Kleene's number realizability (by ECT); Lifschitz's (number) realizability; Kleene's functional realizability (by  $(\mathcal{L}_F, N(\Sigma_1^0))\text{-GCC}^1$ ) and van Oosten's functional realizability.

Moreover, this shows that  $(\mathcal{L}, RH(\mathcal{R}))\text{-GC}_\mathbf{L}$  follows from  $(\mathcal{R}, \mathcal{R})\text{-GC}_\mathbf{L}$  over  $\mathbf{CDL}\mathbf{f}$ .

We used  $\mathbf{f}$  only in the proof of the last lemma and we do not know if it is definable from other constants.

**3.3. Realizability of intuitionistic systems.** We apply the results from the last subsection to our situation:  $\mathcal{L} \equiv \mathcal{L}' \equiv \mathcal{L}_F$  where  $\mathcal{L}_F$  is considered to include  $\mathcal{L}_{\text{CDL}}$  via either  $\mathfrak{k}$  or  $\mathfrak{o}$ . Setting  $\alpha \mathbf{r}_\mathbf{L} A := A$  and  $\mathbf{b}_A := \lambda\vec{\eta}\alpha.\underline{0}$  for atomic  $A[\vec{\eta}]$ , we have 3.19.

**DEFINITION 3.36** ( $\mathbf{r}_\mathfrak{f}$ ,  $\mathbf{r}'_\mathfrak{f}$ ). Let  $\alpha \mathbf{r}_\mathfrak{f} A := (\alpha \mathbf{r}_\mathbf{L} A)^\mathfrak{k}$  and  $\alpha \mathbf{r}'_\mathfrak{f} A := (\alpha \mathbf{r}_\mathbf{L} A)^\mathfrak{o}$ , where  $QxA[x]$  is treated as  $Q\xi A[\xi(0)]$ .

**3.3.1. realizability of base theories.** Recall  $\mathbf{EL}_0^* = \mathbf{EL}_0^- + \Delta_0^0\text{-AC}^{00}$ . As seen in 3.2.3, for  $\mathbf{r}'_\mathfrak{f}$ -realizability, it is convenient to define the following.

**DEFINITION 3.37** ( $\mathbf{EL}'_0^*$ ,  $\mathbf{EL}'_0$ ). Define

$$\mathbf{EL}'_0^* := \mathbf{EL}_0^- + \Delta_0^0\text{-AC}^{00} + \text{MP} + \Delta_0^0\text{-BKL}; \text{ and } \mathbf{EL}'_0 := \mathbf{EL}'_0^* + \Sigma_1^0\text{-Ind}.$$

**LEMMA 3.38.** (1)  $N(\Sigma_1^0)$  formulae are  $\mathbf{r}_\mathfrak{f}$ -completed in  $\mathbf{EL}_0^- + \Sigma_1^0\text{-Bdg}$ .  
(2)  $N(\Sigma_1^0 \cup \text{B}\exists^1\Pi_1^0)$  are  $\mathbf{r}'_\mathfrak{f}$ -completed in  $\mathbf{EL}'_0^*$ .

**PROOF.** The atomic are trivially completed. Let  $B$  from  $\Delta_0^0$  be completed by  $c_B$ .  $\exists zB[\vec{\eta}, z]$ , i.e.,  $\exists\beta\forall xB[\vec{\eta}, \beta(0)]$  implies  $(\gamma_B|\vec{\eta})\downarrow \wedge B[\vec{\eta}, (\gamma_B|\vec{\eta})(0)]$  by 3.23(1)(i), i.e.,  $\mathbf{g}(\langle \gamma_B|\vec{\eta}, c_B|\vec{\eta} | (\gamma_B|\vec{\eta}) \rangle \mathbf{r}_\mathbf{L} \exists zB[\vec{\eta}, z])$ . By the hypothesis on  $c_B$ , we have

$$\exists\alpha(\alpha \mathbf{r}_\mathbf{L} \exists zB[\vec{\eta}, z]) \rightarrow \exists zB[\vec{\eta}, z].$$

This suffices for (1) by 3.34(2) with 2.11. For (2), for  $A$  from  $\Pi_1^0$ , 3.27(2) yields  $\forall\xi(\xi \in \mathfrak{L}^\circ \pi_A|\alpha|\underline{1}|\gamma \leftrightarrow \xi < \alpha \wedge A[\xi, \gamma])$ . Thus,

$$(\exists\xi < \alpha)A[\xi, \gamma] \text{ iff } \mathbf{r}(\langle \pi_A|\alpha|\underline{1}|\gamma \rangle | (\lambda\xi.\langle \xi, \underline{0}, c_A|\xi|\gamma \rangle)) \mathbf{r}'_\mathfrak{f} (\exists\xi < \alpha)A[\xi, \gamma].$$

$\dashv$

**THEOREM 3.39.** (1)  $\mathbf{EL}'_0^* + (\mathcal{L}_F, N(\Sigma_1^0))\text{-GCC}^1$  is  $\mathbf{r}_\mathfrak{f}$ -realizable in  $\mathbf{EL}'_0^*$ .  
(2)  $\mathbf{EL}'_0^* + (\mathcal{L}_F, N(\Sigma_1^0 \cup \text{B}\exists^1\Pi_1^0))\{-\text{GCC}^1, \text{-GC}_\mathbf{L}^\circ\}$  is  $\mathbf{r}'_\mathfrak{f}$ -realizable in  $\mathbf{EL}'_0^*$ , and so is  $(\mathcal{L}_F, N(\Sigma_1^0 \cup \text{B}\exists^1\Pi_1^0))\text{-GCB}^1$ .

**PROOF.** Since  $\in \mathfrak{L}^\mathfrak{k}$  and  $\in \mathfrak{L}^\circ$  are  $N(\Sigma_1^0)$ , they are completed. Also  $\alpha\beta\downarrow$  is completed by  $\mathbf{g}(\langle \alpha|\beta, c_\delta = \alpha|\beta | (\alpha|\beta)|\alpha|\beta \rangle)$ . Thus, by 3.32 and 3.34(3),  $(\mathcal{L}_F, N(\Sigma_1^0))\text{-GCC}^1$  in (1) and  $(\mathcal{L}_F, N(\Sigma_1^0 \cup \text{B}\exists^1\Pi_1^0))\{-\text{GCC}^1, \text{-GC}_\mathbf{L}^\circ\}$  in (2) are realizable, and so are  $N(\Sigma_1^0)$  axioms of  $\mathbf{EL}'_0^-$ . Moreover  $\text{MP}$  and  $\Delta_0^0\text{-BKL}$  are  $\mathbf{r}'_\mathfrak{f}$ -realizable by 3.38(2) as they are  $N(\Sigma_1^0 \cup \text{B}\exists^1\Pi_1^0)$ . Obviously  $(\mathcal{C}, \mathcal{D})\text{-GC}_\mathbf{L}^\circ$  implies  $(\mathcal{C}, \mathcal{D})\text{-GCB}^1$ .

It remains to realize (d) (in 2.10) of  $\mathbf{EL}_0^-$  and  $\Delta_0^0\text{-AC}^{00}$ . As (d) is of the form  $\exists\delta\forall xA[x, \delta(x), \alpha]$  with  $A$  from  $\Delta_0^0$ , 3.23(1)(i) yields  $\gamma_A$  with

$$\mathbf{g}|\langle\gamma_A|\alpha, c_{\forall xA[x, \delta(x), \eta]}|(\gamma_A|\alpha)|\alpha\rangle_{\mathbf{r}_L}\exists\delta\forall xA[x, \delta(x), \alpha].$$

$\Delta_0^0\text{-AC}^{00}$  is realized similarly by 3.23(1)(ii) (or see more general 3.42(ii) below).  $\dashv$

- COROLLARY 3.40.** (1)  $\mathbf{EL}_0^* + \mathbf{S} \vdash \exists\alpha(\alpha \mathbf{r}_f A)$  iff  $\mathbf{EL}_0^* + \mathbf{S} + (\mathcal{L}_F, N(\Sigma_1^0))\text{-GCC}^1 \vdash A$  for any schema  $\mathbf{S}$  consisting of  $N(\Sigma_1^0)$  formulae.  
(2)  $\mathbf{EL}_0'^* + \mathbf{S} \vdash \exists\alpha(\alpha \mathbf{r}'_f A)$  iff  $\mathbf{EL}_0'^* + \mathbf{S} + (\mathcal{L}_F, N(\Sigma_1^0 \cup \mathbf{B}\exists^1\Pi_1^0))\text{-GCC}_L^2 \vdash A$  for any schema  $\mathbf{S}$  consisting of  $N(\Sigma_1^0 \cup \mathbf{B}\exists^1\Pi_1^0)$  formulae.

These characterizations follow from 3.35. Among  $N(\Sigma_1^0)$  schemata are  $\mathbf{MP}$ ,  $\Sigma_1^0\text{-Ind}$  and  $\Pi_2^0\text{-Ind}$ .

**3.3.2. realizability of the axioms of Intuitionism with the weakest induction.** While 3.40 reduces realizability to the derivability from  $(\mathcal{L}_F, \mathcal{R})\text{-GC}_L$ , showing the latter is often as demanding as showing the former directly, as below. The folklore result 3.8 will be essential in the proof of 3.42(ii).

**PROPOSITION 3.41.**  $\mathcal{L}_F\text{-BFT}$  is (i)  $\mathbf{r}_f$ -realizable in  $\mathbf{EL}_0^* + \Delta_0^0\text{-BFT}$ ; (ii)  $\mathbf{r}'_f$ -realizable in  $\mathbf{EL}_0'^*$ .

**PROOF.** As  $\Delta_0^0\text{-BFT}$  is equivalently  $N(\Sigma_1^0)$ , it suffices to derive  $\mathcal{L}_F\text{-BFT}$  from  $(\mathcal{L}_F, N(\Sigma_1^0))\text{-GC}_L$  in the systems.

Assume  $\mathbf{Fan}[\gamma]$ ,  $\forall u(\gamma(u) = 0 \rightarrow u < \beta)$  and  $(\forall\alpha < \beta)(\forall k(\gamma(\alpha \uparrow k) = 0) \rightarrow \exists k B[\alpha \uparrow k])$ . Then  $(\mathcal{L}_F, N(\Sigma_1^0))\text{-GC}_L$  yields  $\zeta$  with

$$(\forall\alpha < \beta)(\forall k(\gamma(\alpha \uparrow k) = 0) \rightarrow (\zeta|\alpha)\downarrow \wedge \exists\eta(\eta \in_L \zeta|\alpha) \wedge (\forall\eta \in_L \zeta|\alpha)B[\alpha \uparrow \eta(0)]).$$

Particularly, for  $\alpha < \beta$ , if  $\forall k(\gamma(\alpha \uparrow k) = 0)$  then both (a)  $\exists m C[\alpha \uparrow m]$  and (b)  $\forall m(C[\alpha \uparrow m] \rightarrow (\exists k < m)B[\alpha \uparrow k])$  hold, where  $C[u] := |u| > (\zeta|u)(0)$  which is  $\Sigma_1^0$ , and where  $\zeta|u$  is defined analogously to 3.20.

Since (a) means  $\mathbf{Bar}[\gamma, C]$ ,  $\Sigma_1^0\text{-BFT}$  with 2.32(3)(ii) yields  $n$  with

$$(\forall\alpha < \beta)(\forall k(\gamma(\alpha \uparrow k) = 0) \rightarrow (\exists m < n)C[\alpha \uparrow m]),$$

which, with (b), implies  $(\forall\alpha < \beta)(\forall k(\gamma(\alpha \uparrow k) = 0) \rightarrow (\exists k < n)B[\alpha \uparrow k])$ . Here, note  $\mathbf{EL}_0'^* \vdash \Delta_0^0\text{-BFT}$  by 3.5(3).  $\dashv$

**PROPOSITION 3.42.** Both  $\mathcal{L}_F\text{-AC}^{00}$  and  $\mathcal{L}_F\text{-AC}^{01}$  are (i)  $\mathbf{r}_f$ -realizable in  $\mathbf{EL}_0^*$ ; (ii)  $\mathbf{r}'_f$ -realizable in  $\mathbf{EL}_0'^*$ .

**PROOF.** As  $\mathcal{C}\text{-AC}^{01}$  yields  $\mathcal{C}\text{-AC}^{00}$ , it suffices to derive  $\mathcal{L}_F\text{-AC}^{01}$  from  $(\mathcal{L}_F, \{\top\})\text{-GC}_L$  (uniformly for (i) and (ii)).

Assume  $\forall x\exists\beta A[x, \beta]$ , i.e.,  $\forall\xi\exists\beta A[\xi(0), \beta]$ . By  $(\mathcal{L}_F, \{\top\})\text{-GC}_L$ , we have  $\zeta$  with  $\forall x((\zeta|\underline{x})\downarrow \wedge \exists\eta(\eta \in_L \zeta|\underline{x}) \wedge (\forall\eta \in_L \zeta|\underline{x})A[x, \eta])$ . 3.23(1)(ii) applied to  $y = (\zeta|(\underline{x})_0^2)((\underline{x})_1^2)$  yields  $\gamma$  with  $(\gamma|\zeta)\downarrow$  and  $\forall x((\gamma|\zeta)_x = (\zeta|\underline{x}))$ .

We treat (i) and (ii) separately. (i) For  $\in_L \equiv \in_L^\dagger$ , obviously  $\forall xA[x, (\gamma|\zeta)_x]$ . (ii) For  $\in_L \equiv \in_L^\circ$ ,  $\Pi_1^0\text{-BAC}^{01}$ , with 3.8, applied to  $\forall x\exists\eta(\eta \in_L^\circ (\gamma|\zeta)_x)$  yields  $\alpha$  with  $\forall x((\alpha)_x \in_L^\circ (\gamma|\zeta)_x)$ , which implies  $\forall xA[x, (\alpha)_x]$ .  $\dashv$

**THEOREM 3.43.** (1)  $\mathbf{EL}_0^- + \mathbf{MP} + \mathcal{L}_F\{-\text{CC}^1, \text{-AC}^{00}, \text{-AC}^{01}, \text{-BFT}\}$  is  $\mathbf{r}_f$ -realizable in  $\mathbf{EL}_0^- + \mathbf{MP} + \Delta_0^0\text{-AC}^{00} + \Delta_0^0\text{-BFT}$ .

- (2)  $\mathbf{EL}_0^{\prime-} + \mathbf{MP} + \Sigma_1^0\text{-GDM} + \mathcal{L}_F\{-\mathbf{CB}^1, -\mathbf{CC}!^1, -\mathbf{AC}^{00}, -\mathbf{AC}^{01}, -\mathbf{BFT}\}$  is  $\mathbf{r}'_f$ -realizable in  $\mathbf{EL}_0^{\prime*}$ .

As a byproduct, we have the following upper bound result for the semi-Russian axiom NCT (cf. f.n.7).

DEFINITION 3.44 (Church's thesis CT and negative Church's thesis NCT). Let  $\{e\}(k) = n$  abbreviate the  $\Sigma_1^0$  formula asserting that the value of the recursive function with index  $e$  at  $k$  is  $n$  (Kleene bracket).

(CT):  $\forall\alpha\exists e\forall k(\alpha(k) = \{e\}(k))$ ;

(NCT):  $\forall\alpha\neg\forall e\neg\forall k(\alpha(k) = \{e\}(k))$ .

COROLLARY 3.45.  $\mathbf{EL}_0^- + \mathbf{MP} + \mathcal{L}_F\{-\mathbf{CC}^1, -\mathbf{AC}^{00}, -\mathbf{AC}^{01}\} + \mathbf{NCT}$  is  $\mathbf{r}_f$ -realizable in  $\mathbf{EL}_0^- + \mathbf{MP} + \Delta_0^0\text{-AC}^{00} + \mathbf{CT}$ .

**3.3.3. realizability with  $\Sigma_1^0$  induction.** One may wonder if  $\mathcal{C}\text{-FT}$  follows from  $\mathcal{C}\text{-BFT}$  with  $\mathcal{L}_F\text{-AC}^{00}$ , as we can take a function bounding the number  $n$  of branching in  $\mathbf{Fan}[\gamma]$ . This is not the case when  $\mathcal{C} \equiv \Delta_0^0$  by 3.43(1) and 2.33. Here we have to distinguish two ways of bounding:

- depending on nodes  $\forall u(\gamma(u) = 0 \rightarrow u \ll \delta)$  as defined below, and
- only on heights  $\forall u(\gamma(u) = 0 \rightarrow u < \delta)$ .

Now  $\mathcal{L}_F\text{-AC}^{00}$  yields the former, and we need  $\Sigma_1^0\text{-Ind}$  or primitive recursion to enhance it to the latter. This seems analogous to the classical fact mentioned before 2.33 that KL (König's lemma) or  $\mathbf{EL}_0^- + \mathcal{L}_F\text{-LEM} + \Delta_0^0\text{-FT}$  is consistency-wise stronger than  $\mathbf{WKL}_0$  (but also than  $\mathbf{EL}_0 + \mathcal{L}_F\text{-FT}$  or  $\mathbf{IS}_1$ ).

