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Inconsistency Robustness in Foundations Mathematics self proves its own Consistency and Other Matters

Carl Hewitt

*This article is dedicated to Alonzo Church, Stanisław Jaśkowski,
Ludwig Wittgenstein, and Ernst Zermelo.*

Abstract

Inconsistency Robustness is performance of information systems with pervasively inconsistent information. Inconsistency Robustness of the community of professional mathematicians is their performance repeatedly repairing contradictions over the centuries. In the Inconsistency Robustness paradigm, deriving contradictions have been a progressive development and not “game stoppers.” Contradictions can be helpful instead of being something to be “swept under the rug” by denying their existence, which has been repeatedly attempted by Establishment Philosophers (beginning with some Pythagoreans). Such denial has delayed mathematical development. This article reports how considerations of Inconsistency Robustness have recently influenced the foundations of mathematics for Computer Science continuing a tradition developing the sociological basis for foundations.¹

Classical Direct Logic is a foundation of mathematics for Computer Science, which has a foundational theory (for convenience called “Mathematics”) that can be used in any other theory. A bare turnstile is used for Mathematics so that $\vdash\Psi$ means that Ψ is a mathematical proposition that is a theorem of Mathematics and $\Phi\vdash\Psi$ means that Ψ can be inferred from Φ in Mathematics.

The current common understanding is that Gödel proved “Mathematics cannot prove its own consistency, if it is consistent.” However, the formal consistency of mathematics can be proved by a simple argument using standard rules of Mathematics including the following:

- rule of Proof by Contradiction, *i.e.*, $(\neg\Phi\Rightarrow(\Theta\wedge\neg\Theta))\vdash\Phi$
- the rule of Soundness (*a theorem can be used in a proof*²), *i.e.*, $(\vdash\Phi)\Rightarrow\Phi$

Formal Proof.

By definition, $\text{Consistent}\Leftrightarrow\neg\exists[\Psi]\rightarrow\vdash(\Psi\wedge\neg\Psi)$. By Existential Elimination, there is some proposition Ψ_0 such that $\neg\text{Consistent}\Rightarrow\vdash(\Psi_0\wedge\neg\Psi_0)$ which by Soundness and transitivity of implication means $\neg\text{Consistent}\Rightarrow(\Psi_0\wedge\neg\Psi_0)$. Substituting for Φ and Θ , in the rule for Proof by Contradiction, it follows that $(\neg\text{Consistent}\Rightarrow(\Psi_0\wedge\neg\Psi_0))\vdash\text{Consistent}$. Thus, $\vdash\text{Consistent}$.

The above theorem means that consistency is deeply embedded in the architecture of classical mathematics. Please note the following points: **The above argument formally mathematically proves the theorem that mathematics is consistent** and that **it is *not* a premise of the theorem that mathematics is consistent**. Classical mathematics was designed for consistent axioms and consequently the rules of classical mathematics can be used to prove consistency regardless of the axioms, *e.g.*, Euclidean geometry.

By formally consistent, it is meant that a consistency is not inferred. The proof is remarkably tiny consisting of only using proof by contradiction and soundness. In fact, it is so easy that one wonders why this was overlooked by so many great logicians in the past. The proof is also remarkable that it does not use knowledge about the content of mathematical theories (plane geometry, integers, *etc.*). The proof serves to formalize that consistency is built into the very architecture of classical mathematics. However, the proof of formal consistency does not prove *constructive* consistency, which is defined to be that the rules of Classical Direct Logic themselves do not derive a contradiction. Proof of constructive consistency requires a separate inductive proof using the axioms and rules of inference of Classical Direct Logic. The upshot is that, contra Gödel, there seems to be no inherent reason that mathematics cannot prove constructive consistency of Classical Direct Logic (which formalizes classical mathematical theories). However, such a proof is far beyond the current state of the art.ⁱ

The above proof means that “Mathematics is consistent” is a theorem in Classical Direct Logic. This means that the usefulness of Classical Direct Logic depends crucially on the consistency of Mathematics. Good evidence for the consistency of Mathematics comes from the way that Classical Direct Logic avoids the known paradoxes. Humans have spent millennia devising paradoxes.

