

# On the Broader Epistemological Significance of Self-Justifying Axiom Systems

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## Abstract

This article will be a continuation of our research into self-justifying systems. It will introduce several new theorems (one of which will transform our previous infinite-sized self-verifying logics into formalisms of purely finite size). It will explain how self-justification is useful, even when the Incompleteness Theorem clearly does sharply limit its scope.

**Keywords and Phrases:** Gödel's Second Incompleteness Theorem, Hilbert's Second Open Question, Semantic Tableaux Deduction, Consistency.

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# 1 Introduction

Gödel's Incompleteness Theorem has two parts. Its first half indicates no decision procedure can identify all of arithmetic's true statements. Its "Second Incompleteness" result specifies sufficiently strong logics *cannot* verify their own consistency. Gödel was careful to insert a caveat into his historic paper [11], indicating a *diluted* form of Hilbert's Consistency Program might reach some levels of partial success:

\* *"It must be expressly noted Proposition XI (e.g. Gödel's "Second" Incompleteness Result) represents no contradiction of the formalistic standpoint of Hilbert. For this standpoint presupposes only the existence of a consistency proof by finite means, and there might conceivably be finite proofs which cannot be stated in  $P$  or in ..."*

Some scholars have interpreted \* as, possibly, anticipating attempts to confirm Peano Arithmetic's consistency, via either Gentzen's formalism or Gödel's Dialectica interpretation. On the other hand, the Stanford's Encyclopedia's entry about Gödel quotes him, in its Section 2.2.4, stating he was hesitant to view the Second Incompleteness Theorem as fully ubiquitous, until learning of Turing's work. Moreover, Yourgrau [51] states von Neumann *"argued against Gödel himself"* in the early 1930's, about the definitive termination of Hilbert's consistency program, which *"for several years"* after [11]'s publication, Gödel *"was cautious not to prejudge"*. Also, it is known [6, 13, 51] that Gödel initially presumed the second theorem was false, before proving his stunning result.

In any case several year after he wrote \*'s initial statement, Gödel gave a 1933 lecture [12], where he told his audience that Hilbert's initial 1926 objectives, summarized formally by \*\* below, had *"unfortunately"* no *"hope of succeeding along"* its originally intended plans.

\*\* (Hilbert [17] 1926): *"Where else would reliability and truth be found if even mathematical thinking fails? The definitive nature of the infinite has become necessary, not merely for the special interests of individual sciences, but rather for the honor of human understanding itself."*

Our research, in both the current article and the prior papers [38]-[49] was stimulated by the prospect that we find \*\* enticing, even though the Second Incompleteness Theorem *unequivocally* demonstrates that logics *cannot* recognize their own consistency *in a robust sense*. Accordingly, we have studied *both* generalizations and boundary-case exceptions for the Second Incompleteness Theorem in [38]-[49]. The current article will seek to *both* strengthen these prior results, in the context of axiom systems with *strictly finite cardinalities*, and to also provide a more intuitive explanation of the meaning behind [38]-[49]'s results.

The thesis of this article will be delicate because there can be no doubt that the Second Incompleteness Theorem is sharply robust, when viewed from a conventional purist mathematical

perspective. On the other hand, we will argue that there are certain facets of a “Self-Justifying Logics”, that are tempting under a hard-nosed engineering perspective, contemplating sharply *curtailed forms* of Hilbert’s goals. These results will be fragile *but not fully immaterial*.

In other words, this article will offer a somewhat complicated 2-part interpretation of the Second Incompleteness Theorem where:

1. The Second Incompleteness Theorem is seen as being 100 % robust from a mathematical perspective because of the widely encompassing nature of the 1939 Hilbert-Bernays analysis [18] (centering around their three well-known “Derivability Conditions” [25] ).
2. On the other hand, our discourse will partially appreciate Hilbert’s reluctance to fully embrace the Second Incompleteness Theorem, despite his joint work with Bernays [18] generalizing the Second Incompleteness Effect. (This is because it is awkward to explain how human beings can acquire the mental energy for motivating themselves to cogitate, without possessing some type of instinctive faith in their own self-consistency.)

Thus, the current article will seek to separate a “*mathematical*” from what perhaps should be “*engineering-style*” appreciation of one’s internal consistency. We will seek to define and explore the latter (with the hope that it will help formalize how future 21st century computers can benefit from its engineering-style perspective, while still respecting the strict prohibitions formalized by Gödel’s millennial result.)

As the reader examines this paper, it should be kept in mind that it does focus on semantic tableaux deduction (similar to the earlier discussion that had appeared in [49]’s more abbreviated conference-style summary of our results). A second paper, currently under preparation, will examine Hilbert-style deductive systems (whose self-justification properties are partially analogous and partly quite different from tableaux-style systems). The combination of these two results will formally define both the potential of self-justifying logics and the limitations which the Second Incompleteness Theorem imposes upon them.

## 2 Background Setting

Let  $(\alpha, d)$  denote any axiom system and deduction method satisfying the simple “**Split Rule**” below<sup>1</sup>. This pair will be called “**Self Justifying**” when:

- i one of  $\alpha$ ’s theorems will state that the deduction method  $d$ , applied to the system  $\alpha$ , will produce a consistent set of theorems, and

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<sup>1</sup>Our “Split Rule” is the trivial requirement that all the axiom sentences in  $\alpha$  are technically *proper axioms*, and that deduction method  $d$  is required to include **BOTH** a finite number of rules of inference and whatever “logical axioms” are needed (*if any ?*) by  $d$ ’s methodology. (This trivial Split-Rule notation convention will help us to provide a precisely formalized statement of our results. .)

ii the axiom system  $\alpha$  is in fact consistent.

For any  $(\alpha, d)$ , it is easy to construct a second  $\alpha^d \supseteq \alpha$  that satisfies the Part-i requirement. For instance,  $\alpha^d$  could consist of all of  $\alpha$ 's axioms plus an added “**SelfRef**( $\alpha, d$ )” sentence, defined as stating:

- There is no proof (using  $d$ 's deduction method) of  $0 = 1$  from the *union* of the system  $\alpha$  with *this* sentence “SelfRef( $\alpha, d$ )” (looking at itself).

Kleene [20] noted how to encode rough analogs of “SelfRef( $\alpha, d$ )”. Each of Kleene, Rogers and Jeroslow [20, 31, 19] noted  $\alpha^d$  may, however, be inconsistent (despite SelfRef( $\alpha, d$ )'s assertion), thus causing it to violate Part-ii's requirement.

This problem arises in many contexts besides Gödel's paradigm, where  $\alpha$  was an extension of Peano Arithmetic (see [1, 2, 3, 4, 5, 7, 9, 11, 14, 15, 16, 18, 21, 23, 24, 27, 28, 29, 30, 31, 32, 34, 35, 36, 37, 41, 43, 47]). Such results formalize paradigms where self-justification is infeasible, due to diagonalization issues. (It should, perhaps, be added that among this lengthy list of articles, it was especially [1, 4, 11, 24, 29, 34, 37]'s incompleteness results that influenced our work in [38]-[49].) In any case, the main point is that most logicians have hesitated to employ an analog of a SelfRef( $\alpha, d$ ) axiom because  $\alpha^d = \alpha + \text{SelfRef}(\alpha, d)$  is typically inconsistent.

Our research in [38, 40, 44, 46, 45] focused on paradigms where self-justification is feasible. It involved weakening the properties a logic can prove about addition and/or multiplication (to avoid potential difficulties). To be more precise, let  $Add(x, y, z)$  and  $Mult(x, y, z)$  denote 3-way predicates specifying  $x + y = z$  and  $x * y = z$ . Then a logic will be said to **recognize** successor, addition and multiplication as **Total Functions** iff it includes sentences 1-3 as axioms.

$$\forall x \exists z \quad Add(x, 1, z) \tag{1}$$

$$\forall x \forall y \exists z \quad Add(x, y, z) \tag{2}$$

$$\forall x \forall y \exists z \quad Mult(x, y, z) \tag{3}$$

A logic  $\alpha$  will be called **Type-M** iff it contains 1-3 as axioms, **Type-A** iff it contains only (1) and (2) as axioms, **Type-S** iff it contains only (1) as an axiom, and **Type-NS** iff it contains none of these axioms. The relationship of these constructs to self-justification is explained by items (a) and (b):

- The existence of Type-A systems that can recognize their own consistency under semantic tableaux deduction, while proving analogs of all Peano Arithmetic's  $\Pi_1$  theorems (in a slightly different language), were demonstrated in [42, 44]. Also, [40, 45] noted that some specialized forms of Type-NS systems can likewise recognize their own Hilbert consistency.
- The above evasions of the Second Incompleteness Theorem are known to be near-maximal in a mathematical sense. This is because the combined work of Pudlák, Solovay, Nelson

and Wilkie-Paris [26, 29, 34, 37] implied no natural Type-S system can recognize its Hilbert consistency, and Willard subsequently [41, 47, 48] hybridized their formalisms with some techniques of Adamowicz-Zbierski [1, 2] to establish that most Type-M systems cannot recognize their own semantic tableaux consistency.