DEFINITION 3.46 ( $\mathcal{C}\text{-LBFT}$ ). Let  $\mathbf{LBFan}[\gamma] := \mathbf{Fan}[\gamma] \wedge \forall u(\gamma(u) = 0 \rightarrow u \ll \delta)$  where  $u \ll \delta := (\forall k < |u|)(u(k) < \delta(u \upharpoonright k))$ . For a class  $\mathcal{C}$  of formulae, define the following axiom schema:

( $\mathcal{C}\text{-LBFT}$ ):  $\mathbf{LBFan}[\gamma] \wedge \mathbf{Bar}[\gamma, \{u: B[u]\}] \rightarrow \exists m \forall \alpha (\forall k (\gamma(\alpha \upharpoonright k) = 0) \rightarrow (\exists n < m) B[\alpha \upharpoonright n])$ ,

for any  $B$  from  $\mathcal{C}$ .

LEMMA 3.47. (1)  $\mathbf{EL}_0 + \mathcal{C}\text{-BFT} \vdash \mathcal{C}\text{-LBFT}$ .

(2)  $\mathbf{EL}_0^- + \Pi_1^0\text{-AC}^{00} + \mathcal{C}\text{-LBFT} \vdash \mathcal{C}\text{-FT}$ .

PROOF. (1) Defined the following, which is equivalently  $\Delta_0^0$ .

$$C[d, e, \delta] := \forall u(|u| = |d| \wedge (\forall k < |d|)(u(k) < d(k)) \rightarrow \delta(u) < e).$$

Since  $\forall d \exists v(|v| = |d| + 1 \wedge d \subset v \wedge C[d, v(|d|), \delta])$ , by  $\Delta_0^0\text{-DC}^0$  we can take  $\beta$  such that  $\forall n C[\beta \upharpoonright n, \beta(n), \delta]$ . Then  $\forall u(\gamma(u) = 0 \rightarrow u \ll \delta)$  implies  $\forall u(\gamma(u) = 0 \rightarrow u < \beta)$ .

(2)  $\Pi_1^0\text{-AC}^{00}$ , applied to  $\mathbf{Fan}[\gamma]$ , yields  $\delta$  with  $\forall u(\gamma(u) = 0 \rightarrow u \ll \delta)$ .  $\dashv$

Next let us realize  $\Sigma_2^0\text{-DC}^0$ , which implies  $\Sigma_1^0\text{-DC}^1$  by 2.14 and  $\Sigma_2^0\text{-Ind}$  by 2.16(3)(i). This might be the most non-trivial part of the present article. The trick is the use of semi-classical principle. For, the realizing theory does not need to be intuitionistic since  $\mathbf{i}\Sigma_1$  and  $\mathbf{IS}_1$  are known to be mutually interpretable. We do not know if  $\Sigma_2^0\text{-Ind}$  (or  $\Sigma_2^0\text{-DC}^0$ ,  $\Sigma_1^0\text{-DC}^1$ ) can be realizable directly in  $\mathbf{i}\Sigma_1$ . Let us start with  $\mathbf{r}_f$ -realizability.

DEFINITION 3.48 (closure under  $\mathcal{C}$  functions). A class  $\mathcal{S}$  is called *closed under  $\mathcal{C}$  functions* iff (i)  $\mathcal{S} \wedge \mathcal{C} \wedge \neg\mathcal{C} \subseteq \mathcal{S}$  and (ii) for  $C$  from  $\mathcal{C}$  and  $D$  from  $\mathcal{S}$ , there is  $D_C$  from  $\mathcal{S}$  with  $\mathbf{EL}_0^- \vdash \exists!yC[x, y] \rightarrow (D_C[x] \leftrightarrow \exists y(C[x, y] \wedge D[x, y]))$ .

PROPOSITION 3.49. (1)  $\Delta_0^0(\Sigma_1^0) \cap N(\Sigma_1^0)$  is closed under  $\Sigma_1^0$  functions.  
(2) If  $\mathcal{S} \subseteq N(\Sigma_1^0)$  and is closed under  $\Sigma_1^0$  functions, both  $\exists^0\mathcal{S}\text{-DC}^0$  and  $\exists^0\mathcal{S}\text{-Ind}$  are  $\mathbf{r}_f$ -realizable in  $\mathbf{EL}_0 + \mathcal{S}\text{-Ind}$ .

PROOF. (1) is by induction on  $D$ :  $\exists!yC[y]$  yields

$$\exists y(C[y] \wedge (D_1[y] \rightarrow D_2[y])) \leftrightarrow (\exists y(C[y] \wedge D_1[y]) \rightarrow \exists y(C[y] \wedge D_2[y])).$$

(2) As  $\mathcal{S}\text{-Ind}$  is  $N(\Sigma_1^0)$ , it suffices derive  $\mathcal{S}\text{-DC}^0$  in  $\mathbf{EL}_0 + (\mathcal{L}_F, N(\Sigma_1^0))\text{-GCC}^1 + \mathcal{S}\text{-Ind}$  by 2.16(2)(i)(3)(i), 3.40(1) and 3.42(i). Let  $\forall x, y(A[x, y] \rightarrow \exists zA[y, z])$  with  $A$  from  $\mathcal{S}$ , say  $\forall x, y(A[x, y] \rightarrow (\gamma|\underline{x}|y)\downarrow \wedge A[y, (\gamma|\underline{x}|y)(0)])$  by  $(\mathcal{L}_F, N(\Sigma_1^0))\text{-GCC}^1$ . Fix  $x, y$  with  $A[x, y]$ . We prove  $\exists!uC[n, u] \wedge D_C[n]$  by  $\mathcal{S}\text{-Ind}$  on  $n$ , where

$$\begin{aligned} C[n, u] &::= |u| = n+2 \wedge u \upharpoonright 2 = \langle x \rangle * \langle y \rangle \wedge (\forall k < n)(u(k+2) = (\gamma|\underline{u}(k)|\underline{u}(k+1))(0)); \\ D[k, u] &::= A[u(k), u(k+1)], \end{aligned}$$

and  $D_C$  is by the closure under  $\Sigma_1^0$  functions. If it is done,  $\Sigma_1^0\text{-AC}^{00}$  yields  $\beta$  with  $\forall n \exists u(C[n, u] \wedge u(n) = \beta(n))$ .

As  $C[0, \langle x \rangle * \langle y \rangle]$ ,  $D_C[0]$  is by  $A[x, y]$ . If  $\exists!uC[n, u] \wedge D_C[n]$ , say  $C[n, v]$ , then  $D_C[n]$  means  $A[v(n), v(n+1)]$  and hence  $(\gamma|\underline{v}(n)|\underline{v}(n+1))\downarrow \wedge A[v(n+1), z]$  with  $z = (\gamma|\underline{v}(n)|\underline{v}(n+1))(0)$ . Thus  $C[n+1, v * \langle z \rangle]$  and so  $D_C[n+1]$ .  $\dashv$

As  $\Pi_1^0 \subseteq \Delta_0^0(\Sigma_1^0) \cap N(\Sigma_1^0)$ ,  $\Sigma_2^0\{-\text{DC}^0, \text{-Ind}\}$  is  $\mathbf{r}_f$ -realizable in  $\mathbf{EL}_0 + \Sigma_2^0\text{-DNE}$ , by 3.3(2), the other folklore.

For this argument functionality is not essential: ECT in Kleene's number realizability can substitute GCC, and so  $\mathbf{i}\Sigma_2$  is realizable in  $\mathbf{I}\Sigma_1$ . Wehmeier [48] identified the strengths of  $\mathbf{i}\Sigma_1$ ,  $\mathbf{i}\Pi_{n+2}$  and  $\mathbf{i}\Sigma_{n+3}$  by this realizability, but left  $\mathbf{i}\Sigma_2$ . Burr [10] identified it by another method. Our argument shows that Wehmeier's method could deal with  $\mathbf{i}\Sigma_2$ . If we extend this number realizability to  $\mathcal{L}_F$  in an obvious manner,  $\Sigma_2^0\text{-DC}^0$  and CT are also realizable. By allowing  $\Sigma_n$  oracle, we can interpret  $\mathbf{i}\Sigma_{n+2} + \Sigma_{n+2}\text{-DNE}$  in  $\mathbf{I}\Sigma_{n+1}$ .

For  $\mathbf{r}'_f$ -realizability, this does not seem to work well. We employ a more elaborated way, which works also in the first order setting, i.e., Lifschitz's number realizability, with recursive indices substituting functions. However, in this case we do not know if we can enhance  $\Sigma_2^0$  to  $\exists^0(\Delta_0^0(\Sigma_1^0) \cap N(\Sigma_1^0))$  as in the previous case.

DEFINITION 3.50 ( $(\mathcal{C}, \mathcal{D})\text{-EUB}$ ). The schema of *extended uniform bounding*  $(\mathcal{C}, \mathcal{D})\text{-EUB}$  is defined as follows.

$$\begin{aligned} ((\mathcal{C}, \mathcal{D})\text{-EUB}): \quad & \forall x(D[x] \rightarrow \exists yC[x, y]) \\ & \rightarrow \exists \alpha \forall n (\forall x < n)(D[x] \rightarrow (\exists y < \alpha(n))C[x, y]), \end{aligned}$$

for  $C$  from  $\mathcal{C}$  and  $D$  from  $\mathcal{D}$ .

LEMMA 3.51.  $(\Pi_1^0, \Pi_1^0)\text{-EUB}$  is  $\mathbf{r}'_f$ -realizable in  $\mathbf{EL}'_0 + \text{LPO}$ .



PROOF. Let  $C$  and  $D$  be  $\Pi_1^0$ . Let  $D$  be  $\mathbf{r}'_f$ -completed by  $c_D$ , by 3.38(2). Define  $A$  and  $B$  as follows:

$$\begin{aligned} A[n, m, \zeta] &::= (\forall x < n)(D[x] \rightarrow (\zeta|\underline{x}|(c_D|\underline{x}))(0) \leq m); \\ B[\alpha] &::= \forall n(\forall x < n)(D[x] \rightarrow (\exists y < \alpha(n))C[x, y]). \end{aligned}$$

As  $A$  is equivalently  $\Sigma_1^0$  by LPO, 3.23(1)(ii) yields  $\gamma_A$  with

$$\forall n \exists m A[n, m, \zeta] \rightarrow (\gamma_A|\zeta)\downarrow \wedge \forall n A[n, (\gamma_A|\zeta)(n), \zeta].$$

Let  $\zeta \mathbf{r}'_f \forall x(D[x] \rightarrow \exists y C[x, y])$ . We prove  $\exists m A[n, m, \zeta]$  by induction on  $n$ . Obviously  $A[0, 0, \zeta]$ . If  $A[n, m, \zeta]$  and  $D[n]$ , then  $c_D|\underline{n} \mathbf{r}'_f D[n]$  and so  $(\zeta|\underline{n}|(c_D|\underline{n}))\downarrow$  which implies  $A[n+1, m', \zeta]$  for  $m' := m + (\zeta|\underline{n}|(c_D|\underline{n}))(0)$ . If  $A[n, m, \zeta]$  and  $\neg D[n]$ , then  $A[n+1, m, \zeta]$ . By  $\Pi_1^0$ -LEM, we have  $\exists m A[n, m, \zeta] \rightarrow \exists m A[n+1, m, \zeta]$ .

Thus  $\forall n A[n, (\gamma_A|\zeta)(n), \zeta]$ . Then

$$(\forall x < n)(D[x] \rightarrow (\zeta|\underline{x}|(c_D|\underline{x}))(0) \leq (\gamma_A|\zeta)(n) \wedge \zeta|\underline{x}|(c_D|\underline{x}) \mathbf{r}'_f \exists y C[x, y])$$

and so  $B[\gamma_A|\zeta]$ . As  $B$  is  $N(\mathbf{B}\exists^1\Pi_1^0)$ , by 3.38(2), let  $B$  be  $\mathbf{r}'_f$ -completed by  $c_B$ . Then  $\mathbf{g}|\langle \gamma_A|\zeta, c_B|\langle \gamma_A|\zeta \rangle \mathbf{r}'_f \exists \alpha B[\alpha]$ .

Therefore  $\lambda \zeta. \mathbf{g}|\langle \gamma_A|\zeta, c_B|\langle \gamma_A|\zeta \rangle \mathbf{r}'_f$ -realizes the instance of  $(\Pi_1^0, \Pi_1^0)$ -EUB.  $\dashv$

PROPOSITION 3.52.  $\Pi_1^0$ -DC<sup>0</sup> is  $\mathbf{r}'_f$ -realizable in  $\mathbf{EL}'_0 + \text{LPO}$ . Hence so are  $\Sigma_2^0$ -DC<sup>0</sup>,  $\Sigma_1^0$ -DC<sup>1</sup> and  $\Sigma_2^0$ -Ind.

PROOF. By 3.39(2) and 3.51, it suffices to derive  $\Pi_1^0$ -DC<sup>0</sup> in  $\mathbf{EL}'_0 + (\Pi_1^0, \Pi_1^0)$ -EUB. Let  $A$  be  $\Pi_1^0$ , and assume  $\forall x, y(A[x, y] \rightarrow \exists z A[y, z])$ . Then  $(\Pi_1^0, \Pi_1^0)$ -EUB yields  $\alpha$  with  $(\forall v < n)(A[(v)_0^2, (v)_1^2] \rightarrow (\exists z < \alpha(n))A[(v)_1^2, z])$ .

Fix  $x, y$  with  $A[x, y]$ .  $\Delta_0^0$ -DC<sup>0</sup> yields  $\beta$  with

$$\beta|2 := \langle x+1 \rangle * \langle y+1 \rangle \text{ and } \beta(k+2) := \alpha((\beta(k), \beta(k+1))).$$

Define the following, where  $u < \beta := (\forall k < |u|)(u(k) < \beta(k))$ .

$$\begin{aligned} B[n, \beta] &::= (\exists u < \beta)C[u, n]; \\ C[u, n] &::= |u| = n+2 \wedge u(0) = x \wedge (\forall k \leq n)A[u(k), u(k+1)]. \end{aligned}$$

$B$  is  $\Pi_1^0$  by 2.23(2)(i) and 3.7.  $\Sigma_1^0$ -Ind and MP yield  $\Pi_1^0$ -Ind. It remains to see  $\forall n B[n, \beta]$  by  $\Pi_1^0$ -Ind, as it implies  $\exists \gamma(\gamma(0) = x \wedge \forall k A[\gamma(k), \gamma(k+1)])$  by  $\Pi_1^0$ -BKL with 3.5(2)(i).

Obviously  $\langle x \rangle * \langle y \rangle$  witnesses  $B[0, \beta]$ . Let  $B[n, \beta]$ , say  $u < \beta \wedge C[u, n]$ . Since  $(u(n), u(n+1)) < (\beta(n), \beta(n+1))$ ,  $A[u(n), u(n+1)]$  yields

$$z < \alpha((\beta(n), \beta(n+1))) = \beta(n+2) \text{ with } A[u(n+1), z].$$

So  $C[u * \langle z \rangle, n+1] \wedge u * \langle z \rangle < \beta$ .  $\dashv$

THEOREM 3.53. (1)  $\mathbf{EL}_0 + \Sigma_1^0$ -DC<sup>1</sup> +  $\Sigma_2^0$ {-DC<sup>0</sup>, -Ind} +  $\mathcal{L}_F$ -FT is  $\mathbf{r}'_f$ -realizable in  $\mathbf{EL}_0 + \Delta_0^0$ -BFT +  $\Sigma_2^0$ -DNE.

(2)  $\mathbf{EL}'_0 + \Sigma_1^0$ {-GDM, -DC<sup>1</sup>} +  $\Sigma_2^0$ {-DC<sup>0</sup>, -Ind} +  $\mathcal{L}_F$ -FT is  $\mathbf{r}'_f$ -realizable in  $\mathbf{EL}'_0 + \text{LPO}$ .

**3.3.4. realizability with  $\Pi_2^0$  induction.** It is natural to ask how to realize  $\Pi_{n+2}^0$ -Ind and  $\Sigma_{n+3}^0$ -Ind. As Wehmeier [48] mentioned, they are all realizable in  $\mathbf{IS}_2$  by Kleene's number realizability. This remains to hold for our two kinds of functional realizability. It is technically convenient to introduce the following schema.

DEFINITION 3.54 (( $\mathcal{C}, \mathcal{D}$ )-RDC). For classes  $\mathcal{C}, \mathcal{D}$  of formulae, define the following axiom schemata:

$$\begin{aligned} ((\mathcal{C}, \mathcal{D})\text{-RDC}^1): \quad & \forall \alpha (D[\alpha] \rightarrow \exists \beta (D[\beta] \wedge C[\alpha, \beta])) \\ & \rightarrow \forall \gamma (D[\gamma] \rightarrow \exists \delta ((\delta)_0 = \gamma \wedge \forall n C[(\delta)_n, (\delta)_{n+1}])), \end{aligned}$$

for any  $C$  from  $\mathcal{C}$  and  $D$  from  $\mathcal{D}$ .