Having a powerful system like Direct Logic is important in computer science because computers must be able to formalize all logical inferences (including inferences about their own inference processes) without requiring recourse to human intervention. Any inconsistency in Classical Direct Logic would be a potential security hole because it could be used to cause computer systems to adopt invalid conclusions.

ⁱ This paragraph builds on [Meyer 2016].

The recently developed self-proof of consistency (above) shows that the current common understanding that Gödel proved “Mathematics cannot prove its own consistency, if it is consistent” is inaccurate.

It is very important to distinguish between the following:

- “self-reference” using the **Y** fixed point
- recursion using types

Gödel famously thought that mathematics necessarily has the “self-referential”³ proposition “*I’m unprovable.*” which allegedly comes from a **Y** fixed-point construction. **Using types, it is impossible to construct such a “self-referential” proposition because the **Y** fixed points do not exist.**ⁱ In this way, consistency of mathematics is preserved without giving up power.

Mathematical Foundation for Computer Science

Computer Science brought different concerns and a new perspective to mathematical foundations including the following requirements:⁴ [Arabic numeral superscripts refer to endnotes at the end of this article]

- provide powerful inference machinery so that arguments (proofs) can be short and understandable and all logical inferences can be formalized
- establish standard foundations so people can join forces and develop common techniques and technology
- incorporate axioms thought to be consistent by the overwhelming consensus of working professional mathematicians, e.g., natural numbers [Dedekind 1888, Peano 1889], real numbers [Dedekind 1888], sets of integers, reals, *etc.*
- facilitate inferences about the mathematical foundations used by computer systems.

Classical Direct Logic is a foundation of mathematics for Computer Science, which has a foundational theory (for convenience called “Mathematics”) that can be used in any other theory. A bare turnstile is used for Mathematics so that $\vdash\Psi$ means that Ψ is a mathematical proposition that is a theorem of Mathematics and $\Phi \vdash\Psi$ means that Ψ can be inferred from Φ in Mathematics.

ⁱ Fixed points on Mathematical sentences do not exist in Mathematics that is grounded on mathematical objects, e.g., complex numbers, rectangles, etc.

Mathematics self proves its own consistency

A mathematically significant idea involves:

“...a very high degree of unexpectedness, combined with inevitability and economy.” [Hardy 1940]

The following rules are fundamental to classical mathematics:

- Proof by Contradiction, *i.e.* $(\neg\Phi \Rightarrow (\Theta \wedge \neg\Theta)) \vdash \Phi$, which says that a proposition can be proved by showing that it implies a contradiction.
- Soundness, *i.e.* $(\vdash \Phi) \Rightarrow \Phi$, which says that a theorem can be used in a proof.⁵

Theorem: Mathematics self proves its own formal consistency.⁶

*Formal Proof*⁷ By definition,

$\neg\text{Consistent} \Leftrightarrow \exists [\Psi] \rightarrow \vdash (\Psi \wedge \neg\Psi)$.⁸ By the rule of Existential

Elimination, there is some proposition Ψ_0 such that

$\neg\text{Consistent} \Rightarrow \vdash (\Psi_0 \wedge \neg\Psi_0)$ which by the rule of Soundness and

transitivity of implication means $\neg\text{Consistent} \Rightarrow (\Psi_0 \wedge \neg\Psi_0)$. Substituting

for Φ and Θ , in the rule for Proof by Contradiction, we have

$(\neg\text{Consistent} \Rightarrow (\Psi_0 \wedge \neg\Psi_0)) \vdash \text{Consistent}$. Thus, $\vdash \text{Consistent}$.