Other fascinating efforts to evade the Second Incompleteness Theorem have used the Kreisel-Takeuti “CFA” system [23] or the *interpretational framework* of Friedman, Nelson, Pudlák and Visser [10, 26, 29, 36]. These systems are unrelated to our approach because they do not use Kleene-like “*I am consistent*” axiom-sentences. Instead, CFA uses the special properties of “second order” generalizations of Gentzen’s *cut-free* Sequent Calculus, and the interpretational approach formalizes how some systems recognize their Herbrand consistency on localized sets of integers, which unbeknownst to themselves, includes all integers. (These alternate results are interesting but unrelated to our approach.)

### 3 Defining Notation and Earlier Results

A function  $F$  will be called **Non-Growth** iff  $F(a_1 \dots a_j) \leq \text{Maximum}(a_1 \dots a_j)$  holds. Six examples of non-growth functions are

1. *Integer Subtraction* (where  $x - y$  is defined to equal zero when  $x \leq y$ ),
2. *Integer Division* (where  $x \div y$  equals  $x$  when  $y = 0$ , and it equals  $\lfloor x/y \rfloor$  otherwise),
3. *Maximum*( $x, y$ ),
4. *Logarithm*( $x$ ) =  $\lfloor \text{Log}_2(x) \rfloor$
5. *Root*( $x, y$ ) =  $\lfloor x^{1/y} \rfloor$  . and
6. *Count*( $x, j$ ) designating the number of “1” bits among  $x$ ’s rightmost  $j$  bits.

The term **U-Grounding Function** referred in [44] to a set of primitives, which included the preceding functions plus the *growth operations* of addition and  $\text{Double}(x) = x + x$ . Our language  $L^*$  was built out of these symbols, plus the primitives of “0”, “1”, “=” and “ $\leq$ ”.

In a context where  $t$  is any term in [44]’s language  $L^*$ , the quantifiers in  $\forall v \leq t \Psi(v)$  and  $\exists v \leq t \Psi(v)$  were called *bounded quantifiers*. Any formula in  $L^*$ , all of whose quantifiers are bounded, was called a  $\Delta_0^*$  formula. The  $\Pi_n^*$  and  $\Sigma_n^*$  formulae were then defined by the usual rules that:

1. Every  $\Delta_0^*$  formula is considered to be “ $\Pi_0^*$ ” and also “ $\Sigma_0^*$ ”.
2. A wff is called  $\Pi_n^*$  when it is encoded as  $\forall v_1 \dots \forall v_k \Phi$  with  $\Phi$  being  $\Sigma_{n-1}^*$
3. Also, a wff is called  $\Sigma_n^*$  when it is encoded as  $\exists v_1 \dots \exists v_k \Phi$ , where  $\Phi$  is  $\Pi_{n-1}^*$ .

Our articles [38, 42, 44] used the symbol  $D$  to denote a deduction method. They focused mostly around the semantic tableaux deductive methodology, whose formal definition can be found in the textbooks by Fitting and Smullyan [8, 33] and whose definition is also reviewed by Appendix A of the current article.

Our articles [43, 44] also considered an improved faster deductive technology, called **Tab-k deduction**, that consists of a speeded-up version of a tableaux, which permits a *limited analog* of Gentzen-style deductive cuts for  $\Pi_k^*$  and  $\Sigma_k^*$  formulae. Thus, if  $H$  denotes a sequence of ordered pairs  $(t_1, p_1), (t_2, p_2), \dots (t_n, p_n)$ , where  $p_i$  is a Semantic Tableaux proof of the theorem  $t_i$ , then  $H$  has been called a “**Tab-k Proof**” of a theorem  $T$  from  $\alpha$ ’s axioms iff  $T = t_n$  and also:

1. Each of the “intermediately derived theorems”  $t_1, t_2, \dots, t_{n-1}$  have a complexity no greater than that of either a  $\Pi_k^*$  or  $\Sigma_k^*$  sentence.
2. Each proper axiom in  $p_i$ ’s proof comes either from  $\alpha$  or is one of  $t_1, t_2, \dots, t_{i-1}$ .

Thus, a Tab-k proof is essentially a generalization of a classic semantic tableaux proof that essentially owns the equivalent of an extra specialized modus ponens rule for  $\Pi_k^*$  and  $\Sigma_k^*$  sentences.

Let us say an axiom system  $\alpha$  has a **Level-J Understanding** of its own consistency under a deduction method  $D$  iff  $\alpha$  can prove that there exists no proofs using its axioms and  $D$ ’s deduction of both a  $\Pi_J^*$  theorem and its negation. In this notation, items A and B summarize [39, 41, 43, 44, 47]’s main results:

- A. For any axiom system  $A$  using  $L^*$ ’s U-Grounding language, [44] showed its  $IS_D(A)$  formalism could prove all  $A$ ’s  $\Pi_1^*$  theorems and simultaneously verify its Level-1 consistency under Tab-1 deduction.
- B. Two negative results, tightly complementing item A’s positive result, were exhibited in [39, 41, 43, 47]. The first was that [39, 41, 47] showed most systems are unable to verify their Level-0 consistency under semantic tableaux deduction, when they included statement (3)’s “Type-M” axiom that multiplication is a total function. Moreover, [43] offered an alternate form of this incompleteness result, showing statement (2)’s *far weaker* Type-A systems cannot verify their Level-0 consistency under Tab-2 deduction.

The contrast between these positive and negative results has led to our conjecture that automated theorem provers are likely to eventually achieve a fragmentary part of the ambitions that were suggested by Hilbert in \*\*. This is because the question of whether a formalism can support an *idealized Utopian* conception of its own consistency is *different* from exploring the degrees to which theorem-provers can possess a *fragmentary knowledge* of their own consistency. The Incompleteness Theorem has demonstrated an Utopian idealized form of self-justification is

unobtainable, but our research has found some diluted cousins of this construct are feasible and warrant examination.

In summary, it should be kept in mind, during the remainder of this article, that the Hilbert-Bernays Derivability Conditions [16, 18, 25] impose severe limits upon any evasion of the Second Incompleteness Theorem. On the other hand, it appears that a human’s faith in his own consistency is an essential prerequisite to gain the needed psychological motivation for stimulating cogitation? (This is why we suspect Hilbert was never willing to concede that all facets of his consistency program were hopeless.) A broad theme of this paper will, thus, be that it is helpful to distinguish between the goals of a theoretical-oriented study of arithmetic from that of a more engineering-styled approach, since the Second Incompleteness Theorem is a perfect result from the first perspective while it permits for well-defined limited-scale part-way exceptions from the second vantage point.

## 4 The $IS_D(A)$ Axiom System

In a context where  $A$  denotes any axiom system using  $L^*$ ’s U-Grounding language,  $IS_D(A)$  was defined in [44] to be an axiomatic formalism capable of recognizing all of  $A$ ’s  $\Pi_1^*$  theorems and corroborating its own Level-1 consistency under  $D$ ’s deductive method. It consisted of the following four groups of axioms:

**Group-Zero:** Two of the Group-zero axioms did define the constant-symbols,  $\bar{c}_0$  and  $\bar{c}_1$ , designating the integers of 0 and 1. The Group-zero axioms will also define the growth functions of addition and  $Double(x) = x + x$ . The net effect of these axioms will be to set up a machinery to define any integer  $n \geq 2$  using fewer than  $3 \cdot \lceil \text{Log } n \rceil$  logic symbols.

**Group-1:** This axiom group did consist of a finite set of  $\Pi_1^*$  sentences, denoted as  $F$ , which can prove any  $\Delta_0^*$  sentence that holds true under the standard model of the natural numbers. (Any finite set of  $\Pi_1^*$  sentences  $F$  with this property may be used to define Group-1, as [44] noted.)

**Group-2:** Let  $\ulcorner \Phi \urcorner$  denote  $\Phi$ ’s Gödel Number, and  $\text{HilbPrf}_A(\ulcorner \Phi \urcorner, p)$  denote a  $\Delta_0^*$  formula indicating  $p$  is a Hilbert-styled proof of theorem  $\Phi$  from axiom system  $A$ . For each  $\Pi_1^*$  sentence  $\Phi$ , the Group-2 schema of [44] did contain an axiom of form (4). (Thus  $IS_D(A)$  can trivially prove all  $A$ ’s  $\Pi_1^*$  theorems.)

$$\forall p \{ \text{HilbPrf}_A(\ulcorner \Phi \urcorner, p) \Rightarrow \Phi \} \quad (4)$$

**Group-3:** This final part of the  $IS_D(A)$  essentially represented a self-referencing  $\Pi_1^*$  axiom, indicating  $IS_D(A)$  meets §3’s criteria of being “Level-1 consistent” under deductive method  $D$ . It amounts, thus, to the following declaration:

# No two proofs exist for a  $\Pi_1^*$  sentence and its negation, when  $D$ 's deductive method is applied to an axiom system, consisting of the union of Groups 0, 1 and 2 with **this sentence** (looking at itself).