LEMMA 3.55. (1)  $\mathbf{EL}_0^- + (\mathcal{C}, \exists^1 \mathcal{C})\text{-RDC}^1 \vdash \mathcal{C}\text{-DC}^1$ .

(2)  $\mathbf{EL}_0^- + (\mathcal{C}, \mathcal{D})\text{-RDC}^1 \vdash (\mathcal{C}, \exists^1 \mathcal{D})\text{-RDC}^1$ .

PROOF. As (1) is easy, we show (2).

Assume  $\forall \alpha (\exists \xi D[\alpha, \xi] \rightarrow \exists \beta (\exists \eta D[\beta, \eta] \wedge C[\alpha, \beta]))$ . For  $\gamma$  with  $\exists \eta D[\gamma, \eta]$ , say  $D[\gamma, \eta]$ , ( $\mathcal{C}, \mathcal{D}$ )-RDC<sup>1</sup> applied to  $\forall \alpha (D[(\alpha)_0^2, (\alpha)_1^2] \rightarrow \exists \beta D[(\beta)_0^2, (\beta)_1^2] \wedge C[(\alpha)_0^2, (\beta)_0^2])$  yields  $\delta$  such that  $(\delta)_0 = (\gamma, \eta)$  and  $\forall n C[(\delta)_n, (\delta)_{n+1}]$ .  $\dashv$

Our goal is to show the realizability of  $\exists^1 \Pi_\infty^0 \{-\text{DC}^1, -\text{DC}^0, \text{-Ind}\}$ . By 2.16(2)(i)(3)(i) and the last lemma, it suffices to realize  $(\exists^1 \Pi_\infty^0, \exists^1 \Pi_\infty^0)\text{-RDC}^1$ .

LEMMA 3.56. (1) (i)  $\Pi_n^0 \rightarrow \Pi_{n+1}^0 \subseteq \forall^0 \neg \Pi_n^0$  over  $\mathbf{EL}_0^- + \Sigma_n^0\text{-DNE}$ ; and

(ii)  $(\forall \xi \in_L^0 \alpha) A[\xi, \alpha]$  is  $\Pi_2^0$  over  $\mathbf{EL}_0'^*$  if  $A$  is  $\Pi_2^0$ .

(2) For  $B$  from  $\Pi_1^0$ ,  $\mathbf{EL}_0^- + \Delta_0^0\text{-BKL}$  proves

$$\forall n (\exists \eta < \alpha) (\forall k < n) B[k, (\eta)_k, (\eta)_{k+1}] \rightarrow (\exists \eta < \alpha) \forall k B[k, (\eta)_k, (\eta)_{k+1}].$$

(3) (i)  $\Pi_\infty^0 \subseteq \exists^1 \Pi_1^0$  over  $\mathbf{EL}_0^- + \Pi_1^0\text{-AC}^{01}$ . Hence (ii)  $\mathbf{EL}_0^- + \Pi_1^0\text{-AC}^{01} \vdash \exists^1 \Pi_\infty^0\text{-AC}^{01}$ ,  $\mathbf{EL}_0^- + \Pi_1^0\text{-DC}^1 \vdash \exists^1 \Pi_\infty^0\text{-DC}^1$  and  $\mathbf{EL}_0^- + (\mathcal{C}, \Pi_1^0)\text{-RDC}^1 \vdash (\mathcal{C}, \exists^1 \Pi_\infty^0)\text{-RDC}^1$ .

PROOF. (1)(i) By 2.24(1)(ii),  $\Sigma_n^0\text{-DNE}$  yields

$$\Pi_n^0 \rightarrow \forall^0 \Sigma_n^0 = \forall^0 (\Pi_n^0 \rightarrow \Sigma_n^0) = \forall^0 (\Pi_n^0 \rightarrow \neg \neg \Sigma_n^0) = \forall^0 \neg (\Pi_n^0 \wedge \neg \Sigma_n^0) \subseteq \forall^0 \neg \Pi_n^0.$$

(ii) Take  $B$  from  $\Pi_1^0$  with  $(\xi \in_L^0 \alpha \rightarrow A[\xi, \alpha]) \leftrightarrow \forall x \neg B[x, \xi, \alpha]$  by (i). Then  $(\forall \xi \in_L^0 \alpha) A[\xi, \alpha]$  is equivalent to  $(\forall \xi < (\alpha)_0^2) \forall x \neg B[x, \xi, \alpha]$ , i.e.,  $\forall x \neg (\exists \xi < (\alpha)_0^2) B[x, \xi, \alpha]$  which is equivalently  $\Pi_2^0$  by 3.5(2)(ii) and MP.

(2) Let  $C$  be  $\Delta_0^0$  such that  $\forall \eta, k (B[k, \eta, \eta'] \leftrightarrow \forall \ell C[k, \eta | \ell, \eta' | \ell])$  by 2.14. The premise implies  $\forall z (\exists u < \alpha) (|u| = z \wedge (\forall k, \ell < z) C[k, (u)_k | \ell, (u)_{k+1} | \ell])$ , where  $(u)_k$  is as in 3.8. Apply  $\Delta_0^0\text{-BKL}$ .

(3)  $\Pi_1^0\text{-AC}^{01}$  yields the Skolem functions for any  $\Pi_\infty^0$  formula under the necessary existence assumption. More precisely, we can show, by meta-induction on  $k \leq n$  with  $\Pi_1^0\text{-AC}^{01}$ , that  $\forall x_k \exists y_k \dots \forall x_0 \exists y_0 C[x_n, \dots, x_0, y_n, \dots, y_0]$  is equivalent to  $\exists \alpha \forall x_k, \dots, x_0 C[x_n, \dots, x_0, y_{k+1}, (\alpha)_k(x_k), \dots, (\alpha)_0(x_k, \dots, x_0)]$ , for any  $\Delta_0^0$ -formula  $C$ .  $\dashv$

DEFINITION 3.57 (rec). Let rec be such that

$$\mathbf{EL}_0^- \vdash (\text{rec}|\xi|\eta|0 \simeq \xi)^{\mathfrak{k}} \wedge (\text{rec}|\xi|\eta|z+1 \simeq \eta | (\text{rec}|\xi|\eta|z) | z)^{\mathfrak{k}}.$$

The existence of  $\text{rec}$  is directly by 3.23(1)(ii), but it can also be constructed by  $\text{fix}$  and  $\mathbf{d}$  as in the usual theories of operations and numbers (cf. [5, VI.2.8] and [43, Chapter 9, 3.8]). However, we need  $\Pi_2^0\text{-Ind}$  as well as  $\Delta_0^0\text{-AC}^{00}$  to imply  $\forall z((\text{rec}|\xi|\eta|z)\downarrow)$  from  $\forall z((\text{rec}|\xi|\eta|z)\downarrow \rightarrow (\text{rec}|\xi|\eta|z+1)\downarrow)$ . This is why we need  $\Pi_2^0\text{-Ind}$ .

In the following, (i) is just by constructing the realizer in this way, whereas (ii) requires further tricks.

**THEOREM 3.58.** The schema  $(\mathcal{L}_F, \exists^1\Pi_\infty^0)\text{-RDC}^1$  are (i)  $\mathbf{r}_F$ -realizable in  $\mathbf{EL}_0^* + \Pi_2^0\text{-Ind}$ ; (ii)  $\mathbf{r}'_F$ -realizable in  $\mathbf{EL}'_0 + \Pi_2^0\text{-Ind}$ .

**PROOF.** By 3.56(3)(ii), it suffices to realize  $(\mathcal{L}_F, \Pi_1^0)\text{-RDC}^1$ . By 3.23(1)(ii) construct  $\epsilon$  so that, for any  $\zeta, \zeta', \gamma$ ,

$$\epsilon|\zeta|\zeta'|\beta|\gamma|\underline{0} \simeq \mathbf{g}|\langle\gamma, \langle\zeta', \underline{0}\rangle\rangle; \quad \epsilon|\zeta|\zeta'|\gamma|\underline{z+1} \simeq \mathbf{u}|(\mathbf{r}|(\epsilon|\zeta|\zeta'|\gamma|\underline{z})|(\theta|\zeta)),$$

where  $\theta := \lambda\zeta\xi.\zeta|(\xi)_0^2|((\xi)_1^2)_0^2$ . The last  $\simeq$  means that, for any  $\eta$ ,

$$\eta \in_{\mathbf{L}} \epsilon|\zeta|\zeta'|\gamma|\underline{z+1} \text{ iff } (\exists\xi \in \epsilon|\zeta|\zeta'|\beta|\gamma|\underline{z}) (\eta \in_{\mathbf{L}} \zeta|(\xi)_0^2|((\xi)_1^2)_0^2).$$

Note that  $(\alpha|\dots|\beta)\downarrow$  is  $\Pi_2^0$  by  $\Delta_0^0\text{-AC}^{00}$ . By 3.23(1)(ii), we can take  $\epsilon''$  such that, for any  $\zeta, \zeta', \gamma$ ,

$$\forall z(\epsilon|\zeta|\zeta'|\gamma|\underline{z}\downarrow) \rightarrow \epsilon''|\zeta|\zeta'|\gamma\downarrow \wedge \forall z((\epsilon''|\zeta|\zeta'|\gamma)_z \simeq \mathbf{r}|(\epsilon|\zeta|\zeta'|\gamma|\underline{z})|\mathbf{p}_0).$$

For (i), set  $\epsilon' = \epsilon''$  and, for (ii), by 3.27(2) take also  $\epsilon'$  so that, for any  $\zeta, \zeta', \gamma$ ,

$$\forall z(\epsilon|\zeta|\zeta'|\gamma|\underline{z}\downarrow) \rightarrow \left( \forall \eta (\eta \in_{\mathbf{L}} \epsilon'|\zeta|\zeta'|\gamma \leftrightarrow \left( \eta \leq \epsilon''|\zeta|\zeta'|\gamma \wedge \forall z ((\eta)_{z+1} \in_{\mathbf{L}} \theta|\zeta|(\eta)_z) \right) \right).$$

Let  $A$  be  $\Pi_1^0$  and  $B$  be arbitrary  $\mathcal{L}_F$  formula. We  $\mathbf{r}_L$ -realize  $(\{B\}, \{A\})\text{-RDC}^1$ . By 2.8(1)(iii), 3.19 and 3.39, we may assume that  $A$  contains no  $\rightarrow$  except  $\neg$  applied to atomic subformulae. Then, by 3.56(1)(ii),  $\eta \mathbf{r}_L A$  is equivalently  $\Pi_2^0$ .

Assume  $\zeta \mathbf{r}_L \forall \alpha(A[\alpha] \rightarrow \exists \beta(A[\beta] \wedge B[\alpha, \beta]))$  and  $\zeta' \mathbf{r}_L A[\gamma]$ . By  $\Pi_2^0\text{-Ind}$  on  $z$  we can show:

- (a)  $\epsilon|\zeta|\zeta'|\gamma|\underline{z}\downarrow \wedge (\forall \eta \in_{\mathbf{L}} \epsilon|\zeta|\zeta'|\gamma|\underline{z})(((\eta)_1^2)_0^2 \mathbf{r}_L A[(\eta)_0^2])$
- (b)  $(\exists \eta \leq \epsilon''|\zeta|\zeta'|\gamma)((\eta)_z \in_{\mathbf{L}} \epsilon|\zeta|\zeta'|\gamma|\underline{z} \wedge (\forall k < z)((\eta)_{k+1} \in_{\mathbf{L}} \theta|\zeta|(\eta)_k))$  and
- (c)  $(\forall \eta \in_{\mathbf{L}} \epsilon'|\zeta|\zeta'|\gamma)(\mathbf{p}_0|(\mathbf{p}_1|(\eta)_z) \mathbf{r}_L A[\mathbf{p}_0|(\eta)_z])$

By 3.23(1)(ii) take  $\nu$  such that  $(\mathbf{p}_0|(\nu|\eta))_z = \mathbf{p}_0|(\eta)_z$ ,  $(\mathbf{p}_0|(\mathbf{p}_1|(\nu|\eta)) = \lambda\xi.\underline{0}$  and  $(\mathbf{p}_1|(\mathbf{p}_1|(\nu|\eta)))|z = \mathbf{p}_1|(\mathbf{p}_1|(\eta)_{z+1})$  for any  $\eta, z$ . Now (c) yields

$$(\forall \eta \in_{\mathbf{L}} \epsilon'|\zeta|\zeta'|\gamma)(\mathbf{p}_1|(\mathbf{p}_1|(\nu|\eta)) \mathbf{r}_L \forall z B[(\mathbf{p}_0|(\nu|\eta))_z, (\mathbf{p}_0|(\nu|\eta))_{z+1}]).$$

To show  $\mathbf{r}|(\epsilon'|\zeta|\zeta'|\gamma)|\nu \mathbf{r}_L \exists \eta((\eta)_0 = \gamma \wedge \forall z B[(\eta)_z, (\eta)_{z+1}])$ , it remains to show  $\exists \eta(\eta \in_{\mathbf{L}} \epsilon'|\zeta|\zeta'|\gamma)$ .  $\Sigma_1^0\text{-AC}^{00}$  yields  $\alpha = \epsilon''|\zeta|\zeta'|\gamma$ . (i) is done. For (ii) apply 3.56(2) to (b).  $\dashv$

By 2.16(2)(i)(3)(i) and 3.55, the next corollary follows.

**COROLLARY 3.59.**  $\exists^1\Pi_\infty^0\{-\text{DC}^1, -\text{DC}^0, -\text{Ind}\}$  are (i)  $\mathbf{r}_F$ -realizable in  $\mathbf{EL}_0^* + \Pi_2^0\text{-Ind}$ ; (ii)  $\mathbf{r}'_F$ -realizable in  $\mathbf{EL}'_0 + \Pi_2^0\text{-Ind}$ .

**3.3.5. realizability with full induction and full bar induction.** For the sake of completeness, let us realize even stronger induction schemata, beyond  $\Pi_\infty^0\text{-Ind} = \Sigma_\infty^0\text{-Ind}$ . The self-realizability of full induction  $\mathcal{L}_F\text{-Ind}$  was known (e.g., from [29]). Here we recall and hierarchize it.

- DEFINITION 3.60. (1)  $\Lambda_{n,0}^i := \forall^i \Sigma_n^0$ ;  $\Lambda_{n,m+1}^i := \forall^i (\Lambda_{n,m}^i \rightarrow \Sigma_n^0)$  for  $i < 2$ .  
(2)  $\Xi_{n,0} := \Pi_{n+1}^0$ ;  $\Xi_{n,m+1} := \forall^1 (\Xi_{n,m} \rightarrow \Sigma_n^0)$ .  
(3)  $\Theta_0^1$  is the closure of  $\Delta_0^0$  under  $\wedge, \vee, \forall^0, \exists^0$  and  $\exists^1$ ;  $\Theta_{m+1}^1$  is that of  $\Theta_m^1$  under  $\wedge, \vee, \forall^0, \exists^0, \forall^1, \exists^1$  and  $\Theta_m^1 \rightarrow (-)$ .

$\Theta_m^1$  is the second order analogue of Burr's  $\Theta_m$  from [10]. Note that  $\Theta_m^1$ 's exhaust  $\mathcal{L}_F$  and  $\Xi_{n,m} \subseteq \Theta_m^1$ . Moreover,  $\Xi_{n,m+1}$  is equivalent to  $\Lambda_{n+1,m}^1$  over  $\mathbf{EL}_0^- + \Sigma_{n+1}^0\text{-DNE}$ . The next is enough to generalize 3.58.

LEMMA 3.61. If  $A$  is  $\Theta_m^1$  whose  $\Delta_0^0$  subformulae contain no  $\rightarrow$  except  $\neg$  applied to atomic subformulae, then both  $\alpha \mathbf{r}_f A$  and  $\alpha \mathbf{r}'_f A$  are equivalently  $\Xi_{1,m}$  over  $\mathbf{EL}_0^*$  and  $\mathbf{EL}'_0^*$ , respectively.

PROOF.  $(\alpha|\dots|\beta)\downarrow$  is  $\Pi_2^0$  by  $\Delta_0^0\text{-AC}^{00}$ . For  $\exists, \vee$  in the case of  $\mathbf{r}'_f$  with  $m=0$ , use 3.56(1)(ii).  $\Xi_{n,m}$  is closed under  $\wedge$ , as  $(A \rightarrow B) \wedge (C \rightarrow D)$  is equivalent to  $\forall n((n=0 \rightarrow A) \wedge (n>0 \rightarrow C) \rightarrow (n=0 \rightarrow B) \wedge (n>0 \rightarrow D))$ .  $\neg$

THEOREM 3.62.  $(\mathcal{L}_F, \Theta_m^1)\text{-RDC}^1$ , and hence  $\Theta_m^1\{-\text{DC}^1, \text{-DC}^0, \text{-Ind}\}$ , are  $\mathbf{r}_f$ -realizable in  $\mathbf{EL}_0^* + \Xi_{1,m}\text{-Ind}$ , and  $\mathbf{r}'_f$ -realizable in  $\mathbf{EL}'_0 + \Xi_{1,m}\text{-Ind}$ .