A Natural Deductionⁱ proof is given below:

1) $\neg\text{Consistent}$	// hypothesis to derive a contradiction just in this subargument
2) $\exists[\Psi] \rightarrow \vdash (\Psi \wedge \neg\Psi)$	// definition of inconsistency using 1)
3) $\vdash (\Psi_0 \wedge \neg\Psi_0)$	// rule of Existential Elimination using 2)
4) $\Psi_0 \wedge \neg\Psi_0$	// rule of Soundness using 3)
$\vdash \text{Consistent}$	// rule of Proof by Contradiction using 1) and 4)

Natural Deduction Proof of Consistency of Mathematics

ⁱ [Jaśkowski 1934] developed Natural Deduction *cf.* [Barker-Plummer, Barwise, and Etchemendy 2011]

Please note the following points:

- The above argument formally mathematically proves that mathematics is formally consistent and that **it is not a premise of the theorem that mathematics is consistent.**⁹
- Classical mathematics was designed for consistent axioms and consequently the rules of classical mathematics can be used to prove consistency regardless of other axioms.¹⁰

The above proof means that “Mathematics is consistent” is a theorem in Classical Direct Logic. This means that the usefulness of Classical Direct Logic depends crucially on the consistency of Mathematics. Good evidence for the consistency of Mathematics comes from the way that Classical Direct Logic avoids the known paradoxes. Humans have spent millennia devising paradoxes.

Computer Science needs very strong foundations for mathematics so that computer systems are not handicapped. It is important not to have inconsistencies in mathematical foundations of Computer Science because they represent security vulnerabilities.

The recently developed self-proof of consistency (above) shows that the current common understanding that Gödel proved “Mathematics cannot prove its own consistency, if it is consistent” is inaccurate. But the situation is even more interesting because Wittgenstein more than a half-century ago showed that contradiction in mathematics results from the kind of “self-referential” sentence that Gödel used in his proof. Fortunately, using types, it can be proved that the kind “self-referential” sentence that Gödel used in his proof cannot be constructed because required **Y** fixed points do not exist. Consequently, using a types, consistency of mathematics can be preserved without giving up power.

Gödel and other philosophers developed the First-order Thesis that weakened the foundations of mathematics so that, as expressed, “self-referential” propositions do not infer contradiction.¹¹ The weakened foundations (based on first-order logic) enabled some limited meta-mathematical theorems to be proved. However, as explained in this article, the weakened foundations are cumbersome, unnatural, and unsuitable as the mathematical foundation for Computer Science.

By the above formalized proof, Mathematics (\vdash) proves its own consistency. However, the proof does so without regard to the content of Mathematics. For example, Mathematics includes the Peano/Dedekind categorical

axiomatization of the natural numbers. The consistency proof doesn't lead to any technical problems as long as there are no inconsistencies, *e.g.*,

- the Peano/Dedekind categorical axiomatization doesn't infer any contradictions
- there are no “self-referential” propositions in Mathematics

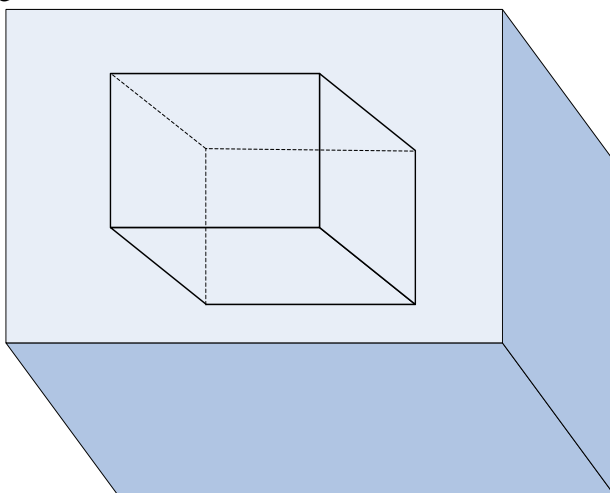
Monster-Barring

“But why accept the counterexample? ... Why should the theorem give way...? It is the ‘criticism’ that should retreat.... It is a monster, a pathological case, not a counterexample.”

Delta, student in [Lakatos, 1976, pg. 14].

The Euler formula for polyhedra is $V - E + F = 2$, which can be proved in a variety of different ways.

But the hollow cube below is a counterexample because $V - E + F = 4$.



Counterexample to Euler's Formula

In the face of this counterexample, it becomes important to characterize polyhedra more rigorously. For example,

- A Regular solid
- A convex solid with polyhedral faces
- A surface consisting of a system of polygons
- *etc.*

Lakatos has called this strategy “*monster-barring*.”

Wittgenstein: “self-referential” propositions lead to inconsistency in mathematics

All truth passes through three stages:

First, it is ridiculed.