One encoding of #, as a self-referencing  $\Pi_1^*$  axiom, appears in [44]. Thus, the below sentence (5) represents [44]'s  $\Pi_1^*$  styled encoding for # in a context where:

- i.  $\text{Prf}_{\text{IS}_D(A)}(a, b)$  is a  $\Delta_0^*$  formula indicating that  $b$  is a proof of a theorem  $a$  under  $\text{IS}_D(A)$ 's axiom system and  $D$ 's deduction method, and
- ii.  $\text{Pair}(x, y)$  is a  $\Delta_0^*$  formula indicating that  $x$  is a  $\Pi_1^*$  sentence and  $y$  represents  $x$ 's negation.

$$\forall x \forall y \forall p \forall q \quad \neg [ \text{Pair}(x, y) \wedge \text{Prf}_{\text{IS}_D(A)}(x, p) \wedge \text{Prf}_{\text{IS}_D(A)}(y, q) ] \quad (5)$$

**Remark 4.1** A fully formal summary of the techniques that [44] used to encode sentence (5) is provided by the combination of Appendices B and C. The former appendix summarizes our methods for generating the Gödel numbers of semantic tableaux and Tab- $k$  proofs in an optimally compressed manner. The latter appendix explores how sentence (5)'s self-referencing statement is precisely encoded.

**Notation.** An operation  $I(\bullet)$  that maps an initial axiom system  $A$  onto an alternate system  $I(A)$  will be called **Consistency Preserving** iff  $I(A)$  is consistent whenever all of  $A$ 's axioms hold true under the standard model of the natural numbers. In this context, [44] demonstrated:

**Theorem 4.2** Suppose the symbol  $D$  denotes either semantic tableaux deduction or its Tab-1 generalization. Then the  $\text{IS}_D(\bullet)$  mapping operation is consistency preserving (e.g.  $\text{IS}_D(A)$  will be consistent whenever all of  $A$ 's axioms hold true under the standard model of the natural numbers).

We emphasize the most difficult part of [44]'s result was neither the definition of its  $\text{IS}_D(A)$ 's axiom system nor the  $\Pi_1^*$  fixed-point encoding of (5)'s Group-3 axiom. Instead, the key challenge was the confirming of Theorem 4.2's "Consistency Preservation" property.

The confirming of this property is subtle because its invariant breaks down when  $D$  is a deduction method only slightly stronger than either semantic tableaux or Tab-1 deduction. Thus, Pudlák's and Solovay's work [29, 34] implies Theorem 4.2's analog fails when  $D$  represents Hilbert deduction, and [43] showed its generalization fails even when  $D$  represents Tab-2 deduction.

## 5 A Finitized Generalization of Theorem 4.2's Methodology

One difficulty with  $IS_D(A)$  was is that it employed an infinite number of different incarnations of sentence (4) in its Group-2 scheme (since it contained one incarnation of this sentence for each  $\Pi_1^*$  sentence  $\Phi$  in  $L^*$ 's language). Such a Group-2 schema is awkward because it simulates  $A$ 's  $\Pi_1^*$  knowledge almost via a brute-force enumeration.

Our Definition 5.1 and Theorems 5.2 and 5.7 will show how to mostly overcome this problem by compressing the infinite number of instances of sentence (4) in  $IS_D(A)$ 's Group-2 schema into a purely finite structure.

**Definition 5.1** Let  $\beta$  denote any finite set of axioms that have  $\Pi_1^*$  encodings. Then  $IS_D^\#(\beta)$  will denote an axiom system, similar to  $IS_D(A)$ , except its Group-2 scheme will employ  $\beta$ 's set of axioms, instead of using an infinite number of applications of statement (4)'s scheme. (Thus, the “*I am consistent*” statement in  $IS_D^\#(\beta)$ 's Group-3 axiom will be the same as before, except that the “*I am*” fragment of its self-referencing statement will reflect these changes in Group-2 in the obvious manner.)

**Theorem 5.2** Let  $D$  again denote either semantic tableaux or Tab-1 deduction, and  $\beta$  again denote a set of  $\Pi_1^*$  axioms. Then  $IS_D^\#(\beta)$  will be consistent whenever all  $\beta$ 's axioms hold true under the standard model. (In other words,  $IS_D^\#(\beta)$  will satisfy an analog of Theorem 4.2's consistency preservation property for  $IS_D(A)$ .)

Theorem 5.2's proof is almost identical to [44]'s proof of Theorem 4.2. Its proof is too lengthy to repeat here. Instead §9 will briefly summarize its proof. This abbreviated discussion should be sufficient to explain the gist behind the proof's core formalism, without delving into [44]'s full details.

Our next definition will enable us to formalize the main application of Theorem 5.2 that will be considered here. It will essentially explain how **finite-sized** self-justifying logics can provide an **infinite amount** of “kernelized”  $\Pi_1^*$  styled information.

**Definition 5.3** Let  $Test_i(t, x)$  denote any  $\Delta_0^*$  formula, and  $\ulcorner \Psi \urcorner$  denote  $\Psi$ 's Gödel number. Then  $Test_i(t, x)$  will be called a **Kernelized Formula** iff Peano Arithmetic can prove every  $\Pi_1^*$  sentence  $\Psi$  satisfies (6)'s identity:

$$\Psi \iff \forall x \text{ } Test_i(\ulcorner \Psi \urcorner, x) \quad (6)$$

There are infinitely many  $\Delta_0^*$  predicates  $Test_1(t, x)$ ,  $Test_2(t, x)$ ,  $Test_3(t, x)$  ... satisfying this kernelized condition (one of which is illustrated by Example 5.4). An enumerated list of all the available kernels is called a **Kernel-List**.

**Example 5.4** The set of true  $\Sigma_1^*$  sentences is r.e. This implies there exists a  $\Delta_0^*$  formula, called say  $\text{Probe}(g, x)$ , such that  $g$  is the Gödel number of a  $\Sigma_1^*$  statement that holds true in the Standard Model if and only if (7) is true:

$$\exists x \quad \text{Probe}(g, x) \wedge x \geq g \quad (7)$$

Now, let  $\text{Pair}(t, g)$  denote a  $\Delta_0^*$  formula that specifies  $t$  is the Gödel number of a  $\Pi_1^*$  statement and  $g$  is the  $\Sigma_1^*$  formula which is its negation. Then our notation implies that  $t$  is a true  $\Pi_1^*$  statement if and only if (8) holds true:

$$\forall x \quad \neg [\exists g \leq x \quad \text{Pair}(t, g) \wedge \text{Probe}(g, x)] \quad (8)$$

Thus if  $\text{Test}_0(t, x)$  denotes the  $\Delta_0^*$  formula of  $\neg [\exists g \leq x \quad \text{Pair}(t, g) \wedge \text{Probe}(g, x)]$ , it is one example of what Definition 5.3 would call a “Kernelized Formula”.

**Definition 5.5** Let us recall Definition 5.3 defined **Kernel-List** to be an enumeration of all the kernelized formulae  $\text{Test}_1(t, x)$ ,  $\text{Test}_2(t, x)$ ,  $\text{Test}_3(t, x)$ ... . Assuming  $\text{Test}_i(t, x)$  is the  $i$ -th element in this list and  $\Psi$  is an arbitrary  $\Pi_1^*$  sentence, the  **$i$ -th Kernel Image** of  $\Psi$  will be defined as the following  $\Pi_1^*$  sentence:

$$\forall x \quad \text{Test}_i(\ulcorner \Psi \urcorner, x) \quad (9)$$

**Example 5.6** The Definitions 5.3 and 5.5 suggest that there is a subtle relationship between a sentence  $\Psi$  and its  $i$ -th kernel image. This is because Definition 5.3 indicates that Peano Arithmetic can prove the invariant (6), indicating that  $\Psi$  is equivalent to its  $i$ -th kernel image. However, a weak axiom system can be plausibly uncertain about whether this equivalence does formally hold. This invariant is duplicated below:

$$\Psi \iff \forall x \quad \text{Test}_i(\ulcorner \Psi \urcorner, x) \quad (10)$$

Thus if a weak axiom system proves statement (9) (rather than  $\Psi$ ), it will not be able to equate these two results (unless it is able to verify (10)’s identity). This problem will apply to Theorem 5.7’s formalism. However, Theorem 5.7 will still remain of much interest because §6 will illustrate a methodology that can overcome many of Theorem 5.7’s limitations.