PROOF. The proof is the same as 3.58, but now (a) and (c) are  $\Xi_{1,m}$  if  $A$  is  $\Theta_m^1$ , where  $\Pi_2^0 \equiv \Xi_{1,0} \subseteq \Xi_{1,m}$ .  $\neg$

Note that  $\exists^1 \Pi_1^0 = \Theta_0^1$  over  $\mathbf{EL}_0^* + \Pi_1^0\text{-AC}^{01}$  by 2.11. Thus 3.58 can be seen as the instance of 3.62 for  $m=0$ .

Remark 3.63. As  $\exists^1 \Pi_1^0 = \exists^1 \neg \Sigma_1^0$  has a universal formula over  $\mathbf{EL}_0^-$ , so does  $\Theta_0^1$  over  $\mathbf{EL}_0^* + \Pi_1^0\text{-AC}^{01}$ .

For  $m > 0$ , since  $\exists^1 \Xi_{1,m}$  has a universal formula (defined easily from a universal  $\Sigma_1^0$  formula) over  $\mathbf{EL}_0^-$ , 3.31(2)(ii) and 3.61 tell us that  $\Theta_m^1$  has a universal formula over  $\mathbf{EL}_0^* + (\mathcal{L}_F, N(\Sigma_1^0))\text{-GCC}^1$ . By a close look at the proof of 3.31(2)(ii), we see that  $(\mathcal{L}_F, N(\Sigma_1^0))\text{-GCC}^1$  can actually be weakened to  $(\Xi_{1,m}, \Xi_{1,m-1})\text{-GCC}^1$ .

As  $\neg \Theta_m \subseteq \Theta_{m+1}$ , by the usual diagonalization, the formalized strict hierarchy theorem can be proved.

Similarly, Burr's  $\Theta_{m+1}$  has a universal formula in the presence of ECT. This suggests that, in certain contexts,  $\Theta_m$ 's and  $\Theta_m^1$ 's behave as nicely as  $\Sigma_m^i$ 's and  $\Pi_m^i$ 's do in the classical context.

A similar strategy by 3.61 applies to bar induction. This is the last Brouwerian axiom that we realize.

THEOREM 3.64.  $(\Theta_m^1, \mathcal{L}_F)\text{-Bl}_M$  is  $\mathbf{r}_f$ -realizable in  $\mathbf{EL}_0^* + \Xi_{1,m}\text{-Bl}_D$ , and  $\mathbf{r}'_f$ -realizable in  $\mathbf{EL}'_0 + \Xi_{1,m}\text{-Bl}_D$ .

PROOF. As  $(\mathcal{L}_F, \Delta_0^0)\text{-GCB}^1$  implies  $\mathcal{L}_F\text{-CB}^0$ , it suffices to realize  $\Theta_m^1\text{-Bl}_D$ , by 2.39(4) and 3.39. Assume

$$\zeta \mathbf{r}_l \text{Bar}[0, \{u: \alpha(u) = 0\}] \wedge \forall u(\alpha(u) = 0 \rightarrow A[u]) \wedge \forall u(\forall x A[u * \langle x \rangle] \rightarrow A[u]).$$

3.23(1)(ii) yields  $\gamma, \delta, \epsilon$  with

$$\begin{aligned} & \gamma|\xi|\underline{u}|\eta \simeq \xi|\underline{u^*}\langle\eta(0)\rangle; \\ & \delta|\zeta|\alpha|\xi|\underline{u} \simeq \begin{cases} (\zeta)_1^3|\underline{u}|(c_{\alpha(u)=0}|\alpha|\underline{u}) & \text{if } \alpha(u) = 0; \\ (\zeta)_2^3|\underline{u}|(\lambda\eta.\gamma|\xi|\underline{u}|\eta) & \text{otherwise} \end{cases}; \\ & \epsilon := \lambda\zeta.\text{fix}(\delta|\zeta|\alpha). \end{aligned}$$

Let  $B[u] := (\epsilon|\zeta|\underline{u})\downarrow \wedge (\epsilon|\zeta|\underline{u} \mathbf{r}_L A[u])$ . If  $\alpha(u) = 0$  then  $\epsilon|\zeta|\underline{u} \mathbf{r}_L A[u] \equiv B[u]$ . As  $\text{Bar}[0, \{u: \alpha(u) = 0\}]$  by 3.38, it remains to show  $\forall x B[u^*\langle x \rangle] \rightarrow B[u]$ : we may assume  $\alpha(u) \neq 0$ , and  $\epsilon|\zeta|\underline{u} \simeq (\zeta)_2^3|\underline{u}|(\lambda\eta.\epsilon|\zeta|\underline{u^*}\langle\eta(0)\rangle)$ . Thus  $\forall x B[u^*\langle x \rangle]$ , i.e.,  $(\lambda\eta.\epsilon|\zeta|\underline{u^*}\langle\eta(0)\rangle) \mathbf{r}_L \forall x A[u^*\langle x \rangle]$  yields  $\epsilon|\zeta|\underline{u} \mathbf{r}_L A[u]$ . Hence  $\lambda\zeta.(\epsilon|\zeta|(\cdot))$  realizes  $\{A\}\text{-Bl}_D$ .  $\dashv$

One may wonder if this can be extended to the ‘‘bar version’’ of dependent choice, defined as follows:

$$\begin{aligned} ((\mathcal{C}, \mathcal{D})\text{-BarDC}_M): & \text{Bar}[0, \{u: B[u]\}] \wedge \forall u, v (B[u] \rightarrow B[u^*v]) \\ & \wedge \forall u, \beta \exists \gamma A[u, \beta, \gamma] \wedge \forall \alpha (\forall u (B[u] \rightarrow A[u, (\alpha)_{\prec u}, (\alpha)_u]) \\ & \quad \rightarrow \exists \delta \forall u (A[u, (\delta)_{\prec u}, (\delta)_u] \wedge (B[u] \rightarrow (\delta)_u = (\alpha)_u)) \\ & \text{where } (\gamma)_{\prec u} \text{ is such that } ((\gamma)_{\prec u})_x = (\gamma)_{u^*\langle x \rangle} \text{ and } A \text{ is from } \mathcal{C} \text{ and } B \text{ from } \\ & \mathcal{D}. \end{aligned}$$

Among similar axioms are *transfinite dependent choice* [31, 32] and *bar recursion* [4, Section 6.4]. In our context, this extension is not proper, since

$$\mathbf{EL}_0^- + \forall^0\mathcal{C}\text{-AC}^{01} + \mathcal{D}\text{-CB}^0 + \exists^1\forall^0\mathcal{C}\text{-Bl}_D \vdash (\mathcal{C}, \mathcal{D})\text{-BarDC}_M.$$

We can show by applying  $\exists^1\forall^0\mathcal{C}\text{-Bl}_D$  to the following, where we may assume that  $B$  is  $\Delta_0^0$  similarly to 2.39(4):

$$A'[u] := \exists \delta \forall v (A[u^*v, (\delta)_{\prec u^*v}, (\delta)_{u^*v}] \wedge (B[u^*v] \rightarrow (\delta)_{u^*v} = (\alpha)_{u^*v})).$$

## §4. Lower Bounds: Forcing and Negative Interpretations.

**4.1. Gödel–Gentzen negative interpretation.** Gödel–Gentzen negative interpretation  $N$ , sometimes called double negation translation, is the standard way of interpreting logical symbols of classical logic intuitionistically. In arithmetic, since  $\neg\neg A$  is equivalent to  $A$  for atomic  $A$ , if we consider the classical  $\forall$  and  $\exists$  as abbreviations defined from  $\wedge, \rightarrow, \perp, \forall$ , we may identify  $A^N$  with  $A$ , and intuitionistic theories are extensions of classical ones with new logical symbols  $\vee$  and  $\exists$  in the same sense as modal logics are extensions with  $\Box$  and  $\Diamond$ . Here, however, we consider  $\vee$  and  $\exists$  are primitive symbols even in the classical theories, which extend intuitionistic ones by  $\mathcal{L}_F\text{-LEM}$ .

**DEFINITION 4.1** ( $N$ ). For a formula  $A$ , define

$$\begin{aligned} A^N & := \neg\neg A \text{ for atomic } A; \\ (A \Box B)^N & := A^N \Box B^N \text{ for } \Box \equiv \wedge, \rightarrow; & (\forall \xi A)^N & := \forall \xi A^N; \\ (A \vee B)^N & := \neg(\neg A^N \wedge \neg B^N); & (\exists \xi A)^N & := \neg\forall \xi \neg A^N, \end{aligned}$$

where  $QxA[x]$  is considered as  $Q\xi A[\xi(0)]$ .

- LEMMA 4.2. (1)  $A^N$  intuitionistically follows from  $B_1^N, \dots, B_n^N$ , if  $A$  classically follows from  $B_1, \dots, B_n$ .
- (2)  $((\exists x < y)A)^N$  and  $((\forall x < y)A)^N$  are equivalent to  $\neg(\forall x < y)\neg A^N$  and  $(\forall x < y)A^N$ , respectively.
- (3)  $\mathbf{EL}_0^- + \Sigma_n^0\text{-DNE} \vdash A^N \leftrightarrow A$  if  $A$  is negative in  $\Pi_{n+1}^0$ , i.e., built up by  $\wedge, \rightarrow$  and  $\forall$  from  $\Pi_{n+1}^0$  formulae.
- (4)  $\mathbf{EL}_0^- + \Sigma_n^0\text{-DNE} \vdash A \rightarrow A^N$  if  $A$  is built up by  $\wedge, \forall$  and  $\exists$  from those formulae negative in  $\Pi_{n+1}^0$ .

- COROLLARY 4.3. (1)  $\mathbf{EL}_0^- \vdash (\mathbf{EL}_0^-)^N$ ; and  $\Pi_{n+1}^0$ -preservingly  $N$  interprets  $\mathbf{EL}_0^- + \mathcal{L}_F\text{-LEM}$  in  $\mathbf{EL}_0^- + \Sigma_n^0\text{-DNE}$ .
- (2) Over  $\mathbf{EL}_0^- + \Sigma_n^0\text{-DNE}$ , (i)  $\Pi_{n+1}^0\text{-Ind}$ , (ii)  $\Sigma_n^0\text{-Bdg}$  and (iii)  $\Sigma_n^0\text{-Ind}$  are equivalent to their  $N$ -interpretations; if  $n \geq 1$ , so are (iv)  $\mathcal{C}\text{-BI}_D$  and (v)  $(\mathcal{C}, \mathcal{D})\text{-BI}_M$  for  $\mathcal{C} \in \{\Sigma_k, \Lambda_{k,m}^i, \Xi_{k,m} \mid k \leq n\}$ ,  $\mathcal{D} \in \{\Pi_\ell^0, \Sigma_{\ell+1}^0 \mid \ell < n\}$ .

Recall 3.60, the definitions of  $\Lambda_{n,m}^i, \Xi_{n,m}$ .  $\Lambda_{1,m}^1$  is the  $N$ -interpretation of  $\Pi_{m+1}^1$  normal form, over MP.

While  $N$  will be one of our main tools for lower bound proof, it yields some result for a semi-Russian axiom KA, introduced by Veldman [45]. This asserts the existence of counterexample of  $\Delta_0^0\text{-WFT}$ .

DEFINITION 4.4 (KA). Let  $\text{KA} := \exists \gamma \text{KA}[\gamma]$  where

$$\text{KA}[\gamma] := (\forall \alpha < \underline{2}) \exists n (\gamma(\alpha \upharpoonright n) = 0) \wedge \forall m (\exists u < \underline{2}) (|u| = m \wedge (\forall k < m) (\gamma(u \upharpoonright k) > 0)).$$

PROPOSITION 4.5.  $\mathbf{EL}_0^- + \text{MP} + \Delta_0^0\text{-AC}^{00} + \text{NCT} \vdash \text{KA}$ .

PROOF. Let  $\{c\}$  be the computable counterexample, i.e.,

$$\mathbf{EL}_0^- + \Sigma_1^0\text{-Bdg} \vdash \text{CT} \rightarrow \text{KA}[\{c\}].$$

Applying  $N$  to this, with 4.2(3) with  $n = 1$ , we have

$$\mathbf{EL}_0^- + \text{MP} + \Sigma_1^0\text{-Bdg} \vdash \text{NCT} \rightarrow \text{KA}[\{c\}].$$

$\Delta_0^0\text{-AC}^{00}$  yields  $\gamma$  with  $\{c\} = \gamma$ . ⊣

Classically  $\mathcal{L}_F\text{-AC}^{00}$  implies  $(\mathcal{L}_F\text{-CA})^{\text{ch}}$ . As a refinement, it is known that, even intuitionistically,  $\Pi_1^0\text{-AC}^{00}$  implies  $(\Sigma_1^0\text{-CA})^{\text{ch}}$  and hence it is of the strength of  $\mathbf{ACA}_0$ . Here  $\Pi_1^0\text{-AC}^{00}$  can be weakened to  $\Pi_1^0\text{-AC}!^{00}$ , and even to SBAC! defined below, which restricts the  $\Pi_1^0$  formulae to be of a special form. With SBAC, we can refine the classical implication from KL (König's lemma) to  $\mathbf{ACA}_0$  (cf. [39, Theorem III.7.2]) as follows.

DEFINITION 4.6 (semi-bounded axiom of choice SBAC and SBAC!). SBAC is defined as follows and SBAC! is defined with  $\exists$  replaced by  $\exists!$  in the premise.

$$(\text{SBAC}): \forall x \exists y \text{SB}_{C,D,t}[x, y] \rightarrow \exists \alpha \forall x \text{SB}_{C,D,t}[x, \alpha(x)], \text{ for } C \text{ and } D \text{ both from } \Delta_0^0, \text{ where } \text{SB}_{C,D,t}[x, y] := C[x, y] \vee (y < t[x] \wedge \forall z D[x, y, z]).$$

- LEMMA 4.7. (1)  $\mathbf{EL}_0^- + \text{LPO} + \Delta_0^0\text{-FT} \vdash (\text{SBAC})^N$ .
- (2)  $\mathbf{EL}_0^- + \text{LPO} + \text{SBAC!} \vdash (\Sigma_1^0\text{-CA})^{\text{ch}}$ .

PROOF. (1) As in the proof of 2.33, we may assume  $C[x, y] \wedge C[x, z] \rightarrow y = z$ . Let  $A \equiv \text{SB}_{C,D,t}$ . Define  $\gamma$  by

$$\gamma(u) = 0 \leftrightarrow (\forall n < |u|) \left( u(n) \neq 0 \rightarrow (\forall x \leq n) \left( u(x) \neq 0 \wedge \left( \left( \begin{array}{c} C[x, u(x)-1] \vee \\ u(x) \leq t[x] \wedge \\ (\forall z < |u|) D[x, u(x)-1, z] \end{array} \right) \right) \right) \right).$$

We prove  $\text{Fan}[\gamma]$ . By LPO, there are two cases:

- if  $\neg \exists y C[|u|, y]$  then  $\forall z (\gamma(u * \langle z \rangle) = 0 \rightarrow z \leq t[x])$ ;
- if  $C[|u|, y]$  for some  $y$  then  $\forall z (\gamma(u * \langle z \rangle) = 0 \rightarrow z \leq \max(y+1, t[x])$ .

Obviously  $\gamma(u) = 0 \rightarrow \gamma(u * \langle 0 \rangle) = 0$ .

If  $\forall k (\gamma(\beta \upharpoonright k) = 0)$  and  $\forall x (\beta(x) \neq 0)$ , then we have

$$\forall k (\forall x \leq k) (C[x, \alpha(x)] \vee (\alpha(x) < t[x] \wedge (\forall z < k) D[x, \alpha(x), z]))$$

for  $\alpha(x) := \beta(x) - 1$ , and, as “ $\forall k (\forall x \leq k)$ ” is same as “ $\forall x (\forall k \geq x)$ ”, we also have  $\forall x (C[x, \alpha(x)] \vee (\alpha(x) < t[x] \wedge \forall z D[x, \alpha(x), z])$  and so  $\forall x A^N[x, \alpha(x)]$ .

Thus  $\forall \alpha \neg \forall x A^N[x, \alpha(x)] \rightarrow \forall \beta (\forall k (\gamma(\beta \upharpoonright k) = 0) \rightarrow (\forall x (\beta(x) \neq 0) \rightarrow \perp))$  and, by MP,

$$(*) \quad \forall \alpha \neg \forall x A^N[x, \alpha(x)] \rightarrow \text{Bar}[\gamma, \{u: (\exists x < |u|) (u(x) = 0)\}].$$

Assume  $(\forall x \exists y A[x, y])^N$ . For any  $n$ ,  $\forall x \neg \forall y \neg (C[x, y] \vee (y < t[x] \wedge (\forall z < n) D[x, y, z]))^N$  and, by MP,  $(\forall x < n) \exists y (C[x, y] \vee (y < t[x] \wedge (\forall z < n) D[x, y, z]))$ . With  $\Sigma_1^0\text{-Ind}$  yielded by 2.33, we can show  $\exists u (|u| = k+1 \wedge \gamma(u) = 0 \wedge u(k) \neq 0)$  for  $k < n$ . Particularly,  $\exists v (|v| = n \wedge v(n) \neq 0 \wedge \gamma(v) = 0)$ . By  $\Delta_0^0\text{-FT}$ ,  $\neg \text{Bar}[\gamma, \{u: (\exists k < |u|) (u(k) = 0)\}]$ , and hence, by (\*),  $\neg \forall \alpha \neg \forall x A^N[x, \alpha(x)]$ , i.e.,  $(\exists \alpha \forall x A[x, \alpha(x)])^N$ .