Second, it is violently opposed.

Third, it is accepted as being self-evident.

Arthur Schopenhauer (1788-1860)

Early on, Wittgenstein correctly noted that Gödel's “self-referential” proposition infers inconsistency in mathematics:ⁱ

Let us suppose [Gödel's writings are correct and therefore] I proveⁱⁱ the improvability (in Russell's system) of [Gödel's “self-referential” propositionⁱⁱⁱ] P ; [*i.e.*, $\vdash \neg P$ where $P \Leftrightarrow \neg P$] then by this proof I have proved P [*i.e.*, $\vdash P$]. Now if this proof were one in Russell's system [*i.e.*, $\vdash P$] — I should in this case have proved at once that it belonged [*i.e.*, $\vdash P$] and did not belong [*i.e.*, $\vdash \neg P$] because $\neg P \Leftrightarrow \vdash P$] to Russell's system.

But there is a contradiction here! [*i.e.*, $\vdash P$ and $\vdash \neg P$]

According to [Monk 2007]:¹²

Wittgenstein hoped that his work on mathematics would have a cultural impact, that it would threaten the attitudes that prevail in logic, mathematics and the philosophies of them. On this measure it has been a spectacular failure.



Ludwig Wittgenstein

Unfortunately, recognition of the worth of Wittgenstein's work on mathematics came long after his death. For decades, professional work logicians

ⁱ Wittgenstein in 1937 published in Wittgenstein 1956, p. 50e and p. 51e]

ⁱⁱ Wittgenstein was granting the supposition that Gödel had proved inferential undecidability (sometimes called “incompleteness”) of Russell's system, *e.g.*, $\vdash \neg P$. However, inferential undecidability is easy to prove using the “self-referential” proposition P :

Proof. Suppose to obtain a contradiction that $\vdash P$. Both of the following can be inferred:

1) $\vdash \neg P$ from the hypothesis because $P \Leftrightarrow \neg P$

2) $\vdash P$ from the hypothesis by Adequacy.

But 1) and 2) are a contradiction. Consequently, $\vdash \neg P$ follows from proof by contradiction.

ⁱⁱⁱ constructed using a Υ fixed point exploiting an untyped sentences for mathematics

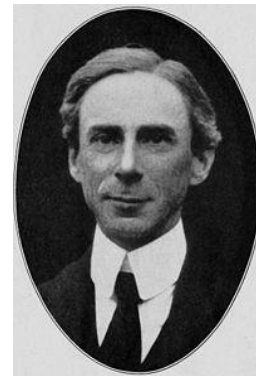
mistakenly believed that they had been completely victorious over Wittgenstein.

contra Gödel et. al

*“Men... think in herds ...
they only recover their senses slowly, and one by one.”*
Charles Mackay

That mathematics self proves its own consistency contradicts the [Gödel 1931] article claiming (using a “self-referential” propositionⁱ “*I'm unprovable.*”) that mathematics cannot prove its own consistency.

One resolution is not to have “self-referential” propositions.ⁱⁱ This can be achieved by carefully arranging the rules using types so that “self-referential” propositions cannot be constructed as shown below.ⁱⁱⁱ The basic idea is to use types for propositions so that **Y** fixed points do not exist and consequently cannot be used to construct “self-referential” propositions. The motivation is that Mathematical propositions should be grounded on mathematical objects, e.g., complex numbers, rectangles, etc. Mathematical propositions are not free-floating and solipsistic.



Bertrand Russell

However, there is a crucial difference between how Russell used types and the method used in Direct Logic. Russell attempted to use types as the fundamental mechanism for preventing inconsistencies by restricting the domain of mathematics to object that can be described by a strict hierarchical type system. However, he ran into trouble because his type mechanism was too strict and prevented ordinary mathematical reasoning.^{iv}

ⁱ constructed using a **Y** fixed point that does not exist for typed Mathematical sentences
ⁱⁱ There do not seem to be any practical uses of “self-referential” propositions in the mathematical foundations of Computer Science.
ⁱⁱⁱ It is important to note that disallowing “self-referential” propositions does not place restrictions on recursion in computation, e.g., the Actor Model, untyped lambda calculus, etc.
^{iv} In order to be able to carry out ordinary mathematical reasoning, Russell introduced an (unmotivated) patch called “ramified types” that collapsed the type hierarchy.