**Theorem 5.7** *Let  $A$  denote any system, whose axioms hold true in arithmetic’s standard model, and  $i$  denote the index of any of Definition 5.3’s kernelized formulae  $\text{Test}_i(t, x)$ . Then it is possible to construct a finite-sized collection of  $\Pi_1^*$  sentences, called say  $\beta_{A,i}$ , where  $IS_D^\#(\beta_{A,i})$  satisfies the following invariant:*

*If  $\Psi$  is one of the  $\Pi_1^*$  theorems of  $A$  then  $IS_D^\#(\beta_{A,i})$  can prove (9)’s statement (e.g. it will prove the “the  $i$ -th kernelized image” of  $\Psi$ ).*

**Proof Sketch:** Our justification of Theorem 5.7 will use the following notation:

1.  $\text{Check}(t)$  will denote a  $\Delta_0^*$  formula that produces a Boolean value of “True” when  $t$  represents the Gödel number of a  $\Pi_1^*$  sentence.
2.  $\text{HilbPrf}_A(t, q)$  will denote a  $\Delta_0^*$  formula that indicates  $q$  is a Hilbert-style proof of the theorem  $t$  from axiom system  $A$ .
3. For any kernelized  $\text{Test}_i(t, x)$  formula,  $\text{GlobSim}_i$  will denote (11)’s  $\Pi_1^*$  sentence. (It will be called  $A$ ’s  $i$ –th “**Global Simulation Sentence**”.)

$$\forall t \ \forall q \ \forall x \ \{ [ \text{HilbPrf}_A(t, q) \ \wedge \ \text{Check}(t) ] \implies \text{Test}_i(t, x) \} \quad (11)$$

In this notation, Theorem 5.7 shall be satisfied by any version of the axiom system  $\text{IS}_D^\#(\beta)$ , whose Group-2 schema  $\beta$  is a finite sized consistent set of  $\Pi_1^*$  sentences that has (11) as an axiom. (This includes the minimal sized such system, denoted as  $\beta_{A,i}$ , that has only (11) as an axiom.) This is because if  $\Psi$  is any  $\Pi_1^*$  theorem of  $A$  whose proof is denoted as  $\bar{p}$ , then both the  $\Delta_0^*$  predicates of  $\text{HilbPrf}_A(\ulcorner \Psi \urcorner, \bar{p})$  and  $\text{Check}(\ulcorner \Psi \urcorner)$  will hold true. Moreover,  $\text{IS}_D^\#$ ’s Group-1 axiom subgroup was defined so that it can automatically prove all  $\Delta_0^*$  sentences that are true. Hence,  $\text{IS}_D^\#(\beta_{A,i})$  will prove these two statements and then automatically corroborate (via axiom (11)) the further statement of:

$$\forall x \ \text{Test}_i(\ulcorner \Psi \urcorner, x) \quad (12)$$

Thus for each of the infinite number of  $\Pi_1^*$  theorems that  $A$  proves, the above defined formalism will prove a matching statement that corresponds to its  $i$ –th kernelized image.  $\square$

## 6 L-Fold Generalizations of Theorem 5.7

Theorem 5.7 is of interest because every axiom system  $A$  will have its formalism  $\text{IS}_D^\#(\beta_{A,i})$  prove the  $i$ –th kernelized image of every  $\Pi_1^*$  theorem that  $A$  proves. This fact is helpful because (6)’s invariance holds for all  $\Pi_1^*$  sentences. Moreover, our “U-Grounded”  $\Pi_1^*$  sentences capture all Conventional Arithmetic’s *crucial*  $\Pi_1$  information because they can view multiplication as a 3-way  $\Delta_0^*$  predicate  $\text{Mult}(x, y, z)$  via (13)’s encoding of this predicate.

$$[ (x = 0 \vee y = 0) \implies z = 0 ] \ \wedge \ [ (x \neq 0 \wedge y \neq 0) \implies ( \frac{z}{x} = y \ \wedge \ \frac{z-1}{x} < y ) ] \quad (13)$$

One difficulty with  $\text{IS}_D^\#(\beta)$  and  $\text{IS}_D^\#(\beta_{A,i})$  was mentioned by Example 5.6. It was that while Peano Arithmetic can corroborate (6)’s invariance for every  $\Pi_1^*$  sentence  $\Psi$ , these latter systems cannot also do so.

While there will probably never be a perfect method for fully resolving this challenge, there is a pragmatic engineering-style solution that is often available. This is essentially because our

proof of Theorem 5.7 employed a formalism  $\beta$  that used essentially only one axiom sentence (e.g. (11)'s  $\Pi_1^*$  declaration ).

Since the  $IS_D^\#(\beta)$  formalism was intended for use by any finite-sized system  $\beta$ , it is clearly possible to include any finite number of formally true  $\Pi_1^*$  sentences in  $\beta$ . Thus for some fixed constant  $L$ , one can easily let  $\beta$  include  $L$  copies of (11)'s axiom framework for a finite number of different  $\text{Test}_1, \text{Test}_2 \dots \text{Test}_L$  predicates, each of which satisfy Definition 5.3's criteria for being kernelized formulae. In this case,  $IS_D^\#(\beta)$  will formally map each initial  $\Pi_1^*$  theorem  $\Psi$  of some axiom system  $A$  onto  $L$  resulting different  $\Pi_1^*$  theorems of the form (9).

**Remark 6.1** Our basic conjecture is, essentially, that a goodly number of issues, concerning logic-based engineering applications called say  $E$ , may have convenient solutions via self-justifying logics, that follow the preceding outlined L-fold strategy. Thus, we are suggesting that if  $\beta$  is a large-but-finite set of axioms, that consists of  $L$  copies of (11)'s axiom framework for different  $\text{Test}_1 \dots \text{Test}_L$  predicates, then some future engineering applications  $E$  may possibly have their needs met by an  $IS_D^\#(\beta)$  formalisms, when a software engineer meticulously chooses an appropriately constructed finite-sized  $\beta$ .

**Remark 6.2** The preceding was not meant to overlook that the Second Incompleteness Theorem is a robust result, applying to all logics of sufficient strength. Our suggestion, however, is that computers are becoming so powerful, in both speed and memory size as the 21st century is progressing, that there will likely emerge engineering-style applications  $E$  that will benefit from  $IS_D^\#(\beta)$ 's self-referencing formalisms when a *large-but-finite-sized*  $\beta$  is delicately chosen. Moreover, it is of interest to speculate whether such computers can partially imitate a human being's approximate instinctive conjectures about his own consistency (that, as common colloquially held conjectures, seem to serve as *essential prerequisites* for humans to gain their motivation to cogitate).

Sections 7-10 will examine the preceding issues in further detail. Also, Section 9 will offer an intuitive summary of the techniques that [44] used to prove Theorem 4.2, so that the reader can understand [44]'s gist without reading the full details of [44]'s formal proof.

## 7 Comparing Type-M and Type-A Formalisms

Let us recall axioms (1)-(3) indicated Type-A systems differ from Type-M formalisms by treating Multiplication as a 3-way relation (rather than as a total function). For the sake of accurately characterizing what our systems can and cannot do, we have described our results as being fringe-like exceptions to the Second Incompleteness Theorem, from the perspective of an Utopian view of Mathematics, while perhaps being more significant results from an engineering-style perspective

of knowledge. Our goal in this section will be to amplify upon this perspective by taking a closer look at Type-A and Type-M formalisms.

Let us assume that  $x_0 = 2 = y_0$  and that  $x_1, x_2, x_3, \dots$  and  $y_1, y_2, y_3, \dots$  are defined by the recurrence rules of:

$$x_{i+1} = x_i + x_i \quad \text{AND} \quad y_{i+1} = y_i * y_i \quad (14)$$

The sequences  $x_0, x_1, x_2, \dots$  and  $y_0, y_1, y_2, \dots$  will thus represent the growth rates associated with the addition and multiplication primitives, lying in the statements (2) and (3)’s “**Type-A**” and “**Type-M**” axioms.

Since  $x_0 = 2 = y_0$ , the rule (14) implies  $y_n = 2^{2^n}$  and  $x_n = 2^{n+1}$ . The  $y_0, y_1, y_2, \dots$  sequence will, thus, grow much more quickly than the  $x_0, x_1, x_2, \dots$  sequence (since  $y_n$ ’s binary encoding will have an  $\text{Log}(y_n) = 2^n$  length while  $x_n$ ’s binary encoding will have a shorter length of size  $\text{Log}(x_n) = n + 1$  ).

Our prior papers noted that the difference between these growth rates was the reason that [39, 41, 47] showed all natural Type-M systems, recognizing integer-multiplication as a total function, were unable to recognize their tableaux-styled consistency — while [38, 40, 44] showed some Type-A systems could simultaneously prove all Peano Arithmetic  $\Pi_1^*$  theorems and corroborate their own tableaux consistency. Their gist was that a Gödel-like diagonalization argument, which causes an axiom system to become inconsistent as soon as it proves a theorem affirming its own tableaux consistency, stems, ultimately, from the exponential growth in the series  $y_0, y_1, y_2, \dots$ .