(2) Let  $B$  be  $\Sigma_1^0$  of  $\mathcal{L}_S$ , say  $B^{\text{ch}}[x] \equiv \exists y C[x, y]$ . As before, now we may assume  $C[x, y] \wedge C[x, z] \rightarrow y = z$ . LPO yields  $\forall x \exists! y (C[x, y] \vee (y = 0 \wedge \forall z \neg C[x, z]))$ . Now SBAC! yields  $\alpha$  with  $\forall x (C[x, \alpha(x)] \vee (\alpha(x) = 0 \wedge \forall z \neg C[x, z]))$ . Because  $\forall x (\exists i < 2) (i = 0 \leftrightarrow C[x, \alpha(x)])$ , there is  $\beta$  with  $\forall x (\beta(x) = 0 \leftrightarrow C[x, \alpha(x)])$ . Then  $\forall x (\beta(x) = 0 \leftrightarrow B^{\text{ch}}[x])$ .  $\dashv$

Thus in the presence of LPO, we cannot strengthen  $\Delta_0^0\text{-WFT}$  to  $\Delta_0^0\text{-FT}$  unless going beyond Finitism.

How about  $\mathcal{C}\text{-WFT}$ ,  $(\mathcal{C}, \mathcal{D})\text{-BI}_M$  or  $\mathcal{C}\text{-BI}_D$ ? By 2.32(3)(ii) and 2.29(1), the first to ask are  $\Pi_1^0\text{-WFT}$  and  $\Sigma_1^0\text{-BI}_D$ . The below answers this with help of  $\Sigma_2^0\text{-DNE}$  or MP. (1) refines Berger's [7], where he relies on classical logic but with a slightly weaker variant of WFT. We weaken  $\Sigma_2^0\text{-DNE}$  and MP in the next subsections.

LEMMA 4.8. (1)  $\mathbf{EL}_0^- + \Sigma_2^0\text{-DNE} + \Pi_1^0\text{-WFT} \vdash ((\Sigma_1^0\text{-CA})^{\text{ch}})^N$ .

(2)  $\mathbf{EL}_0^- + \text{MP} + \Sigma_1^0\text{-BI}_D \vdash ((\Sigma_1^0\text{-CA})^{\text{ch}})^N$ .

PROOF. (1) Let  $A$  be  $\Sigma_1^0$ , say  $A[x]^{\text{ch}} \equiv \exists y C[x, y]$  with  $C$  being  $\Delta_0^0$ . Recall  $v < \underline{2} := (\forall k < |v|) (v(k) < 2)$ . Define

$$D[u] := (\forall x < |u|) (u(x) = 0 \leftrightarrow (\exists y < |u|) C[x, y]);$$

$$B[u] := (\forall v < \underline{2}) \neg D[u * v].$$

We show  $(\forall \alpha < \underline{2}) (\forall k \neg B[\alpha \upharpoonright k] \rightarrow \forall x (\alpha(x) = 0 \leftrightarrow \exists y C[x, y]))$ . Let  $\forall k \neg B[\alpha \upharpoonright k]$ , i.e.,  $\forall k \neg (\forall v < \underline{2}) \neg D[(\alpha \upharpoonright k) * v]$ . By MP, we have  $\forall k (\exists v < \underline{2}) D[(\alpha \upharpoonright k) * v]$ . If  $\alpha(x) = 0$ ,

taking  $v < \underline{2}$  with  $D[(\alpha \uparrow (x+1)) * v]$ , as  $((\alpha \uparrow (x+1)) * v)(x) = \alpha(x) = 0$ , we now have  $(\exists y < |(\alpha \uparrow (x+1)) * v|)C[x, y]$ , and  $\exists y C[x, y]$ . Conversely if  $C[x, y]$ , taking  $v < \underline{2}$  with  $D[(\alpha \uparrow (x+y+1)) * v]$ , since  $(\exists z < |(\alpha \uparrow (x+y+1)) * v|)C[x, z]$  we can conclude  $\alpha(x) = ((\alpha \uparrow (x+y+1)) * v)(x) = 0$ .

We show  $((\exists \alpha < \underline{2}) \forall x (\alpha(x) = 0 \leftrightarrow \exists y C[x, y]))^N$ , which is, by MP, equivalent to

$$\neg(\forall \alpha < \underline{2}) \neg \forall x (\alpha(x) = 0 \leftrightarrow \exists y C[x, y]).$$

Suppose for contradiction  $(\forall \alpha < \underline{2}) \neg \forall x (\alpha(x) = 0 \leftrightarrow \exists y C[x, y])$ . Then, by the above,  $(\forall \alpha < \underline{2}) \neg \forall k \neg B[\alpha \uparrow k]$  and, by  $\Sigma_2^0$ -DNE,  $(\forall \alpha < \underline{2}) \exists k B[\alpha \uparrow k]$ .  $\Pi_1^0$ -WFT yields  $n$  with  $(\forall \alpha < \underline{2}) (\exists k < n) B[\alpha \uparrow k]$  and so  $(\forall \alpha < \underline{2}) \neg D[\alpha \uparrow n]$ . However we can construct  $u < \underline{2}$  with  $|u| = n$  and  $(\forall k < n)(u(k) = 0 \leftrightarrow (\exists y < n) C[x, y])$ , a contradiction.

(2) By 4.3(1)(2)(iv), it suffices to show  $(\Sigma_1^0\text{-CA})^{\text{ch}}$  in  $\mathbf{EL}_0^- + \mathcal{L}_F\text{-LEM} + \Sigma_1^0\text{-Bl}_D$ . We prove  $\Pi_1^0\text{-AC}^{00}$  classically by 4.7(2). Let  $A$  be  $\Pi_1^0$  and  $B[u] := (\exists k < |u|) \neg A[k, u(k)]$ . Then  $\neg B[\langle \rangle]$  and  $B[u] \rightarrow B[u * v]$ . Now  $\forall k \exists x A[k, x]$  yields  $\forall x B[u * \langle x \rangle] \rightarrow B[u]$ , and, by  $(\Sigma_1^0, \Sigma_1^0)\text{-Bl}_M$  with 2.29(3), also  $\neg \text{Bar}[\underline{0}, \{u: B[u]\}]$ , i.e.,  $\exists \alpha \forall n \neg B[\alpha \uparrow n]$ .  $\dashv$

Thus, only with this famous negative interpretation  $N$ , we have the following lower bound results. For the lower bounds of  $\Sigma_1^0\text{-Ind}$ ,  $\Sigma_1^0\text{-Bl}_D$  and  $\Pi_1^0\text{-WFT}$  with LPO, more works are required as in the next subsections.

**COROLLARY 4.9.**  $\mathbf{ACA}_0$  is interpretable

- (i)  $\Pi_2^0$ -preservingly in  $\mathbf{EL}_0^- + \text{LPO} + \Delta_0^0\text{-FT}$  and in  $\mathbf{EL}_0^- + \text{MP} + \Sigma_1^0\text{-Bl}_D$ ;
- (ii)  $\Pi_3^0$ -preservingly in  $\mathbf{EL}_0^- + \Sigma_2^0\text{-DNE} + \Pi_1^0\text{-WFT}$ ; and
- (iii)  $\Delta_0^1$ -preservingly in  $\mathbf{EL}_0^- + \text{LPO} + \Pi_1^0\text{-AC}!^{00}$ .

**PROOF.** (i) By 4.7, 4.8(2) and 4.3(1) with  $n = 1$ . (ii) Similar.

(iii)  $\mathbf{EL}_0^- + \text{LPO} + \Pi_1^0\text{-AC}!^{00}$  trivially includes  $\mathbf{EL}_0^- + \text{LPO} + \text{SBAC}!$  and, by 4.7(2), also includes  $\mathbf{EL}_0^- + (\Sigma_1^0\text{-CA})^{\text{ch}}$ . As  $(\Sigma_1^0\text{-CA})^{\text{ch}}$  implies  $\Pi_\infty^0\text{-LEM}$  and so  $\Delta_0^1\text{-LEM}$ ,  $\mathbf{EL}_0^- + (\Sigma_1^0\text{-CA})^{\text{ch}}$  proves  $((\Sigma_1^0\text{-CA})^{\text{ch}})^N \wedge \Delta_0^1\text{-LEM}$ , and so interprets  $\Delta_0^1$ -preservingly  $(\mathbf{ACA}_0)^{\text{ch}}$  by  $N$ .  $\dashv$

**4.2. Coquand–Hofmann forcing interpretation.** Gödel–Gentzen negative interpretation  $N$  yields the  $\Pi_1$  conservation of  $\mathbf{PA}$  over  $\mathbf{HA}$ . Friedman–Dragalin translation (also known as Friedman’s  $A$ -translation) was introduced to enhance it to  $\Pi_2$  conservation, or equivalently to show the admissibility of MP-rule. We start by recalling this well-known technique:

$$\begin{aligned} C^A &: \equiv C \vee A \text{ if } C \text{ is atomic;} \\ (C \square D)^A &: \equiv C^A \square D^A \text{ for } \square \equiv \wedge, \rightarrow, \vee; \\ (Qx C)^A &: \equiv Qx(C^A) \text{ for } Q \equiv \forall, \exists. \end{aligned}$$

For any  $\Sigma_1$  formula  $A[x]$ , since  $\mathbf{HA} \vdash A[x]^N \leftrightarrow \neg \neg A[x]$ , if  $\mathbf{PA} \vdash \forall x A(x)$  then  $\mathbf{HA} \vdash \neg \neg A[x]$ , to which by applying  $A[x]$ -translation, we have  $\mathbf{HA} \vdash (\neg \neg A[x])^{A[x]}$ , i.e.,  $\mathbf{HA} \vdash (A[x] \vee A[x] \rightarrow A[x]) \rightarrow A[x]$  and hence  $\mathbf{HA} \vdash \forall x A[x]$ . However, this combination of the negative interpretation  $N$  and  $A[x]$ -translation does not necessarily preserve another  $\Pi_2$  sentence  $\forall x B[x]$ . Thus, it does not uniformly preserve  $\Pi_2$  sentences. Moreover,  $A$ -translation is not  $\{\perp\}$ -preserving, unless  $A$  is equivalent to  $\perp$ , and so does not yield the consistency-wise implication.



Coquand–Hofmann forcing overcomes this disadvantage, by replacing single  $A$  with a finite set of such  $A$ 's. We further generalize this technique to general  $\exists^0\mathcal{C}$  but assuming  $\mathcal{C}$ -LEM.

Below we consider any  $\alpha$  to code a finite set of  $(x, \xi)$ 's: e.g.,

$$(x, \xi) \in \alpha := (\exists k < \alpha(0))((\alpha \ominus 1)_k = \langle x \rangle * \xi),$$

and also  $(x, \xi)$  to code  $\exists u P[x, u, \xi]$ . (Thus  $\exists u \text{Tr}_P[u, \alpha]$  means the disjunction of all formulae “belonging to”  $\alpha$ .) As an example, we can take  $P$  from  $\Pi_n^0$  so that  $\exists u P[x, u, \xi]$  is a universal  $\Sigma_{n+1}^0$  formula.

**DEFINITION 4.10** ( $\text{Tr}_P, \Vdash_P$ ). (1)  $\text{Tr}_P[u, \alpha] := (\exists(x, \xi) \in \alpha) P[x, u, \xi]$ .  
 (2)  $\alpha \Vdash_P A := A \vee \exists u \text{Tr}_P[u, \alpha]$ .

Since  $\text{Tr}_P[u, \alpha]$  is  $(\exists k < \alpha(0)) P[(\alpha \ominus 1)_k(0), u, (\alpha \ominus 1)_k \ominus 1]$ , we see that  $\exists u \text{Tr}_P[u, \alpha]$  is  $\Sigma_{n+1}^0$  if  $P$  is  $\Pi_n^0$ .

**DEFINITION 4.11** ( $\Vdash_P$ ). To an  $\mathcal{L}_F$  formula  $B$ , assign  $\alpha \Vdash_P B$  as follows:

$$\begin{aligned} \alpha \Vdash_P B &:= \alpha \Vdash_P B \text{ for atomic ;} \\ \alpha \Vdash_P B \rightarrow C &:= (\forall \beta \supseteq \alpha)((\beta \Vdash_P B) \rightarrow (\beta \Vdash_P C)); \\ \alpha \Vdash_P B \square C &:= (\alpha \Vdash_P B) \square (\alpha \Vdash_P C) \text{ for } \square \equiv \wedge, \vee; \\ \alpha \Vdash_P Q\xi B &:= Q\xi(\alpha \Vdash_P B) \text{ for } Q \equiv \forall, \exists, \end{aligned}$$

where  $QxB[x]$  is treated as  $Q\xi B[\xi(0)]$ .

The connection to Friedman's  $A$ -translation is clear in the atomic case. The extension to compound formulae is by Kripke semantics, where the monotonicity is (1)(ii) of the next lemma. (2) in the lemma, asserting the  $\Vdash_P$  respects intuitionistic reasonings, easily follows, and (3) corresponds to the assertion that  $B^A \leftrightarrow B \vee A$  if  $C$  is  $\Sigma_1$ , which allowed us to show  $A[x]^{A[x]} \leftrightarrow A[x] \vee A[x]$ , the key fact to show MP-rule.

**LEMMA 4.12.** (1)  $\mathbf{EL}_0^-$  proves

(i)  $B \leftrightarrow (\emptyset \Vdash_P B)$  and (ii)  $\alpha \subseteq \beta \rightarrow (\alpha \Vdash_P B \rightarrow \beta \Vdash_P B) \wedge (\alpha \Vdash_P B \rightarrow \beta \Vdash_P B)$ .

(2) If  $C$  intuitionistically follows from  $B_1, \dots, B_n$ , then

$$\mathbf{EL}_0^- \vdash (\alpha \Vdash_P B_1) \wedge \dots \wedge (\alpha \Vdash_P B_n) \rightarrow (\alpha \Vdash_P C).$$

(3) If  $C, D, \exists x \neg E, E \in \mathcal{C}$  for all subformulae  $C \rightarrow D$  and  $\forall x E$  of  $B$ , then

$$\mathbf{EL}_0^- + \mathcal{C}\text{-LEM} \vdash (\alpha \Vdash_P B) \leftrightarrow (\alpha \Vdash_P B).$$

(4) If  $F$  is built up by  $\wedge, \vee, \forall, \exists$  from those  $B$ 's which satisfy the condition of (3), then

$$\mathbf{EL}_0^- + \mathcal{C}\text{-LEM} \vdash F \leftrightarrow (\emptyset \Vdash_P F).$$

(5) If  $B$  is as in (3), then

$$\mathbf{EL}_0^- + \mathcal{C}\text{-LEM} \vdash \alpha \Vdash_P (B \rightarrow G) \leftrightarrow (B \rightarrow \alpha \Vdash_P G).$$

So  $\alpha \Vdash_P ((\forall x < y)G) \leftrightarrow (\forall x < y)(\alpha \Vdash_P G)$ .

PROOF. (3) By induction on  $B$ . The atomic case is trivial. The case of  $\wedge$  is by  $(C \vee F) \wedge (D \vee F) \leftrightarrow (C \wedge D) \vee F$ .

$\alpha \Vdash_P C \rightarrow D$  is, by induction hypothesis, equivalent to

$$(\forall \beta \supseteq \alpha)((C \vee \exists u \text{Tr}_P[u, \beta]) \rightarrow (D \vee \exists u \text{Tr}_P[u, \beta])),$$

to  $C \rightarrow (\forall \beta \supseteq \alpha)(D \vee \exists u \text{Tr}_P[u, \beta])$ , by  $\mathcal{C}$ -LEM to  $\neg C \vee D \vee (\forall \beta \supseteq \alpha)\exists u \text{Tr}_P[u, \beta]$  and to  $(C \rightarrow D) \vee \exists u \text{Tr}_P[u, \alpha]$ .

By induction hypothesis,  $\alpha \Vdash_P \exists x E$  is equivalent to  $\exists x(E \vee \exists u \text{Tr}_P[u, \alpha])$  and to  $(\exists x E) \vee \exists u \text{Tr}_P[u, \alpha]$ . Similarly  $\alpha \Vdash_P \forall x E$  is to  $\forall x(E \vee \exists u \text{Tr}_P[u, \alpha])$  and to  $(\forall x E) \vee \exists u \text{Tr}_P[u, \alpha, u]$ , but by  $\exists x \neg E \vee \forall x E$ .