In this paper, types are used to prevent the construction of “self-referential” sentences and to provide the foundations for sets. The difficulties encountered by Russell are avoided as follows:

- having integers¹³ as primitive axiomatized using the full Dedekind/Peano axioms
- constructing sets from the characteristic functions of typed functions
- types are used to resolve the usual paradoxes with sets, *e.g.*, there is no set of all sets, *etc.*¹⁴

The above approach provides a very usable foundation for ordinary mathematical reasoning. Combining types and sets as the foundation has the advantage of using the strengths of each without the limitations of trying to use just one because each can be used to make up for the limitations of the other. The key idea is compositionality, *i.e.*, composing new entities from others. Types can be composed from other types and sets can be composed from other sets.ⁱ

Computer Scientists did not initially set out to overthrow Gödel's approach to incompleteness. However over time, Gödel's sentence "*I'm unprovable.*" became an obstacle to the Computer Scientist's security requirements because its construction using **Y** fixed points introduces inconsistency into Mathematics. Fortunately, strong parameterized types enabled them to show that Gödel's sentence is neither valid nor needed in mathematics. However, once Gödel's sentence was thrown out, whether or not mathematics can prove its consistency once again became an open question. At this point, the Computer Scientists discovered a remarkably simple proof that mathematics does formally prove its consistency. So Computer Science is in relatively good shape and is coming to a consensus around using strong parameterized types for the mathematical foundations of Computer Science and also using them in the foundations of their programming languages.

ⁱ Compositionality avoids standard foundational paradoxes. For example, Direct Logic composes sentences from others using types so there are no “self-referential” propositions.

So where does this leave traditional senior philosophers and logicians who previously thought that they *owned* this subject matter because of their previous publications? There are at least two possibilities:

- The field splits and senior traditionalists try to ignore the Computer Scientists' prestigious published volume and its reviews.
- Some younger philosophers and logicians join with the Computer Scientists pushing forward with strong parameterized types in foundations. At this point, the above Computer Scientists are firmly ensconced in their field and have a head start in that they have held two international symposia at Stanford and published a well-regarded volume of articles on their results in what is arguably the most prestigious academic series of volumes in the area. But there is still much work to be done!

Classical Direct Logic

“I suspect there are few today who share ... [the] belief that there should be a single overarching theory embracing all of mathematics.”
[Dowson 2006]

Classical Direct Logic must meet the following challenges:

- *Consistent* to avoid security holes
- *Powerful* so that computer systems can formalize all logical inferences
- *Principled* so that it can be easily learned by software engineers
- *Coherent* so that it hangs together without a lot of edge cases
- *Intuitive* so that humans can follow computer system reasoning
- *Comprehensive* to accommodate all forms of logical argumentation
- *Inconsistency Robust* to be applicable to pervasively inconsistent theories of practice with
 - Inconsistency Robust Direct Logic for logical inference about inconsistent information
 - Classical Direct Logic for Mathematics used in inconsistency-robust theories

In Direct Logic, unrestricted recursion is allowed in programs by using recursive definitions.

There are uncountably many Actors.¹⁵ For example, $\text{CreateReal}_\bullet[\]$ is a nondeterministic procedure that can return any real numberⁱ between 0 and 1 whereⁱⁱ

$\text{CreateReal}_\bullet[\] \equiv [(0 \text{ either } 1), \forall \text{Postpone } \text{CreateReal}_\bullet[\]]$

where

- $\text{CreateReal}_\bullet[\]$ is the result of sending the Actor CreateReal the message $[\]$
- $(0 \text{ either } 1)$ is the nondeterministic choice of 0 or 1,
- $[first, rest]$ is the list that begins with *first* and whose remainder is *rest*, and
- **Postpone** *expression* delays execution of *expression* until the value is needed.

Each $\text{CreateReal}_\bullet[\]$ is one of uncountably many Actors.