This growth will, thus, facilitate an intense cascading amount of self-referencing, using the identity  $\text{Log}(y_n) \cong 2^n$ , that will, ultimately, invoke the force of Gödel’s seminal diagonalization machinery. It will thus raise the following enticing question:

\*\*\* How natural are exponentially growing sequences, such as  $y_0, y_1, y_2, \dots$ , whose  $n$ —th member needs  $2^n$  bits for its encoding, when such lengths are greater than the number of atoms in the universe when merely  $n > 100$  ? Is the use of such a sequence for corroborating the Second Incompleteness Effect resting upon an almost artificial construct (with an inherently dizzying growth rate) ?

We will not attempt to derive a Yes-or-No answer to Question \*\*\* because we think that such a direct response is too simplistic. Our point is that both a positive and negative reply to \*\*\* are useful in different respects. This because the theoretical existence of a sequence integers of  $y_0, y_1, y_2, \dots$ , whose binary encodings are doubling in length, is tempting from the perspective of an Utopian view of mathematics, while awkward from an engineering styled perspective. We therefore ask: “*Why not be tolerant of both perspectives?*”

One virtue of this tolerance is it ushers in a greater understanding for the statements \* and \*\* that Gödel and Hilbert made during 1926 and 1931. This is because the Incompleteness Theorem

demonstrates no formalism can display an understanding of its own consistency in an idealized Utopian sense. On the other hand, §6 suggested these two remarks by Gödel and Hilbert might receive more sympathetic interpretations, if one sought to explore such questions from a less ambitious almost engineering-style perspective.

Our main thesis is supported by a theorem from [46]. It indicated that tableaux variations of self-justifying systems have no difficulty in recognizing that an infinitized generalization of a computer's floating point multiplication (with rounding) is a total function. The latter differs from integer-multiplication, by not having its output become double the length of its input when a number is multiplied by itself. Thus, the intuitive reason [46]'s multiplication-with-rounding operation is compatible with self-justification is because it avoids the inexorable exponential growth under rule (14)'s sequence  $y_0, y_1, y_2 \dots$ .

Also, Theorem 7.1 indicates self-justifying logics can view double-precision integer multiplication similarly as a total function. In particular for any arbitrary pair of integers  $(a, b)$ , let us employ a notation convention where:

1. **Size(a,b)** denotes the maximum of  $\lceil 1 + \text{Log}_2 a \rceil$  and  $\lceil 1 + \text{Log}_2 b \rceil$ .
2. The quantities **Left(a,b)** and **Right(a,b)** represent the multiplicative product of the integers  $a$  and  $b$ , insofar as **Right(a,b)** represents the rightmost bits of this product of length **Size(a,b)**, and **Left(a,b)** encodes the remaining bits to the left of **Right(a,b)** (whose length will also be bounded by **Size(a,b)**).

Within this context, Theorem 7.1 indicates self-justifying logics self-justification are able to view double-precision integer-multiplication as a total function.

**Theorem 7.1** *Let us assume the  $A$  in  $IS_D(A)$  and  $\beta$  in  $IS_D^\#(\beta)$  are axiom systems all of whose  $\Pi_1^*$  theorems are true statements under the standard model of the natural numbers. Then if  $D$  corresponds to either semantic tableaux or Tab-1 deduction, it is possible to formalize systems  $A^* \supseteq A$  and  $\beta^* \supseteq \beta$  such that  $IS_D(A^*)$  and  $IS_D^\#(\beta^*)$  are self-justifying extensions of respectively  $IS_D(A)$  and  $IS_D^\#(\beta)$  which can recognize each of the double-multiplicative precision operations of  $\text{Size}(a, b)$ ,  $\text{Left}(a, b)$  and  $\text{Right}(a, b)$  as total functions.*

**Proof Sketch;** The justification of Theorem 7.1 is similar to [46]'s analysis of Floating Point Multiplication (with rounding). Our proof of Theorem 7.1 will therefore be quite abbreviated.

The first point is that it is straightforward to develop three  $\Delta_0^*$  formulae, called  $\theta_1(a, b, y)$ ,  $\theta_2(a, b, y)$  and  $\theta_3(a, b, y)$ , that are the graphs of the functions **Size(a,b)**, **Left(a,b)** and **Right(a,b)**. It is also easy to construct a finite set of  $\Pi_1^*$  sentences, holding true in the Standard Model, called  $\gamma$ , that know how to correctly interpret these three  $\Delta_0^*$  formulae, insofar as  $\gamma$  knows:

1. For each  $a$  and  $b$ , there exists no more than one integer  $y$  that satisfies each of our three  $\theta_j(a, b, y)$  formulae.
2. For each  $a$  and  $b$ , our three  $\theta_j(a, b, y)$  formulae correctly simulate the graphs of the respective functions of  $\text{Size}(a, b)$ ,  $\text{Left}(a, b)$  and  $\text{Right}(a, b)$ .

Since our U-Grounding language contains the built-in function primitives of “Maximum” and “Double( $x$ )”, the Group-1 component of  $\text{IS}_D$  and  $\text{IS}_D^\#$  can easily verify that the operation  $F(a, b)$ , defined below is a total function:

$$F(a, b) = \text{Double}(\text{Double}(\text{Double}(\text{Max}(a, b)))) \quad (15)$$

This implies, in turn, that there exists a  $\Pi_1^*$  sentence, called  $\gamma^*$ , that will enable our formalism to verify that each of  $\text{Size}(a, b)$ ,  $\text{Left}(a, b)$  and  $\text{Right}(a, b)$  are total functions (simply because their output values are less than  $F(a, b)$ ’s output).

The main point is that the hypothesis of Theorem 7.1 indicated that all the axioms of  $A$  and  $\beta$  did hold true under the Standard Model, and the preceding paragraph showed the same was true for all the axioms in  $\gamma$  and  $\gamma^*$ . Hence all the axioms in  $A^* = A + \gamma + \gamma^*$  and  $\beta^* = \beta + \gamma + \gamma^*$  also hold true in the Standard Model. By Theorems 4.2 and 5.2, this implies that  $\text{IS}_D(A)$  and  $\text{IS}_D^\#(\beta)$  are self-justifying formalism satisfying Theorem 7.1’s claims.  $\square$

**Remark 7.2** One subtle aspect is that our positive results, involving [46]’s floating point multiplication primitive and Theorem 7.1’s analogous double precision multiplication operation, *should not be confused* with a quite different exploration of integer multiplication in the context of our analysis of Herbrand consistency in [48]. The latter took advantage of the fact that our deployed Herbrand-styled proofs in [48] were exponentially longer than their tableaux counterparts (thus allowing [48] to formalize a limited use of multiplication). This was because [48]’s deductive methods were exponentially less efficient at an inherent level. Thus [48]’s result, while of theoretical interest, is basically irrelevant to the core engineering environments, which constitutes the main focus of Theorems 4.2–7.1.

Remark 7.2’s contrast between [48]’s results and Theorem 7.1 is, once again, connected to the distinction between the engineering and mathematical viewpoints about the main intentions of theorem-proving. Theorem 7.1 is helpful from an engineering perspective because most pragmatic applications of integer multiplication are analogous to either computerized double-precision multiplication or its quadruple-precision or hexagonal generalizations.

Theorem 7.1 (and its quadruple-precision and hexagonal generalizations) indicate these operations are compatible with a formalism recognizing its own semantic tableaux consistency.

## 8 A Different Type of Evidence Supporting Our Thesis

Let us recall Pudlák and Solovay [29, 34] observed that essentially all Type-S systems, containing merely statement (1)’s axiom that successor is a total function, cannot verify their own consistency under Hilbert deduction. (See also related work by Buss-Ignjatovic [5], Hájek and Švejdar [35], as well as [40]’s Appendix A.)

It turns out that [43] generalized these results to show that Equation (2)’s Type-A systems are unable to verify their own consistency under the Tab–2 deduction system (defined in §3). At the same time, the  $IS_D$  and  $IS_D^\#$  frameworks, from Sections 4 and 5, can verify their own consistency under Tab–1 deduction. Our goal in this section will be to illustrate how the tight contrast between these positive and negative results is analogous to the differing growth rates of the sequences  $x_0, x_1, x_2, \dots$  and  $y_0, y_1, y_2, \dots$  from rule (14).

During our discussion  $G_i(v)$  will denote the scalar-multiplication operation that maps an integer  $v$  onto  $2^{2^i} \cdot v$ . Also,  $\Upsilon_i$  will denote the statement, in the U-Grounding language, that declares that  $G_i$  is a total function. Our paper [43] proved that  $\Upsilon_i$  has a  $\Pi_2^*$  encoding. It also implied that  $G_i$  satisfied:

$$G_{i+1}(v) = G_i(G_i(v)) \quad (16)$$

It was noted in [43] that this identity implies one can construct an axiom system  $\beta$ , comprised of solely  $\Pi_1^*$  sentences, where a semantic tableaux proof can establish  $\Upsilon_{i+1}$  from  $\beta + \Upsilon_i$  in a constant number of steps. This implies, in turn, that a Tab–2 proof from  $\beta$  will require no more than  $O(n)$  steps to prove  $\Upsilon_n$  (when it uses the obvious  $n$ -step process to confirm in chronological order  $\Upsilon_1, \Upsilon_2, \dots, \Upsilon_n$ ).