(5) If  $\alpha \Vdash_P (B \rightarrow G)$  and  $B$  then, by (4) and (1)(ii),  $\alpha \Vdash_P B$  and  $\alpha \Vdash_P G$ . If  $B \rightarrow (\alpha \Vdash_P G)$  then, for  $\beta \supseteq \alpha$ , we can see that  $\beta \Vdash_P B$  implies  $B \vee \exists u \text{Tr}[u, \beta]$  by (3),  $(\alpha \Vdash_P G) \vee (\beta \Vdash_P \perp)$  and so, by (1)(ii),  $\beta \Vdash_P G$ , i.e.,  $\alpha \Vdash_P (B \rightarrow G)$ .  $\dashv$

COROLLARY 4.13. (1) If  $B$  is  $\Pi_\infty^0$ ,  $\mathbf{EL}_0^- \vdash B \leftrightarrow (\emptyset \Vdash_P B)$ ;  
(2) if  $B$  is  $\Sigma_{n+1}^0$ , then  $\mathbf{EL}_0^- + \Sigma_n^0\text{-LEM} \vdash (\alpha \Vdash_P B) \leftrightarrow (\alpha \Vdash_P B)$ .

DEFINITION 4.14 (self-forcible). A schema  $S$  is called *self-forcible for  $\mathcal{C}$*  if, for any  $P \in \mathcal{C}$ ,  $S$  implies  $\emptyset \Vdash_P S$ .

COROLLARY 4.15. (i)  $\mathbf{EL}_0^- \vdash (\emptyset \Vdash_P \mathbf{EL}_0^-)$ ; (ii) in  $\mathbf{EL}_0^- + \Sigma_{k+1}^0\text{-LEM}$ ,  $\Sigma_k^0\text{-Ind}$  and  $\Pi_k^0\text{-Ind}$  are self-forcible for  $\mathcal{L}_F$ .

LEMMA 4.16. Over  $\mathbf{EL}_0^- + \Sigma_n^0\text{-LEM}$ , the following are self-forcible for  $\Pi_n^0$ :

- (i)  $\Pi_n^0\text{-WFT}$  if  $n > 0$ ;
- (ii) for  $\mathcal{C}, \mathcal{D} \in \{\Sigma_{n+2k+1}^0, \Lambda_{n+2k+1, m}^1, \Xi_{n+2k+1, m}, \Theta_m^1\}$ , (a)  $\mathcal{C}\text{-Ind}$ , (b)  $\mathcal{C}\text{-Bdg}$ ,  
(c)  $\mathcal{C}\text{-AC}^{0i}$ , (d)  $\mathcal{C}\text{-DC}^i$ , (e)  $(\mathcal{C}, \mathcal{D})\text{-Bl}_M$  and (f)  $\mathcal{C}\text{-Bl}_D$  (if  $n = 0$ ).

PROOF. We may assume  $\exists u \text{Tr}_P[u, \alpha] \equiv \exists l C[l, \alpha]$  with  $C$  being  $\Pi_n^0$ .

(i) If  $\alpha \Vdash_P (\forall \xi < \underline{2}) \exists k B[\xi \upharpoonright k]$  where  $B$  is  $\Pi_n^0$ , then  $(\forall \xi < \underline{2}) \exists k (\alpha \Vdash_P B[\xi \upharpoonright k])$  by 4.13(2), i.e.,  $(\forall \xi < \underline{2}) \exists k (B[\xi \upharpoonright k] \vee \exists l C[l, \alpha])$ . Thus  $(\forall \xi < \underline{2}) \exists k D[\xi \upharpoonright k]$  where

$$D[u] := B[u] \vee C[\upharpoonright u, \alpha]$$

is  $\Pi_n^0 \vee \Pi_n^0 \subseteq \Pi_n^0$  by  $\Sigma_n^0\text{-LEM}$ . Then  $\Pi_n^0\text{-WFT}$  yields  $m$  with  $(\forall \xi < \underline{2}) (\exists k < m) D[\xi \upharpoonright k]$  and so  $(\forall \xi < \underline{2}) (\exists k < m) (\alpha \Vdash_P B[\xi \upharpoonright k])$ . As  $\xi < \underline{2}$  is  $\Pi_1^0$ , by 4.12(3)(5) with  $n > 0$ ,  $\alpha \Vdash_P (\forall \xi < \underline{2}) (\exists k < m) B[\xi \upharpoonright k]$ .

(ii) If  $B$  is  $\Pi_n^0$ , then  $\beta \Vdash_P Q y_{n+2k(+1 \text{ or } 2)} \dots \exists y_{n+1} B[x, y_{n+2}, \dots]$  is equivalent to  $Q \dots \exists y_{n+1} (\beta \Vdash_P B[x, y_{n+1}, \dots])$  and, by 4.13(2), also to

$$Q \dots \exists y_{n+1} \exists \ell (B[x, y_{n+1}, \dots] \vee C[\ell, \beta]).$$

By  $\Sigma_n^0\text{-LEM}$ , if  $A$  is equivalently  $\mathcal{C}$ , so is  $\beta \Vdash_P A[x]$ .

(a) Notice that if  $\alpha \Vdash_P A[0] \wedge (\forall x < n) (A[x] \rightarrow A[x+1])$  then  $(\forall x < n) (\alpha \Vdash_P A[x] \rightarrow \alpha \Vdash_P A[x+1])$  and  $\alpha \Vdash_P A[n]$  by  $\mathcal{C}\text{-Ind}$ . (b) If  $\alpha \Vdash_P (\forall x < m) \exists y A[x, y]$  then  $(\forall x < m) \exists y (\alpha \Vdash_P A[x, y])$  and  $\exists u (\forall x < m) (\exists y < u) (\alpha \Vdash_P A[x, y])$  by  $\mathcal{C}\text{-Bdg}$ . Thus by 4.12(5),  $\exists u (\alpha \Vdash_P (\forall x < m) (\exists y < u) A[x, y])$ . (c) (d) (e) Similar. (f) Use (e) and 2.29(3).  $\dashv$

In the lemma, (ii)(f) seems to require  $n = 0$ : a bar  $\{v: \beta(v) = 0\}$  is interpreted as  $\{v: \alpha \Vdash_P \beta(v) = 0\}$ , i.e.,  $\{v: \beta(v) = 0 \vee \exists u \text{Tr}[u, \alpha]\}$ , to which we cannot apply  $\mathcal{L}_F\text{-Bl}_D$  even if  $\text{Bar}[\underline{0}, \{v: \beta(v) = 0 \vee \exists u \text{Tr}[u, \alpha]\}]$ .

The following is the central trick corresponding to that of  $A$ -translation, namely  $(\neg\neg A[x])^{A[x]} \leftrightarrow A[x]$ .

PROPOSITION 4.17. For  $P$  from  $\Pi_n^0$ ,

$$\mathbf{EL}_0^- + \Sigma_n^0\text{-LEM} \vdash (\emptyset \Vdash_P (\neg\forall v\neg P[x, v, \xi] \rightarrow \exists v P[x, v, \xi])).$$

PROOF.  $\Pi_n^0\text{-LEM}$  yields  $\forall v\exists u(\neg P[x, v, \xi] \vee P[x, u, \xi])$ , which is equivalent to  $\forall v(\neg P[x, v, \xi] \vee \exists u P[x, u, \xi])$ , i.e.,  $\forall v(\{(x, \xi)\} \Vdash_P \neg P[x, v, \xi])$ . By 4.13(2) with 2.24(1)(i), we have  $\{(x, \xi)\} \Vdash_P \forall v\neg P[x, v, \xi]$ .

Thus, if  $\alpha \Vdash_P \neg\forall v\neg P[x, v, \xi]$  then  $\alpha \cup \{(x, \xi)\} \Vdash_P \perp$ , i.e.,  $\exists u \text{Tr}_P[\alpha \cup \{(x, \xi)\}, u]$  which is equivalent to  $\exists u(\text{Tr}_P[\alpha, u] \vee P[x, u, \xi])$ , to  $\exists u(\alpha \Vdash_P P[x, u, \xi])$ , and, again by 4.13(2), to  $\alpha \Vdash_P \exists u P[x, u, \xi]$ .  $\dashv$

THEOREM 4.18. There is a  $\Pi_n^0$  formula  $P$  such that

$$\mathbf{EL}_0^- + \Sigma_n^0\text{-LEM} \vdash (\emptyset \Vdash_P \mathbf{EL}_0^- + \Sigma_{n+1}^0\text{-DNE}).$$

PROOF. Let  $P[x, u, \xi] := \forall y_n \exists y_{n-1} \dots Q y_1 (\xi(x, u, y_n, y_{n-1}, \dots, y_1) = 0)$ . Fix  $A$  from  $\Sigma_{n+1}^0$ . Take  $C$  from  $\Delta_0^0$  with

$$A[x, \alpha] \equiv \exists u \forall y_n \exists y_{n-1} \dots Q y_1 C[x, u, y_n, y_{n-1}, \dots, y_1, \alpha].$$

Take  $\xi$  with  $(\forall x, u, \vec{y})(\xi(x, u, \vec{y}) = 0 \leftrightarrow C[x, u, \vec{y}, \alpha])$  by 2.10(d). Then we have  $\forall x(A[x, \alpha] \leftrightarrow \exists u P[x, u, \xi])$ .

As this argument is possible in  $\mathbf{EL}_0^-$ ,  $\emptyset \Vdash_P \exists \xi \forall x(A[x, \alpha] \leftrightarrow \exists u P[x, u, \xi])$  by 4.12(2) and 4.15(i). By 4.17 with 4.12(2), we finally get  $\emptyset \Vdash_P \neg\neg A[x, \alpha] \rightarrow A[x, \alpha]$ .  $\dashv$

**4.3. Combining negative and forcing interpretations.** Coquand–Hofmann [11] and Avigad [3] combined the interpretation  $A \mapsto \emptyset \Vdash_P A$  with the negative interpretation  $N$ . We follow this way, with the following enhancement. While they considered only the first order case where  $P$  in  $\Vdash_P$  is  $\Delta_0^0$ , we have considered second order cases with  $P$  being  $\Pi_n^0$  but assuming  $\Sigma_n^0\text{-LEM}$ .

- THEOREM 4.19. (1) (a)  $\mathbf{EL}_0^- + \mathcal{L}_F\text{-LEM}$  and so  $\mathbf{I}\Delta_0\text{ex}$  (and  $\mathbf{EFA}$ ) are  $\Pi_2^0$ -preservingly interpretable in  $\mathbf{EL}_0^-$  and (b) so are  $\mathbf{EL}_0^- + \mathcal{L}_F\text{-LEM} + \Sigma_1^0\text{-Bdg}$  and  $\mathbf{B}\Delta_0\text{ex}$  in  $\mathbf{EL}_0^- + \Sigma_1^0\text{-Bdg}$  and hence in  $\mathbf{EL}_0^- + \Delta_0^0\text{-AC}^{00}$ .
- (2)  $\mathbf{EL}_0^- + \mathcal{L}_F\text{-LEM} + \Sigma_1^0\text{-Ind}$  and so  $\mathbf{I}\Sigma_1 = \mathbf{III}_1$  (as well as  $\mathbf{PRA}$ ) are interpretable (a)  $\Pi_1^0$ -preservingly in  $\mathbf{EL}_0^- + \Pi_1^0\text{-Ind}$  and hence in  $\mathbf{EL}_0^- + \Delta_0^0\text{-Bl}_D$ ; (b)  $\Pi_2^0$ -preservingly in  $\mathbf{EL}_0^- + \Sigma_1^0\text{-Ind}$  and hence in  $\mathbf{EL}_0^- + \Delta_0^0\text{-FT}$ .
- (3)  $\mathbf{EL}_0^- + \mathcal{L}_F\text{-LEM} + \Sigma_2^0\text{-Ind}$  and so  $\mathbf{I}\Sigma_2 = \mathbf{III}_2$  are interpretable (a)  $\Pi_2^0$ -preservingly in  $\mathbf{EL}_0^- + \Pi_2^0\text{-Ind}$  and hence in  $\mathbf{EL}_0^- + \Pi_2^0\text{-DC!}^0$  and in  $\mathbf{EL}_0^- + \Pi_1^0\text{-DC!}^1$  and (b)  $\Pi_3^0$ -preservingly in  $\mathbf{EL}_0^- + \text{LPO} + \Sigma_2^0\text{-Ind}$ .
- (4)  $\mathbf{ACA}_0$  is interpretable (a)  $\Pi_2^0$ -preservingly in  $\mathbf{EL}_0^- + \Sigma_1^0\text{-Bl}_D$ , and also in  $\mathbf{EL}_0^- + \text{LPO} + \Delta_0^0\text{-FT}$ ; (b)  $\Pi_3^0$ -preservingly in  $\mathbf{EL}_0^- + \text{LPO} + \Pi_1^0\text{-WFT}$ ; and (c)  $\Delta_0^1$ -preservingly in  $\mathbf{EL}_0^- + \text{LPO} + \Pi_1^0\text{-AC}^{00}$ .

PROOF. (1) By 4.3(1) with  $n=1$ ,  $\mathbf{EL}_0^- + \mathcal{L}_F\text{-LEM}$  is  $\Pi_2^0$ -preservingly interpretable in  $\mathbf{EL}_0^- + \text{MP}$ . The latter is  $\Pi_\infty^0$ -preservingly interpretable in  $\mathbf{EL}_0^-$  by 4.13(1) and 4.18 with  $n=0$ . For (b) use additionally 4.3(2)(ii) with  $n=1$  and 4.16(ii)(b) with  $n=k=0$ , where we can easily see  $\mathbf{EL}_0^- + \Delta_0^0\text{-AC}^{00} \vdash \Sigma_1^0\text{-Bdg}$ .

(2) (a)  $\mathbf{EL}_0^- + \mathcal{L}_F\text{-LEM} + \Sigma_1^0\text{-Ind} = \mathbf{EL}_0^- + \mathcal{L}_F\text{-LEM} + \Pi_1^0\text{-Ind}$  is  $\Pi_1^0$ -preservingly interpretable in  $\mathbf{EL}_0^- + \Pi_1^0\text{-Ind}$  by 4.3(1)(2)(i) with  $n=0$ , and by 2.29(2) further in  $\mathbf{EL}_0^- + \Delta_0^0\text{-Bl}_D$ .

(b) By 4.3(1)(2)(iii) with  $n=1$ ,  $\mathbf{EL}_0^- + \mathcal{L}_F\text{-LEM} + \Sigma_1^0\text{-Ind}$  is  $\Pi_2^0$ -preservingly interpretable in  $\mathbf{EL}_0^- + \text{MP} + \Sigma_1^0\text{-Ind}$ . The latter is  $\Pi_\infty^0$ -preservingly interpretable in  $\mathbf{EL}_0^- + \Sigma_1^0\text{-Ind}$  by 4.13(1), 4.16(ii)(a) with  $n=k=0$  and 4.18 with  $n=0$ , and hence in  $\mathbf{EL}_0^- + \Delta_0^0\text{-FT}$  by 2.33.

(3) (a) By 4.3(1)(2)(i) with  $n=1$ ,  $\mathbf{EL}_0^- + \mathcal{L}_F\text{-LEM} + \Pi_2^0\text{-Ind}$  is  $\Pi_2^0$ -preservingly interpretable in  $\mathbf{EL}_0^- + \text{MP} + \Pi_2^0\text{-Ind}$ , and, by 4.13(1), 4.16(ii)(a) with  $n=k=0$  where  $\Lambda_{1,0}^0 = \Pi_2^0$  and 4.18, further in  $\mathbf{EL}_0^- + \Pi_2^0\text{-Ind}$ . The latter is included in  $\mathbf{EL}_0^- + \Pi_2^0\text{-DC!}^0$  by 2.16(3)(i), and in  $\mathbf{EL}_0^- + \Pi_1^0\text{-DC!}^1$  by 2.16(5) with  $\mathcal{C} \equiv \Delta_0^0$  and 2.16(2)(v).

(b) By 4.3(1)(2)(iii) with  $n=2$ ,  $\mathbf{EL}_0^- + \mathcal{L}_F\text{-LEM} + \Sigma_2^0\text{-Ind}$  is  $\Pi_3^0$ -preservingly interpretable in  $\mathbf{EL}_0^- + \Sigma_2^0\text{-DNE} + \Sigma_2^0\text{-Ind}$  and further in  $\mathbf{EL}_0^- + \text{LPO} + \Sigma_2^0\text{-Ind}$  by 4.13(1), 4.16(ii)(a) with  $(n, k) = (1, 0)$  and 4.18 with  $n=1$ .