There are uncountably many propositions (because there is a different proposition for every real number). Consequently, there are propositions that are not the abstraction of any element of a denumerable set of sentences. For example, $p[x:\mathbb{R}] \equiv \lambda[y:\mathbb{R}] \rightarrow (y=x)$ defines a different predicate $p[x]$ for each real number x , which holds for only one real number, namely x .ⁱⁱⁱ

It is important to distinguish between sentences, and propositions. Sentences^{iv} (which without free variables) can be abstracted into propositions that can be asserted. Furthermore, terms^v can be abstracted into Actors (*i.e.* objects in mathematics).

ⁱ using binary representation.

ⁱⁱ Typically, a result returned by the non-deterministic procedure **Real** is not computable in the sense there is no computable deterministic procedure that can compute its digits.

ⁱⁱⁱ For example $(p[3])[y]$ holds if and only if $y=3$.

^{iv} which are grammar tree structures

^v which are grammar tree structures

Abstraction and parsing are becoming increasingly important in software engineering. *e.g.*,

- The execution of code can be dynamically checked against its documentation. Also Web Services can be dynamically searched for and invoked on the basis of their documentation.
- Use cases can be inferred by specialization of documentation and from code by automatic test generators and by model checking.
- Code can be generated by inference from documentation and by generalization from use cases.

Abstraction and parsing are needed for large software systems so that that documentation, use cases, and code can mutually speak about what has been said and their relationships.

For example:

Propositions

e.g. $\forall [n:\mathbb{N}] \rightarrow \exists [m:\mathbb{N}] \rightarrow m > n$

i.e., for every \mathbb{N} there is a larger \mathbb{N}

Sentences

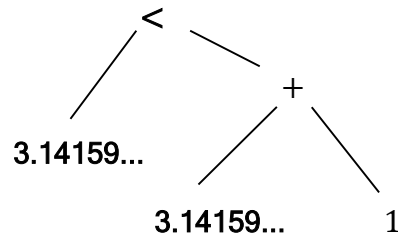
e.g. $(\forall [n:\mathbb{N}] \rightarrow (\exists [m:\mathbb{N}] \rightarrow (m > n)))$

i.e., the sentence that for every \mathbb{N} there is a larger \mathbb{N}

In Direct Logic, a sentence is a grammar tree (analogous to the ones used by linguists). Such a grammar tree has terminals that can be constants. And there are uncountably many constants, *e.g.*, the real numbers:

Of course, because the digits of 3.14159... are computable, there is a expression_1 such that $\lfloor \text{expression}_1 \rfloor = 3.14159\dots$ that can be used to create the sentence $(\text{expression}_1 < (\text{expression}_1 + 1))$.

However the sentence $(\text{expression}_1 < (\text{expression}_1 + 1))$ is not the same as $(3.14159\dots < (3.14159\dots + 1))$ because it does not have the same vocabulary and it is a much larger sentence that has many terminals whereas $(3.14159\dots < (3.14159\dots + 1))$ has just 3 terminals:



Consequently, sentences *cannot* be enumerated.¹⁶

Note: Type theory of Classical Direct Logic is much stronger than constructive type theory with constructive logic¹⁷ because Classical Direct Logic has all of the power of Classical Mathematics.

Mathematics self proves that it is open

“Although everything mathematical is formalizable, it is nonetheless impossible to formalize all of mathematics in a *single* formal system.”

[Gödel 1935]

A fundamental axiom of Mathematics is for each order: \mathbb{N}_+ and P : **Proposition** $\langle \text{order} \rangle^{\mathbb{N}}$ the following Peano/Dedekind induction axiom holds:
 $(P[0] \wedge \forall [i:\mathbb{N}] \rightarrow P[i] \Rightarrow P[i+1]) \Leftrightarrow \forall [i:\mathbb{N}] \rightarrow P[i]$

Mathematics proves that it is open in the sense that it can prove that its proofs cannot be provably computationally enumerated:¹⁸