These observations are significant because  $G_n(1) = 2^{2^n}$ . Thus, [43] established that a Tab–2 proof from  $\beta$  can verify in only  $O(n)$  steps that this quite large integer exists.

This example is helpful because it illustrates the difference between the growth speeds under Tab–1 and Tab–2 deduction, is analogous to the differing growth rates of the sequences  $x_0, x_1, x_2, \dots$  and  $y_0, y_1, y_2, \dots$  from rule (14). Hence once again, a faster growth-rate will usher in the Second Incompleteness Theorem’s power (e.g. see [43]).

This analogy suggests that the Second Incompleteness Theorem has different implications from the perspectives of Utopian and engineering theories about the intended applications of mathematics. Thus, a Utopian may possibly be comfortable with a perspective, that contemplates sequences  $y_0, y_1, y_2, \dots$  with elements growing in length at an exponential speed, but many engineers may be suspicious of such growths.

A hard-core engineer, in contrast, might surmise that the inability of self-justifying formalisms to be compatible with Tab–2 deduction is not as disturbing as it might initially appear to be. This is because Tab–2 differs from Tab–1 deduction by producing exponential growths that are

so sharp that their material realization has no analog in the everyday mechanical reality that is the focus of an engineer's interest.

Our personal preference is for a perspective lying half-way between that of an Utopian mathematician and a hard-nosed engineer. Its dualistic approach suggests some form of diluted partial agreement with Hilbert's goals in \*\* (in a context where the broad significance of the Second Incompleteness Theorem is obviously undeniable).

## 9 Outline of Theorem 5.2's Proof and Its Implications

The prior two sections of this article offered an intuitive explanation about why our self-justifying axiom systems needed omit the assumption that multiplication is a total function and could verify their consistency only under semantic tableaux and Tab-1 deduction.

We already noted Theorem 5.2's observation that  $IS_D^\#$  is consistency-preserving has essentially an analogous proof as [44]'s demonstration that  $IS_D$  is consistency-preserving. It is not our intention to repeat such a proof here.

Instead, our goal will be to provide a brief overview of the techniques that [44] had used. This overview will be sufficient for a reader to appreciate the underlying intuition.

More precisely, two different types of proofs of Theorem 4.2 had appeared in our 2002 conference paper [42] and subsequent journal paper [44]. The latter was more appropriate for an archival journal because its self-justification result applied to both semantic tableaux deduction and its Tab-1 generalization. The more compressed conference paper [42] proved the analog of Theorem 4.2 only for tableaux deduction (using a technique that was somewhat shorter than [44]'s more elaborate result). Our summary of Theorem 4.2's proof, here, will focus on the semantic tableaux deduction methodology so it can apply to either of [42] or [44]'s methods.

Both of [42, 44] justified Theorem 4.2 by means of proofs by contradiction. Thus if Theorem 4.2 was false, they noted a pair of proofs for a  $\Pi_1^*$  sentence and its negation would exist from  $IS_D(A)$ .

Let us call these two proofs  $P$  and  $Q$ . Then [42, 44] both showed (using different constructions) that one could construct from  $(P, Q)$  two other proofs  $(p, q)$  of another  $\Pi_1^*$  sentence and its negation such that:

$$\text{Max}(p, q) < \text{Max}(P, Q) \tag{17}$$

The inequality in (17) is significant because it will enable our proofs-by-contradiction to establish the non-existence of an ordered pair  $(P, Q)$  violating Theorem 4.2's assumption. This is because (17) would otherwise violate the Principle of Induction by showing there exists no such minimal ordered pair  $(P, Q)$  eschewing Theorem 4.2's formalism.

The exact details of these proofs by contradictions are too lengthy to fully summarize here. For the case where  $D$  in Theorem 4.2 is the semantic tableaux deduction method, they used the fact that if  $(P, Q)$  was the ordered pair with minimal  $\text{Max}(P, Q)$  value violating Theorem 4.2's hypothesis, then one could isolate two particular root-to-leaf paths in the tableaux proofs  $P$  and  $Q$  that would enable us to construct an additional pair  $(p, q)$  that violated Theorem 4.2 and satisfied (17)'s inequality.

This construction of  $(p, q)$  from  $(P, Q)$  utilized the fact that Theorem 4.2's axiom system  $\text{IS}_D(\alpha)$  recognized addition but not multiplication as a total function. Otherwise, Theorem 4.2's delicate proof-by-contradiction would collapse entirely (as a result of the exponentially faster growth properties of multiplication that was formalized by the series  $y_1, y_2, y_3, \dots$  under Line (14)'s recurrence relationship).

These observations reinforce the theme of §7 about the contrast between the slower growing series  $x_1, x_2, x_3, \dots$  and its exponentially faster counterpart  $y_1, y_2, y_3, \dots$  under Line (14)'s recurrence relationship. These two series defined the growth rates produced by the addition and multiplication function symbols as, respectively,  $x_n = 2^{n+1}$  and  $y_n = 2^{2^n}$ . They thus illustrated how multiplication's faster growth rate leads to such a dizzying exponential speed-up, that makes one at least partially sympathetic to a hard-nosed engineer's skepticism about its implications.

Thus if one were to preclude such a dizzying growth rate then a partial justification of a diluted version of Hilbert's consistency program would arise, in the context of systems possessing *weak but well defined* knowledges of their own consistency. On the other hand, if the conventional assumption that multiplication is a total function is presumed, then the traditional interpretation of the Second Incompleteness Theorem will prevail.

## 10 Related Reflection Principles

An added point is that there are many types of self-justifying systems available, with some better suited for engineering environments than others.

For instance, our initial 1993 paper [38] employed a Group-3 "*I am consistent*" axiom that was much weaker than the current specimen. The distinction was that [38]'s self-consistency declaration excluded merely the existence of a semantic tableaux proof of  $0 = 1$  from itself, while the sentence (5) is more elaborate because it excludes the existence of simultaneous proofs of a  $\Pi_1^*$  theorem and its negation.

Ideally, one would like to develop self-justifying systems  $S$  that can corroborate the validity of (18)'s reflection principle for all sentences  $\Phi$ .

$$\forall p \ [ \text{Prf}_S^D(\ulcorner \Phi \urcorner, p) \Rightarrow \Phi ] \quad (18)$$

Löb's Theorem establishes, however, that all systems  $S$ , containing Peano Arithmetic's strength,

are able to prove (18)'s invariant *only in the degenerate case* where they do prove  $\Phi$  itself. Also, the Theorem 7.2 from [40] showed essentially all axiom systems, *weaker* than Peano Arithmetic, are unable to prove (18) for all  $\Pi_1^*$  sentences  $\Phi$  simultaneously. Thus, Theorem 10.1 will be near optimal:

**Theorem 10.1** *Let us recall that the difference between Theorem 4.2's axiom system  $IS_D(A)$  and Theorem 5.7's formalism  $IS_D^\#(\beta_{A,i})$  was that the latter replaced  $IS_D(A)$ 's infinite-sized Group-2 axiom schema with  $IS_D^\#(\beta_{A,i})$ 's compact 1-sentence axiom (11), so that the latter system could at least verify (19)'s kernelized statement for each  $\Pi_1^*$  theorem that  $A$  proved.*

$$\forall x \text{ Test}_i(\ulcorner \Psi \urcorner, x) \quad (19)$$

Let likewise  $IS_\#^\lambda(\beta_{A,i})$  denote the modification of [40]'s  $IS^\lambda(A)$  self-justifying system that replaces the latter's Group-2 schema with (11)'s more compact single-sentence axiom declaration (and then has its Group-3 "I am consistent" axiom statement reflect this change, once again). Then in a context where "semtab" is an abbreviation for semantic tableaux deduction, the formalism  $IS_\#^\lambda(\beta_{A,i})$  will be able to:

1. Verify that semantic tableaux deduction supports the following analog of (18)'s self-reflection principle under  $IS_\#^\lambda(\beta_{A,i})$  for any  $\Delta_0^*$  and  $\Sigma_1^*$  sentences  $\Phi$  :

$$\forall p [ \text{Prf}_{IS_\#^\lambda(\beta_{A,i})}^{\text{semtab}}(\ulcorner \Phi \urcorner, p) \Rightarrow \Phi ] \quad (20)$$

2. Verify (21)'s more general "**root-diluted**" reflection principle for  $IS_\#^\lambda(\beta_{A,i})$  whenever  $\theta$  is  $\Sigma_1^*$  and  $\Phi$  is a  $\Pi_2^*$  sentence of the form " $\forall u_1 \dots \forall u_n \theta(u_1 \dots u_n)$ ".

$$\forall p [ \text{Prf}_{IS_\#^\lambda(\beta_{A,i})}^{\text{semtab}}(\ulcorner \Phi \urcorner, p) \implies \forall x \forall u_1 < \sqrt{x} \dots \forall u_n < \sqrt{x} \theta(u_1 \dots u_n) ] \quad (21)$$

As is suggested by the similarity between the definitions of  $IS^\lambda(A)$  and  $IS_\#^\lambda(\beta_{A,i})$ , the proof of Theorem 10.1 is essentially identical to [40]'s analysis of  $IS^\lambda(A)$ . For the sake of brevity, we will not repeat the relevant proof here.