(4) (a)(b)(c) follow from 4.9(i)(ii)(iii), respectively, since  $\mathbf{EL}_0^- + \text{MP} + \Sigma_1^0\text{-Bl}_D$  is interpretable  $\Pi_\infty^0$ -preservingly in  $\mathbf{EL}_0^- + \Sigma_1^0\text{-Bl}_D$  by 4.13(1), 4.16(ii)(f) with  $n=k=0$  and 4.18 with  $n=0$ ; and so is  $\mathbf{EL}_0^- + \Sigma_2^0\text{-DNE} + \Pi_1^0\text{-WFT}$  in  $\mathbf{EL}_0^- + \text{LPO} + \Pi_1^0\text{-WFT}$  by 4.13(1), 4.16(i) with  $n=1$  and 4.18 with  $n=1$ .  $\dashv$

With the hierarchy of  $\Lambda_{n,m}^i$ 's from 3.60, we can hierarchize the interpretability as in 4.20 below. For (d),  $(\Pi_{n+2+m}^0)^N \subseteq \Lambda_{n+1,m}^1$  under  $\Sigma_{n+1}^0\text{-DNE}$  and by recursive indices we can interpret  $\Lambda_{n+1,m}^1$  in  $\Lambda_{n+1,m}^0$ .

**COROLLARY 4.20.** Let  $k < n$  or  $k = n+1$ . We can interpret  $\Pi_{n+2}^0$ -preservingly

- (a)  $\mathbf{EL}_0^- + \mathcal{L}_F\text{-LEM}$  in  $\mathbf{EL}_0^- + \Sigma_n^0\text{-LEM}$ ;
- (b)  $\mathbf{EL}_0^- + \mathcal{L}_F\text{-LEM} + \Sigma_k^0\text{-Bdg}$  in  $\mathbf{EL}_0^- + \Sigma_n^0\text{-LEM} + \Sigma_k^0\text{-Bdg}$ ;
- (c)  $\mathbf{EL}_0^- + \mathcal{L}_F\text{-LEM} + \Sigma_k^0\text{-Ind}$  in  $\mathbf{EL}_0^- + \Sigma_n^0\text{-LEM} + \Sigma_k^0\text{-Ind}$ ;
- (d)  $\mathbf{EL}_0^- + \mathcal{L}_F\text{-LEM} + \Pi_{n+m+2}^0\text{-Ind}$  in  $\mathbf{EL}_0^- + \Sigma_n^0\text{-LEM} + \Lambda_{n+1,m}^1\text{-Ind}$  and hence in  $\mathbf{EL}_0^- + \Sigma_n^0\text{-LEM} + \Lambda_{n+1,m}^0\text{-Ind}$ .

In the first order setting, by letting  $\exists uP[x, u]$  be universal  $\Sigma_{n+1}$ , we obtain the analogous  $\Pi_{n+2}$ -preserving interpretability results: (a)  $\mathbf{I}\Delta_0\mathbf{ex} + \Sigma_{n+1}\text{-Bdg}$  in  $\mathbf{iQ} + \Sigma_{n+1}\text{-Bdg} + \Sigma_n\text{-LEM}$ ; (b)  $\mathbf{I}\Sigma_{n+1}$  in  $\mathbf{i}\Sigma_{n+1} + \Sigma_n\text{-LEM}$ ; (c)  $\mathbf{III}_{n+m+2}$  in  $\mathbf{iQ} + (\Lambda_{n+1,m}^0 \cap \mathcal{L}_1)\text{-Ind} + \Sigma_n\text{-LEM}$ ; and (d)  $\mathbf{PA}$  in  $\mathbf{HA} + \Sigma_n\text{-LEM}$ . However, this does not work for  $\mathbf{I}\Delta_0\mathbf{ex}$  in  $\mathbf{iQ} + \Sigma_n\text{-LEM}$ , since  $\Sigma_1\text{-Bdg}$  seems necessary for universal formula.

We can go further to stronger theories, where  $\Pi_m^1\text{-TI}_0 \equiv \mathbf{ACA}_0 + \Pi_m^1\text{-TI}$  and  $\Pi_\infty^1\text{-TI}_0 \equiv \bigcup_m \Pi_m^1\text{-TI}_0$ .

**THEOREM 4.21.**  $\Pi_{m+1}^1\text{-TI}_0$  is  $\Pi_2^0$ -preservingly interpretable in  $\mathbf{EL}_0^- + \Lambda_{1,m}^1\text{-Bl}_D$ . So is  $\Pi_\infty^1\text{-TI}_0$  in  $\mathbf{EL}_0^- + \mathcal{L}_F\text{-Bl}_D$ .

**PROOF.** By  $\Pi_1^1$  normal form, we may consider  $(\Pi_{m+1}^1)^N \subseteq \Lambda_{1,m}^1$  over  $\mathbf{EL}_0^- + \text{MP}$ . Thus, by 4.3(1)(2)(iv) with  $n=1$  and 4.8(2),  $\Pi_{m+1}^1\text{-TI}_0$  is  $\Pi_2^0$ -preservingly interpretable in  $\mathbf{EL}_0^- + \text{MP} + \Lambda_{1,m}^1\text{-Bl}_D$ . The latter is interpretable  $\Pi_\infty^0$ -preservingly in  $\mathbf{EL}_0^- + \Lambda_{1,m}^1\text{-Bl}_D$  by 4.13(1), 4.16(ii)(f) with  $\mathcal{C} \equiv \Lambda_{1,m}^1$  and 4.18 with  $n=0$ .  $\dashv$

Actually Coquand and Hofmann [11] mentioned the combination of their interpretation of  $\mathbf{IS}_1$  into  $\mathbf{i}\Sigma_1$  further with the modified realizability of  $\mathbf{i}\Sigma_1$  in  $\mathbf{PRA}^\omega$ , the higher order version of primitive recursive arithmetic, as an alternative proof of Parson's Theorem: the  $\Pi_2^0$  conservation of  $\mathbf{IS}_1$  over  $\mathbf{PRA}$ . However we need cut elimination to reduce  $\mathbf{PRA}^\omega$  to  $\mathbf{PRA}$ .<sup>19</sup> This kind of longer combination (of negative, forcing and realizability interpretations in this order) is called *making-a-detour method* in Section 5.4.

## §5. Final Remarks.

**5.1. Summary of results.** Corollary 5.2 below is by 3.43 and 3.53, with 2.29(1). [2] gave a  $\Pi_1^1$ -preserving interpretation of  $\mathbf{WKL}_0$  in  $\mathbf{RCA}_0$ , which also  $\Pi_1^1$ -preservingly interprets  $\mathbf{WKL}_0^*$  in  $\mathbf{RCA}_0^*$  (where we need to show that  $\Sigma_1^0\text{-Bdg}$  is  $\frac{1}{2}$ -forced by formalizing the argument of [40, 4.5 Lemma]). By recursive indices we can  $\Delta_1^1$ -preservingly interpret  $\mathbf{RCA}_0$  in  $\mathbf{IS}_1$  and  $\mathbf{RCA}_0^*$  in  $\mathbf{BS}_1\text{ex}$ . Moreover  $\mathbf{PRA} \vdash \text{Con}(\mathbf{BS}_1\text{ex})$  and  $\mathbf{IS}_1$  is  $\Pi_2$  reducible to  $\mathbf{PRA}$  (see Section 5.2). Hence the combinations in 5.2(1) are finitistically guaranteed and those in 5.2(2) are finitistically justifiable.

DEFINITION 5.1 (functionally realizable analysis  $\mathbf{FR}_0^*$ ,  $\mathbf{FR}_0$ ,  $\mathbf{FR}_m^+$ ,  $\mathbf{FR}_m^{++}$ ).

$$\begin{aligned} \mathbf{FR}_0^- &:= \mathbf{EL}_0^- + \text{MP} + \mathcal{L}_F\{-\text{CB}^1, -\text{CC}^1\}; \\ \mathbf{FR}_0^* &:= \mathbf{FR}_0^- + \mathcal{L}_F\{-\text{AC}^{00}, -\text{AC}^{01}, -\text{WFT}\}; \\ \mathbf{FR}_0 &:= \mathbf{FR}_0^* + \Sigma_1^0\text{-DC}^1 + \Sigma_2^0\{-\text{Ind}, -\text{DC}^0\} + \Pi_1^0\text{-BI} + \mathcal{L}_F\text{-FT}; \\ \mathbf{FR}_m^+ &:= \mathbf{FR}_0 + \Theta_m^1\{-\text{Ind}, -\text{DC}^0, -\text{DC}^1\}; \\ \mathbf{FR}_m^{++} &:= \mathbf{FR}_m^+ + (\Theta_m^1, \mathcal{L}_F)\text{-BI}_M \text{ (cf. 3.60 for the definition of } \Theta_m^1\text{)}. \end{aligned}$$

COROLLARY 5.2. (1) Both  $\mathbf{FR}_0^* + \mathcal{L}_F\text{-CC}^1$  and  $\mathbf{FR}_0^* + \Sigma_1^0\text{-GDM}$  are  $\Pi_\infty^0$ -preservingly interpretable in  $\mathbf{WKL}_0^*$ .  
 (2) Both  $\mathbf{FR}_0 + \mathcal{L}_F\text{-CC}^1$  and  $\mathbf{FR}_0 + \Sigma_1^0\text{-GDM}$  are  $\Pi_\infty^0$ -preservingly interpretable in  $\mathbf{WKL}_0$ .

Moreover these combinations are optimal in the sense of the hierarchies of Brouwerian axioms and of semi-classical principles: by 4.19(2) with 2.16(3)(i),  $\mathbf{EL}_0^-$  together with any of  $\Pi_1^0\text{-Ind}$ ,  $\Delta_0^0\text{-BI}_D$ ,  $\Sigma_1^0\text{-Ind}$ ,  $\Delta_0^0\text{-DC}^0$  and  $\Delta_0^0\text{-FT}$  interprets  $\mathbf{IS}_1$  and hence is not provably consistent in  $\mathbf{PRA}$ ; by 4.19(3)(4)(a),  $\mathbf{EL}_0^-$  with any of  $\Pi_2^0\text{-Ind}$ ,  $\Pi_2^0\text{-DC}^0$ ,  $\Pi_1^0\text{-DC}^1$ ,  $\Sigma_1^0\text{-BI}_D$  and  $\text{LPO} + \Sigma_2^0\text{-Ind}$  interprets  $\mathbf{IS}_2$  and hence is not reducible to  $\mathbf{PRA}$ ; by 4.19(4) with 2.16(2)(iv),  $\mathbf{EL}_0^- + \text{LPO}$  with any of  $\Pi_1^0\text{-AC}^{100}$ ,  $\Pi_1^0\text{-DC}^0$ ,  $\Delta_0^0\text{-FT}$  and  $\Pi_1^0\text{-WFT}$  interprets  $\mathbf{ACA}_0$ ; as shown in 2.35(2),  $\mathbf{EL}_0^- + \text{LLPO} + \Pi_1^0\text{-WC}^0$  and  $\mathbf{EL}_0^- + \text{LPO} + \Pi_1^0\text{-WC}^0$  are both inconsistent. (See also Section 2.5.5.)

Classically,  $\mathbf{CFG} := \mathbf{EL}_0^- + \mathcal{L}_F\text{-LEM} + \Sigma_1^0\{-\text{AC}^{00}, -\text{AC}^{01}, -\text{WFT}, -\text{WC}^0, -\text{WC}^1\}$  is finitistically guaranteed, and  $\mathbf{CFG} + \Pi_1^0\{-\text{BI}, -\text{Ind}\} + \Sigma_1^0\{-\text{Ind}, -\text{DC}^0, -\text{DC}^1\}$  is finitistically justifiable; and these are optimal, as seen in Section 2.5.4.

<sup>19</sup> Generally, there is no interpretation in the sense of f.n.2 of a finitely axiomatizable  $T_1$ , like  $\mathbf{IS}_1$ , in reflexive  $T_2$  (namely  $T_2$  proves the consistency of any finite fragment of  $T_2$ ) of the same consistency strength, since otherwise  $\text{Con}(T_1)$  follows from the consistency of a finite fragment of  $T_2$ , which  $T_2$  proves.  $\mathbf{PRA}$  is reflexive by  $\mathbf{PRA} \equiv_{\Pi_2^0} \mathbf{IS}_1 \vdash \text{Con}(\mathbf{BS}_1(\mathcal{E}^n))$ ; see Section 5.2.

Thus we have completed Figures 1 and 2. Moreover 5.2, 3.62, 3.64, 4.19 and 4.21 with the uses of  $\mathfrak{g}$ , yield the below (some pairs in (d) have stronger preserving as 4.19(4)) as Avigad's [2] method preserves  $\Pi_2^0$ -Ind.

COROLLARY 5.3. The following are, in each case, mutually interpretable  $\Pi_2^0$ -preservingly:

- (a)  $\mathbf{B}\Sigma_1\text{ex}$ ,  $\mathbf{FR}_0^* + \mathcal{L}_F\text{-CC}^1$ ,  $\mathbf{FR}_0^* + \Sigma_1^0\text{-GDM}$ ,  $\mathbf{EL}_0^* \equiv \mathbf{EL}_0^- + \Delta_0^0\text{-AC}^{00}$  and  $\mathbf{EL}_0^- + \Sigma_1^0\text{-Bdg}$ ;
- (b)  $\mathbf{I}\Sigma_1$ ,  $\mathbf{FR}_0 + \mathcal{L}_F\text{-CC}^1$ ,  $\mathbf{FR}_0 + \Sigma_1^0\text{-GDM}$ ,  $\mathbf{EL}_0^- + \Sigma_1^0\text{-Ind}$ ,  $\mathbf{EL}_0^- + \Delta_0^0\text{-FT}$ ,  $\mathbf{EL}_0^- + \Delta_0^0\text{-DC}!^0$  and  $\mathbf{EL}_0^- + \Delta_0^0\text{-DC}^1$ ;
- (c)  $\mathbf{I}\Sigma_2$ ,  $\mathbf{FR}_0^+ + \mathcal{L}_F\text{-CC}^1$ ,  $\mathbf{FR}_0^+ + \Sigma_1^0\text{-GDM}$ ,  $\mathbf{EL}_0^- + \Pi_2^0\text{-Ind}$ ,  $\mathbf{EL}_0^- + \Pi_2^0\text{-DC}!^0$ ,  $\mathbf{EL}_0^- + \Pi_1^0\text{-DC}!^1$  and  $\mathbf{EL}_0^- + \text{LPO} + \Sigma_2^0\text{-Ind}$ ;
- (d)  $\mathbf{ACA}_0$ ,  $\mathbf{FR}_0^{++} + \mathcal{L}_F\text{-CC}^1$ ,  $\mathbf{FR}_0^{++} + \Sigma_1^0\text{-GDM}$ ,  $\mathbf{EL}_0^- + \Sigma_1^0\text{-Bl}_D$ ,  $\mathbf{EL}_0^- + \text{LPO} + \Delta_0^0\text{-FT}$ ,  $\mathbf{EL}_0^- + \text{LPO} + \Pi_1^0\text{-WFT}$  and  $\mathbf{EL}_0^- + \text{LPO} + \Pi_1^0\text{-AC}!^{00}$ .

Moreover, so are theories in (b) with  $\mathbf{EL}_0^- + \Pi_1^0\text{-Ind}$  and  $\mathbf{EL}_0^- + \Delta_0^0\text{-Bl}_D$  but only  $\Pi_1^0$ -preservingly.

Thus we determined the ‘‘interpretability strengths’’ of fragments of Brouwerian axioms for all  $\Sigma_n^0$  and  $\Pi_n^0$  with semi-classical principles below  $\Sigma_1^0\text{-GDM}$ . For classes beyond  $\Pi_\infty^0$ , we have the following hierarchized interpretability, since Avigad's [2] preserves also  $\Xi_{1,m}\text{-Ind}$ , which is interpreted in  $\mathbf{I}\Sigma_{m+2}$  by recursive indices.

COROLLARY 5.4. The following are, in each case, mutually interpretable  $\Pi_2^0$ -preservingly:

- (a)  $\mathbf{I}\Sigma_{m+2}$ ,  $\mathbf{FR}_m^+ + \mathcal{L}_F\text{-CC}^1$ ,  $\mathbf{FR}_m^+ + \Sigma_1^0\text{-GDM}$ ,  $\mathbf{EL}_0^- + \Lambda_{1,m}^0\text{-Ind}$  and  $\mathbf{EL}_0^- + \Lambda_{1,m}^0\text{-DC}!^i$ ;
- (b)  $\Pi_{m+1}^1\text{-TI}_0 \equiv \mathbf{ACA}_0 + \Pi_{m+1}^1\text{-TI}$ ,  $\mathbf{FR}_{m+1}^{++} + \mathcal{L}_F\text{-CC}^1$ ,  $\mathbf{FR}_{m+1}^{++} + \Sigma_1^0\text{-GDM}$  and  $\mathbf{EL}_0^- + \Lambda_{1,m}^1\text{-Bl}_D$ ;
- (c)  $\Pi_{m+1}^1\text{-TI}_0 + \Pi_{n+1}^1\text{-Ind}$ ,  $\mathbf{FR}_{m+1}^{++} + \mathbf{FR}_{n+1}^+ + \mathcal{L}_F\text{-CC}^1$ ,  $\mathbf{FR}_{m+1}^{++} + \mathbf{FR}_{n+1}^+ + \Sigma_1^0\text{-GDM}$  and  $\mathbf{EL}_0^- + \Lambda_{1,m}^1\text{-Bl}_D + \Lambda_{1,n}^1\text{-Ind}$ ;
- (d)  $\Pi_\infty^1\text{-TI}_0$ ,  $\mathbf{FR}_\infty^{++} + \mathcal{L}_F\text{-CC}^1$ ,  $\mathbf{FR}_\infty^{++} + \Sigma_1^0\text{-GDM}$  and  $\mathbf{EL}_0^- + \mathcal{L}_F\text{-Bl}_D$ .