Analogous to our other results, Theorem 10.1 reinforces our theme about how exceptions to the Second Incompleteness Theorem may appear to be *quite minor* from the perspective of an Utopian view of mathematics, while being significant from an engineering standpoint. In Theorem 10.1's particular case, this is because:

- A. The ability of Theorem 10.1's system to support (20)'s self-reflection principle under tableaux proofs for any  $\Delta_0^*$  and  $\Sigma_1^*$  sentence, as well as to support (21)'s root reflection principle for  $\Pi_2^*$  sentences, is clearly significant.
- B. The incompleteness result of [40]'s Theorem 7.2 imposes, however, sharp limitations upon Item A's generality (in that it cannot be extended to fully all  $\Pi_1^*$  sentences, *in an undiluted sense*).

Thus, the tight fit between A and B is reminiscent of other slender borderlines, that separated generalizations and boundary-case exceptions for the Incompleteness Theorem, explored earlier. Once again, the Second Incompleteness Theorem is seen as robust, from an idealized Utopian perspective on mathematics, while permitting caveats from engineering styled perspectives.

This dualistic viewpoint allows one to nicely share *partial (and not full)* agreement with Hilbert's main aspirations in \*\*, while also appreciating the stunning achievement of the Second Incompleteness Theorem.

## 11 Concluding Remarks

At a purely technical level, this article has reached beyond our prior papers in several respects, including §5's demonstration that any initial system  $A$  can have a kernelized image of its  $\Pi_1^*$  knowledge duplicated by  $IS_D^\#(\beta_{A,i})$ 's **strictly finite sized** self-justifying system, as well as Section 6's and Remark 6.2's quite pragmatic L-fold generalizations of Theorem 5.7.

These perspectives help resolve the mystery that has enshrouded the Second Incompleteness Theorem and the statements \* and \*\* of Gödel and Hilbert. This is because we have *meticulously separated* the goals of a pristine theoretical study of mathematical logic from those of a *finite-sized* axiomatic subset of mathematics, intended for modeling mostly an engineering environment.

There is no question that Gödel's Second Theorem is ideally robust, relative to a purely pristine approach to mathematics. On the other hand, we suspect Hilbert was *half-way correct* by speculating in \*\* about humans possessing a knowledge about their own consistency, *in at least some weak and tender sense*, as essentially a prerequisite for *psychologically motivating* their cogitations. Thus in a context where the limitations of axiom systems, that fail to recognize multiplication as a total function, are manifestly obvious, it is legitimate to inquire whether some future specialized 21st century computers might find some *partial-albeit-and-not-full* redeeming value in formalisms having *weak-style* knowledges of their Tab-1 consistency, as well as possessing a knowledge of Peano Arithmetic's  $\Pi_1^*$  theorems.

Sections 5-10 were, thus, intended to provide a unified broad-scale interpretation of our diverse earlier results that had appeared in [38]-[48]. In a context where the Incompleteness Theorem is sufficiently ubiquitous to preclude Hilbert's aspirations in \*\* from ever being fully realized, they show how some *fragmentary portion* of Hilbert's conjectures can be corroborated by *judiciously weakened* logics, using a formalism, that is *much less* than ideally robust, *although not fully immaterial*.

Such partial evasions of the Second Incompleteness Effect are certainly not broad-scale, but they do corroborate a fragment of what Gödel and Hilbert had sought as their desired goals, expressed in the statements \* and \*\*.

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## Appendix A: Definition of a Semantic Tableaux Proof

The definition of a semantic tableaux proof, provided here, will be similar to analogous definitions used in say Fitting's or Smullyan's textbooks [8, 33].

During our discussion, a  **$\Phi$ -Based Candidate Tree** for an axiom system  $\alpha$  will be defined to be a tree structure whose root corresponds to the sentence  $\neg\Phi$ , rewritten in prenex normal form, and whose all other nodes are either axioms of  $\alpha$  or deductions from higher nodes of the tree (using the Rules 1-6 defined below). More precisely, our six rules (below) have " $\mathcal{A} \mapsto \mathcal{B}$ " denote that  $\mathcal{B}$  is a valid deduction from  $\mathcal{A}$ . They specify when such a descendant node  $\mathcal{B}$  is allowed to appear below an ancestor  $\mathcal{A}$  in a candidate tree:

1.  $\Upsilon \wedge \Gamma \mapsto \Upsilon$  and  $\Upsilon \wedge \Gamma \mapsto \Gamma$ .
2.  $\neg\neg\Upsilon \mapsto \Upsilon$ . Other rules for the " $\neg$ " symbol include:  $\neg(\Upsilon \vee \Gamma) \mapsto \neg\Upsilon \wedge \neg\Gamma$ ,  $\neg(\Upsilon \Rightarrow \Gamma) \mapsto \Upsilon \wedge \neg\Gamma$ ,  $\neg(\Upsilon \wedge \Gamma) \mapsto \neg\Upsilon \vee \neg\Gamma$ ,  $\neg\exists v \Upsilon(v) \mapsto \forall v \neg\Upsilon(v)$  and  $\neg\forall v \Upsilon(v) \mapsto \exists v \neg\Upsilon(v)$ .
3. A pair of sibling nodes  $\Upsilon$  and  $\Gamma$  is allowed in a proof tree when their ancestor is  $\Upsilon \vee \Gamma$ .
4. A pair of sibling nodes  $\neg\Upsilon$  and  $\Gamma$  is allowed in a proof tree when their ancestor is  $\Upsilon \Rightarrow \Gamma$ .
5.  $\exists v \Upsilon(v) \mapsto \Upsilon(u)$  where  $u$  denotes a newly introduced "Parameter Symbol".
6.  $\forall v \Upsilon(v) \mapsto \Upsilon(t)$  where  $t$  denotes a "Composite Term". These terms here are built out of combination of the U-Grounding Function symbols, the constant symbols representing "0" and "1" and the parameter symbols  $u_1, u_2, \dots, u_n$ , where each  $u_i$  **was previously** introduced by applying Rule 5 to an ancestor of the node storing " $\Upsilon(t)$ ".

Define a particular leaf-to-root branch in a candidate tree  $T$  to be **Closed** iff it contains both some sentence  $\Upsilon$  and its negation  $\neg\Upsilon$ . A **Semantic Tableaux** proof of  $\Phi$  will then be defined to be a candidate tree whose root stores the sentence  $\neg\Phi$  (written in prenex normal form) and all of whose root-to-leaf branches are closed.

Our current article has, for simplicity, used the preceding definition for a semantic tableaux proof. Some of our prior articles used a minor modification of this definition where there were two additional deduction rules for "bounded quantifiers" of the form " $\exists v \leq t \Upsilon(v)$ " and " $\forall v \leq t \Upsilon(v)$ ". It is technically unnecessary to use special rules for such bounded quantifiers because these two expressions can be treated as being equivalent to (22) and (23), respectively.

$$\exists v \quad v \leq t \wedge \Upsilon(v) \tag{22}$$

$$\forall v \quad v \leq t \Rightarrow \Upsilon(v) \tag{23}$$

Thus, we technically do not need special Elimination Rules for bounded quantifiers of the form " $\exists v \leq t \Upsilon(v)$ " and " $\forall v \leq t \Upsilon(v)$ " because statement (22) allows the former to be eliminated by applying Rules 5 and 1, and likewise (23) can be processed via Rules 6 and 4.

## Appendix B: Summary of Gödel Encoding Method

Every generalization and boundary-case exception for the Second Incompleteness Theorem does require deploying a Gödel encoding methodology (to make it well defined). Such an encoding scheme will be called **Optimally Linearly Compressed** if it requires:

- A. Only  $O(1)$  bits to store each occurrence of any logical symbol appearing in a tableaux proof (except for the objects that Items 5 and 6 of Appendix A called the  $i$ -th “variable” and “parameter” symbols).
- B. No more than  $O(1 + \text{Log}(i))$  bits to encode a proof’s  $i$ -th “variable” and “parameter” symbols. (This  $O(1 + \text{Log}(i))$  magnitude is unavoidable because there is no finite limit to the number of different variable and parameter objects that may appear in one of Appendix A’s semantic tableaux proofs.)

All our published results about either generalizations or boundary-case exception for the Second Incompleteness Theorem have used such optimally compressed encodings.

In particular, our scheme for encoding a semantic tableaux proof will use the following 24 language symbols:

1. The standard connective symbols of  $\wedge$ ,  $\vee$ ,  $\neg$ ,  $\rightarrow$ ,  $\forall$  and  $\exists$ .
2. Two left and two right parenthesis symbols denoted as:  $($ ,  $)$ ,  $($  and  $)$ .
3. Two symbols to represent the special constants of “0” and “1”.
4. Eight function symbols for representing the eight formal U-grounding functions of Addition, Doubling, Subtraction, Division, Logarithm, etc.
5. The relation symbols of “=” and “ $\leq$ ”.
6. The symbol  $\hat{V}$  for designating the presence of a basic variable  $v$  in a logical sentence.
7. The symbol  $\hat{U}$  for designating the presence of a parameter constant  $u$  in a logical sentence (which is produced by Appendix A’s deduction rule 5 for eliminating existential quantifiers).

Define a byte to be an unit consisting of six bits. We may think of a proof as comprising either a sequence of bytes or being an equivalent integer written in base 64. Each of the 24 symbols (above) will be given some unique 6-bit code, ranging between 32 and 55. Our method for representing the presence of the  $i$ -th variable  $v_i$  will be to encode it as a string comprised of  $\lceil \log_{32}(i+1) \rceil + 1$  bytes, where the first byte is the “ $\hat{V}$ ” symbol and the remaining bytes encode  $i$  as a base-32 number. The same convention will be used to denote the presence of the  $i$ -th parameter  $u_i$  except its first byte will be the “ $\hat{U}$ ” symbol.

Our notation has employed *two types* of parenthesis symbols because the first pair of parenthesis symbols will have their usual meaning in punctuating a mathematical sentence, whereas the

latter pair of symbols  $($  and  $)$  will *separate* the individual sentences in a Semantic Tableaux proof tree. For example, consider a tree which stores 1) the sentence  $\psi_1$  as its root, 2) the sentences  $\psi_2$  and  $\psi_3$  as the root's children, and 3)  $\psi_4$  as the child of  $\psi_3$ . There are several possible notation conventions for using the  $($  and  $)$  symbols to encode a Semantic Proof tree. Our encoding convention will presume  $\psi_i$  is an “ancestor” of  $\psi_j$  *if and only if* the range beginning with the parenthesis to  $\psi_i$ 's immediate left and continuing to the matching right parenthesis includes  $\psi_j$ . The example of our 4-node proof tree is thus encoded as:

$$( \psi_1 ( \psi_2 ) ( \psi_3 ( \psi_4 ) ) ) \quad (24)$$

The preceding paragraph summarized our method for encoding semantic tableaux proofs. Its generalization for the encoding of Tab–1 proofs is straightforward. Thus if  $p_1, p_2, \dots, p_n$  collectively constitute a list of semantic tableaux proofs then the natural concatenation of their byte strings will be the corresponding Tab–1 proof.

This “Optimally Linearly Compressed” encoding scheme is essential because all the core axiom systems, employed in this article, are Type-A formalisms, that recognize Addition but not Multiplication as a total function. If such formalisms were less than optimally compressed then our main theorems would lose relevance because the formalization of unnecessarily expansive encodings would be awkward in the context of the slow growth properties of Type-A formalisms. Thus, our results carry much greater significance when their encodings of a proof satisfy the maximal compression properties, defined in this appendix.

## Appendix C: Formal Encoding of the Group-3 Axiom

Let us recall Appendix A reviewed the definition of a semantic tableaux and Tab–1 proof, and Appendix B formalized the encodings of such proofs. The goal of this appendix will be to summarize the methodology used to define Statment (5)'s Group-3 axiom in [44] .

Let  $\text{UNION}(A)$  denote the union of  $\text{IS}_D(A)$ 's Group-Zero, Group-1 and Group-2 axioms. It will be useful to employ the following notation:

- i  $\text{Prf}_{\text{UNION}(A)}^D(t, p)$  will denote a formula designating that  $p$  is a proof of the theorem  $t$  from the axiom system  $\text{UNION}(A)$  using the deduction method  $D$ .
- ii  $\text{ExPrf}_{\text{UNION}(A)}^D(h, t, p)$  will be a formula stating that  $p$  is a proof (using the deduction method  $D$ ) of a theorem  $t$  from the union of the axiom system  $\text{UNION}(A)$  with the added axiom sentence specified by the integer  $h$ .
- iii  $\text{Subst}(g, h)$  will denote Gödel's classic substitution formula — which yields TRUE when  $g$  is an encoding of a formula and  $h$  is an encoding of a sentence that replaces all occurrence of free variables in  $g$  with an encoded term  $\overline{g}$  (that designates  $g$ 's Gödel number.)

- iv  $\text{SubstPrf}_{UNION(A)}^D(g, t, p)$  will denote the natural hybridizations of the constructs from Items (ii) and (iii) which yields a Boolean value of TRUE exactly when there exists some integer  $h$  simultaneously satisfying *both* the conditions  $\text{Subst}(g, h)$  and  $\text{ExPrf}_{UNION(A)}^D(h, t, p)$ .

Each of (i)–(iv) can be encoded as  $\Delta_0^*$  formulae. Thus, Appendices C and D of [40] explained how the first three of these predicates can receive  $\Delta_0^*$  encodings when one applies the theory of LinH functions [16, 22, 50]. Hence, (25) illustrates one possible  $\Delta_0^*$  encoding for  $\text{SubstPrf}_{UNION(A)}^D(g, t, p)$ 's graph. (It is equivalent to the statement “ $\exists h [\text{Subst}(g, h) \wedge \text{ExPrf}_{UNION(A)}^D(h, t, p)]$ ”, but (25) is a  $\Delta_0^*$  formula — *unlike* the quoted expression.)

$$\text{Prf}_{UNION(A)}^D(t, p) \quad \vee \quad \exists h \leq p [\text{Subst}(g, h) \wedge \text{ExPrf}_{UNION(A)}^D(h, t, p)] \quad (25)$$

Let us recall that  $\text{Pair}(x, y)$  is a  $\Delta_0^*$  sentence specifying that  $x$  and  $y$  are the encodings of a  $\Pi_1^*$  and  $\Sigma_1^*$  sentence, that are logical negations of each other. Using (25)'s  $\Delta_0^*$  encoding for  $\text{SubstPrf}_{UNION(A)}^D(g, t, p)$ , we can now explain how statement (5)'s Group-3 Axiom can be formally encoded. Let  $\Gamma(g)$  denote Equation (26)'s formula,  $n$  denote  $\Gamma(g)$ 's Gödel number and  $\overline{n}$  denote a term encoding  $n$  in the U-Grounding language. Then it will turn out that “ $\Gamma(\overline{n})$ ” will be a  $\Pi_1^*$  sentence that is equivalent to this Group-3 axiom.

$$\forall x \forall y \forall p \forall q \neg [\text{Pair}(x, y) \wedge \text{SubstPrf}_{UNION(A)}^D(g, x, p) \wedge \text{SubstPrf}_{UNION(A)}^D(g, y, q)] \quad (26)$$

More precisely, (27) formalizes the encoding of “ $\Gamma(\overline{n})$ ”.

$$\forall x \forall y \forall p \forall q \neg [\text{Pair}(x, y) \wedge \text{SubstPrf}_{UNION(A)}^D(\overline{n}, x, p) \wedge \text{SubstPrf}_{UNION(A)}^D(\overline{n}, y, q)] \quad (27)$$

Thus, if we view “ $\text{SubstPrf}_{UNION(A)}^D(\overline{n}, t, p)$ ” in (27) as our formal method of encoding the concept that was previously informally called “ $\text{Prf}_{IS_D(A)}(t, p)$ ” by Statement (5), then (27) amounts to the formal encoding of (5)'s Group-3 “*I am consistent*” axiom declaration.

**Reminder about the Significance of (27)'s Encoding :** The preceding construction had showed merely that it is possible to encode Sentence (5)'s Group-3 “*I am consistent*” axiom declaration in a well-defined manner as a  $\Pi_1^*$  sentence. It does not answer the more subtle question about whether or not its “*I am consistent*” axiom declaration holds true under the Standard model. As we have noted before, most analogs of (27) produce false statements under the Standard Model because a conventional Gödel-like diagonalization argument will imply that most deduction methods  $D$  will produce axiom systems  $IS_D(A)$  that are inconsistent.

The reason for our particular interest in (27)'s formal encoding is that Theorems 4.2 and 5.2 indicate that  $IS_D(A)$  is consistent when  $D$  denotes either the semantic tableaux or Tab–1 deduction methodologies. Thus (27)'s Fixed-Point construction should be seen as a methodology that has limited applications, but which is also quite helpful (when it is feasible).