Note that  $\mathbf{ACA}_0$  is not interpretable in  $\mathbf{PA} \equiv \mathbf{I}\Sigma_\infty$  by f.n.19.  $\Pi_\infty^1\text{-TI}_0$  is known to be proof theoretically equivalent to  $\mathbf{ID}_1$ ,  $\mathbf{KP}$  and  $\mathbf{CZF}$ , theories of *generalized predicativity*. As  $\mathbf{FR}_\infty^{++}$  contains all the Brouwerian axioms formulated in  $\mathcal{L}_F$  except  $\mathcal{L}_F\text{-CC}^i$  (see f.n.11), this could be ‘‘a marriage of Intuitionism and generalized predicativity’’. However, these are beyond *predicativity* in Feferman's [15] sense, as  $\Pi_2^1\text{-TI}_0 \vdash \text{Con}(\mathbf{ATR}_0)$  (cf. [39, Exercise VII.2.32]). With bar induction restricted to  $\Theta_1^1$ , (c) with  $(m, n) = (0, \infty)$  is in the predicative bound, or ‘‘a marriage of Intuitionism and predicativism’’, as  $\Pi_1^1\text{-TI}_0 = \Sigma_1^1\text{-DC}_0$  by [39, Theorem VIII.5.12].

For the semi-Russian axioms, 3.45 yields the first interpretability below, where by coding functions as recursive indices we interpret  $\mathbf{EL}_0^- + \mathcal{L}_F\text{-LEM} + \Delta_0^0\text{-AC}^{00} + \text{CT}$  in  $\mathbf{B}\Sigma_1\text{ex}$ . By additionally 3.49, 3.62 and 2.29(1), we have the other two. The conserves are proved in Corollary 5.3. NCT is consistent with  $\mathcal{L}_F\text{-CC}^0$  which contradicts CT (see f.n.7). Thus, CT is strictly stronger than NCT and than Veldman's KA by 4.5.

DEFINITION 5.5 (semi-Russian analysis  $\mathbf{SR}_0^-$ ,  $\mathbf{SR}_0^*$ ,  $\mathbf{SR}_0$ ,  $\mathbf{SR}_m^+$ ).

$$\begin{aligned}\mathbf{SR}_0^- &::= \mathbf{EL}_0^- + \mathbf{NCT} + \mathbf{MP} + \mathcal{L}_F\text{-CC}^1; \\ \mathbf{SR}_0^* &::= \mathbf{SR}_0^- + \mathcal{L}_F\{-\mathbf{AC}^{00}, -\mathbf{AC}^{01}\}; \\ \mathbf{SR}_0 &::= \mathbf{SR}_0^* + \Sigma_1^0\text{-DC}^1 + \Sigma_2^0\{-\mathbf{Ind}, -\mathbf{DC}^0\} + \Pi_1^0\text{-BI}; \\ \mathbf{SR}_m^+ &::= \mathbf{SR}_0 + \Theta_m^1\{-\mathbf{Ind}, -\mathbf{DC}^0, -\mathbf{DC}^1\}.\end{aligned}$$

COROLLARY 5.6.  $\mathbf{SR}_0^*$ ,  $\mathbf{SR}_0$  and  $\mathbf{SR}_m^+$  are interpretable in  $\mathbf{BS}_1\mathbf{ex}$ ,  $\mathbf{IS}_1$  and  $\mathbf{IS}_{m+2}$ , resp.,  $\Pi_\infty^0$ -preservingly.

**5.2. Supplement:**  $\mathbf{IS}_1 \vdash \text{Con}(\mathbf{BS}_1\mathbf{ex})$  as well as  $\mathbf{IS}_1 \equiv_{\Pi_2^0} \mathbf{PRA}$  and  $\mathbf{IS}_2 \vdash \text{Con}(\mathbf{IS}_1)$ . To conclude that theories interpretable in  $\mathbf{WKL}_0^*$  are finitistically guaranteed, we used a folklore result  $\mathbf{IS}_1 \vdash \text{Con}(\mathbf{BS}_1\mathbf{ex})$  (and hence  $\mathbf{PRA} \vdash \text{Con}(\mathbf{BS}_1\mathbf{ex})$  by  $\Pi_2$ -reducibility).  $\mathbf{IS}_1 \vdash \text{Con}(\mathbf{EFA})$  and the  $\Pi_2^0$  conservation of  $\mathbf{BS}_1\mathbf{ex}$  over  $\mathbf{EFA}$  are stated in [39, II.8.11, X.4.2], and the version without  $\text{exp}$  is proved in [17, Chapter IV, Section 4(b)]. As we cannot find a reference for the folklore, we briefly sketch a proof with some byproducts.

We formalize  $\mathbf{BS}_1\mathbf{ex}$  by the following rules on the base of one-sided sequent calculus (in which  $\neg$  is a syntactical operation) for classical logic, where  $C$  is  $\Delta_0^0$  and where  $z$  is an eigenvariable in (ind).

$$\begin{array}{c} \frac{(C \text{ is an axiom of } \mathbf{iQex})}{\Gamma, C} \text{ (axiom)} \quad \frac{\Gamma, \neg C[z], C[z+1]}{\Gamma, \neg C[0], C[t]} \text{ (ind)} \\ \frac{\Gamma, (\forall x < t)\exists y C[x, y]}{\Gamma, \exists u(\forall x < t)(\exists y < u)C[x, y]} \text{ (bdg)} \end{array}$$

By the standard partial cut elimination, we may assume that all cut formulae are  $\Sigma_1^0$ ,  $\Pi_1^0$  or  $\Delta_0^0$ . For a (one-sided) sequent  $\Gamma$ , we write  $\Gamma^{(n,m)}$  for the result of replacing all the unbounded quantifiers  $\forall x$  and  $\exists y$  by  $(\forall x < n)$  and  $(\exists y < m)$ , respectively, in  $\Gamma$ . By induction on derivation with free variables at most  $\vec{x}$ , we can show that there is an elementary function  $f$  with  $\forall n(\forall \vec{x} < n)(\bigvee \Gamma^{(n,f(n))})$ . Thus, if  $\mathbf{BS}_1\mathbf{ex} \vdash \perp$  then  $\perp$ .

While cut elimination increases the size of proofs by superexponential, it can be executed in  $\mathbf{IS}_1$ . Indices of elementary function can also be dealt with in  $\mathbf{IS}_1$ , and the required  $f$  is constructed elementarily in the sense of indices from derivation. As  $\forall n(\forall \vec{x} < n)(\bigvee \Gamma^{(n,f(n))})$  is  $\Pi_1^0$ , we can formalize this argument in  $\mathbf{IS}_1$ .

Since  $\mathcal{E}^n$  indices can also be dealt with,  $\mathbf{IS}_1$  proves the consistency of  $\mathbf{BS}_1(\mathcal{E}^n)$ , defined similarly with function symbols for  $\mathcal{E}^n$  (cf. f.n.12). If we allow  $C$  to be  $\Sigma_1^0$  in (ind), such  $f$ 's can be primitive recursive, whose indices can be used in  $\mathbf{IS}_2$ . Thus  $\mathbf{IS}_1$  is reducible to  $\mathbf{PRA}$  over  $\Pi_2$ , and consistent provably in  $\mathbf{IS}_2$ .

It is worth mentioning that, by cut elimination, we can easily show the equivalence between first-order formulation of  $\mathbf{PRA}$  and quantifier-free formulation of  $\mathbf{PRA}$ : proving exactly same quantifier-free formulae with free variables. Tait's [41] identification of Hilbert's Finitism is with the latter, rather than the former.

Notice that this subsection is the only part in which we use cut elimination method, and that the results do not survive for ultrafinitism mentioned in Section 1.8 (but survive for those accepting  $\mathcal{E}^4$  from f.n.12). Actually, it is known [17, Chapter V, 5.29 Corollary] that  $\mathbf{B}\Sigma_1\mathbf{ex}$  cannot prove even the consistency of Robinson Arithmetic  $\mathbf{Q}$ , and hence nor of the intuitionistic variant. Thus *ultrafinitistically guaranteed* parts must be even weaker.

It is interesting that forcing and realizability, which are sometimes seen as model construction methods, require only weaker meta-theories than cut elimination, the central technique in proof theory. For, it has been considered that proof theoretic arguments require weaker meta-theories than model theoretic ones.

### 5.3. Further problems.

**Strength of  $c$ -WFT:** 4.8(1) actually shows that  $c$ -WFT, a restriction of WFT to  $c$ -bars ( $B[u]$ 's of the form  $\forall v(\beta(u*v) = 0)$ ), with  $\mathbf{EL}_0^- + \Sigma_2^0\text{-DNE}$ , interprets  $\mathbf{ACA}_0$ . Can LPO replace  $\Sigma_2^0\text{-DNE}$ ?  $c$ -WFT has a particular significance [6, 8], and is known to be strictly between  $\Delta_0^0\text{-WFT}$  and  $\Pi_1^0\text{-WFT}$  (where the border lies; Fig.2).

**Hierarchy of WWFT and LPO:** In the constructive context, weak weak König's lemma investigated in, e.g., the first author [26], should be called *weak weak fan theorem*  $\mathcal{C}$ -WWFT, since it is a weakened version of  $\mathcal{C}$ -WFT rather than of  $\mathcal{C}$ -WKL. What is the strength of  $\mathcal{C}$ -WWFT+LPO, especially for  $\mathcal{C} \equiv \Pi_1^0$ ?

$\Pi_3^0$  **conservation of  $\Delta_0^0\text{-FT}$ :** While 4.19(4)(b) asserts the  $\Pi_3^0$  conservation of  $\mathbf{EL}_0^- + \mathcal{L}_F\text{-LEM} + \Pi_1^0\text{-WFT}$  over  $\mathbf{EL}_0^- + \text{LPO} + \Pi_1^0\text{-WFT}$ , (a) asserts similar but only  $\Pi_2^0$  one for  $\Delta_0^0\text{-FT}$ . Can it be enhanced to  $\Pi_3^0$ ?

**Effect of WLPO:** We classified the axioms of Intuitionistic Mathematics into the three categories, finitistically non-justifiable, justifiable and guaranteed ones, in the presence of any semi-classical principle beyond LPO or below  $\Sigma_1^0\text{-GDM}$ . Among those in the gap is  $\text{WLPO} \equiv \Pi_1^0\text{-LEM}$ . How is the classification in the presence of it? LPO seems essential in the lower bound proofs (i.e., 4.7(2), 4.12(3) and 2.35(2)(ii)).

**Effect of Baire's category theorem:** It is mentioned in Section 1.5 that the effect of the semi-classical principle LLPO is of our special interest because of its similar status as WKL, which plays a central role in Simpson's "partial realizations of Hilbert's Program". Simpson [38] also mentioned the role of *Baire's category theorem* (BCT).<sup>20</sup> What is to BCT that LLPO is to WKL? And how is the effect of it in the sense of last paragraph?

### 5.4. Related works.

*Similar investigations in set theory.* While we considered the axioms in the language  $\mathcal{L}_F$ , the authors are preparing an article [28] on the same questions in the language of set theory. The abstract treatment in Section 3.2 will be helpful. The axiom of choice along functions can now be formulated without twist, and

<sup>20</sup>A finitistic consistency proof of BCT had not, however, been given until it was given by Avigad [2] almost a decade later.



it is natural to consider also some set theoretic principles, e.g., replacement, collection, subset collection, extensionality and regularity or foundation. Whereas the first two correspond to unique and non-unique axioms of choice, respectively, the others seem specific to set theory. As we want to have  $\omega$  and to stay within the strength of **PRA**, we shall consider “weak weak” set theory in the sense of the second author [33].

*Independence of negated premise.* Our use of realizability allowed us to add Markov’s principle MP to the upper bound results, for the realizing system **CDL** was untyped. With typed systems we can add *independence of negated premise*

$$(\mathcal{C}\text{-INP}): (\neg A \rightarrow \exists x B[x]) \rightarrow \exists x (\neg A \rightarrow B[x]) \text{ for } A \text{ from } \mathcal{C}$$

instead, from which follows Vesley’s [47] alternative formalization of creative subject mentioned in f.n.13. In this way, we could have a marriage of “subjective Intuitionism” and Hilbert’s Finitism. Ishihara and the first author [21] used a translation  $*$  for INP-rule in the same sense as Friedman’s  $A$ -translation is for MP-rule. Following the way from  $A$ -translation to Coquand–Hofmann forcing (cf. Section 4.2), we can define, from  $*$ , a forcing interpreting  $\mathcal{C}$ -INP for reasonable  $\mathcal{C}$ . Avigad’s forcing from [3] can be seen as such an interpretation.

*Complexity of Kleene’s second model.* In the context of **EL**, Kleene’s second model  $\mathfrak{k}$  can be seen as a definable extension, as the systems are not sensitive to the complexity below arithmetic  $\Delta_0^1$ . However, if the system is sensitive (like those we considered), it cannot be seen so, since the atomic formulae  $(\alpha|\beta)\downarrow$  and  $\alpha = \beta|\gamma$  are not in the base complexity. Recently Jäger, Rosebrock and the second author [22] makes use of this unusual complexity, to separate: enumerable by operation; being the domain of an operation; and being the image of an operation. They are equivalent if we interpret ‘operation’ as ‘partial recursive function’.

*Making-a-detour method.* We used realizability interpretations (as upper bound proofs) to embed intuitionistic systems into classical **WKL** $_0^*$  and **WKL** $_0$  and a combination of negative and forcing interpretations (as lower bound proofs) to embed classical ones into intuitionistic ones. The composition of both the directions results in an interpretation of classical ones in classical ones, of the same kind that the second author [37] (with Zumbrunnen) and [34] introduced under the name of “making a detour via intuitionistic systems”. This is the third kind of such model construction methods *for classical theories* that logical connectives are interpreted non-trivially (see Section 1.2), after Cohen’s classical forcing and Krivine’s classical realizability. We would like to stress that interpretations between intuitionistic ones could help studies of classical theories. In the next paper [36] in this series, the second author uses the results of the present article and the making-a-detour method, in order to get interpretations among classical theories of second order arithmetic that are standard in classical reverse mathematics.

*Relation to Veldman’s work.* While we discussed the strength of fan theorem analogously to that of König’s lemma in the classical setting at the beginning of Section 3.3.3, the former is not as strong as the latter. The branching  $\{x: \gamma(u*(x)) = 0\}$  of the fan  $\gamma$  in 4.7(1) has at most  $t[|u|]+2$  elements, and hence

is *almost-finite* and *bounded-in-number* (both from [45, Section 10.2]). With these notions Veldman looks for an axiom which is intuitionistically to (weak) fan theorem as König's lemma is classically to weak König's lemma.

*Proof theoretic ordinals.* In proof theory, the strength of a formal theory is measured by the so-called proof theoretic ordinal. While there are various definitions, almost all definitions assign the same ordinal to the theories that are  $\Pi_2^0$ -equivalent provably in **PRA**. Particularly,  $\omega^\omega$  is assigned to the theories in Corollary 5.2(2) and in Corollary 5.3(b) as well as **SR**<sub>0</sub>;  $\omega^{\omega^\omega}$  to those in Corollary 5.3(c) and as well as **SR**<sub>0</sub><sup>+</sup>; and  $\varepsilon_0 = \sup\{\omega, \omega^\omega, \omega^{\omega^\omega}, \dots\}$  to those in Corollary 5.3(d). Although these are well-known facts, the second author [35] has recently given proofs to them. The ordinal assigned to the theories in Corollary 5.3(a) and in Corollary 5.2(1) as well as **SR**<sub>0</sub><sup>\*</sup> is said to be sometimes  $\omega^2$  and sometimes  $\omega^3$  (as well as  $\omega$ , 0, etc.), depending on which definition of proof theoretic ordinal we take, as discussed in [35, Appendix B]. The ordinal assigned to **EL**<sub>0</sub><sup>-</sup>+ $\Pi_1^0$ -Ind and **EL**<sub>0</sub><sup>-</sup>+ $\Pi_1^0$ -Bl, the other theories in Corollary 5.3, also depends, as we have only  $\Pi_1^0$ -equivalence with those in Corollary 5.3(b).

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SCHOOL OF INFORMATION SCIENCE  
 JAPAN ADVANCED INSTITUTE OF SCIENCE AND TECHNOLOGY  
 ASAHIDAI 1-1,  
 NOMI, 923-1292, JAPAN  
*E-mail:* t-nemoto@jaist.ac.jp

INSTITUTE OF COMPUTER SCIENCE  
 UNIVERSITÄT BERN  
 NEUBRÜCKSTRASSE 10  
 BERN, 3012, SWITZERLAND  
*E-mail:* sato@inf.unibe.ch