Theorem \vdash Mathematics is Open, i.e.,

$\vdash \neg \text{ProofsComputationallyEnumerable}$

Proof.ⁱ

Suppose to obtain a contradiction that it is possible to prove closure, i.e.,

$\vdash \text{ProofsComputationallyEnumerable}$. Then there is a provably computable total procedure $\text{ProofsEnumerator}:\mathbb{N} \rightarrow \text{Proof}$ such that it is provable that

$$\forall [p:\text{Proof}] \rightarrow \exists [i:\mathbb{N}] \rightarrow \text{ProofsEnumerator} \cdot [i] = p$$

$$\forall [i:\mathbb{N}] \rightarrow \text{ProofsEnumerator} \cdot [i] : ?\text{Proof}$$

A subset of the proofs are those proving that certain procedures $\mathbb{N} \rightarrow \mathbb{N}$ are total. Consequently, there is a

$\text{ProvedTotalsEnumerator}:\mathbb{N} \rightarrow (\mathbb{N} \rightarrow \mathbb{N})$ that enumerates the provably total computable procedures $\mathbb{N} \rightarrow \mathbb{N}$ that can be used in the implementation of the following procedure:

$$\text{Diagonal} \cdot [i:\mathbb{N}]:\mathbb{N} \equiv 1 + (\text{ProvedTotalsEnumerator} \cdot [i]) \cdot [i]$$

Consequently:

- Diagonal *is* a proved total procedure because it is implemented using computable proved total procedures.
- Diagonal *is not* a proved total procedure because it differs from every other computable proved total procedure.

The above contradiction completes the proof.

[Franzén 2004] argued that mathematics is inexhaustible because of inferential undecidabilityⁱⁱ of mathematical theories. The above theorem that mathematics is open provides another independent argument for the inexhaustibility of mathematics.

ⁱ This argument appeared in [Church 1934] expressing concern that the argument meant that there is “no sound basis for supposing that there is such a thing as logic.”

ⁱⁱ See section immediately below.

Mathematical provability is computationally undecidable

Mathematics proves that provability in mathematics is computationally undecidable:¹⁹

Theorem $\vdash \neg \text{ProvabilityComputationallyDecidable}$, *i.e.*,

$\vdash \neg \text{ProvabilityComputationallyDecidable}$

Proof. If provability in Mathematicsⁱ were computationally decidable then, the halting problem would be computationally decidable.

Completeness of inference versus inferential undecidability of closed mathematical theories

A closed mathematical theory is an extension of mathematics whose proofs are computationally enumerable. For example, group theory is obtained by adding the axioms of groups to Classical Direct Logic. Similarly, the closed mathematical theory \mathbf{N} has the usual Peano/Dedekind axioms including the induction axiom.

Theorem The proposition $\text{ProofsComputationallyEnumerable}_{\mathbf{N}}$ is true but unprovable in \mathbf{N} , *i.e.*, both of the following hold:

- $\vDash_{\mathbf{N}} \text{ProofsComputationallyEnumerable}_{\mathbf{N}}$
- $\not\vdash_{\mathbf{N}} \text{ProofsComputationallyEnumerable}_{\mathbf{N}}$

Proof:

Mathematics can make use of its types (*i.e.*, $\text{Proposition}_{\mathbf{N}}\langle\omega\rangle$ ⁱⁱ, $\text{Sentence}_{\mathbf{N}}\langle\omega\rangle$ ⁱⁱⁱ and $\text{Domain}_{\mathbf{N}}\langle\omega\rangle$ ^{iv}) in the enumeration of proofs of \mathbf{N} without violating the type rules of Mathematics. Consequently,

$\vDash_{\mathbf{N}} \text{ProofsComputationallyEnumerable}_{\mathbf{N}}$

ⁱ Since Mathematics has all the power of \mathbf{N} .

ⁱⁱ $\text{Proposition}_{\mathbf{N}}\langle\omega\rangle \equiv$

$\text{Proposition}_{\mathbf{N}}\langle 1 \rangle \oplus \text{Proposition}_{\mathbf{N}}\langle 2 \rangle \oplus \text{Proposition}_{\mathbf{N}}\langle 3 \rangle \oplus \dots$

ⁱⁱⁱ $\text{Sentence}_{\mathbf{N}}\langle\omega\rangle \equiv$

$\text{Sentence}_{\mathbf{N}}\langle 1 \rangle \oplus \text{Sentence}_{\mathbf{N}}\langle 2 \rangle \oplus \text{Sentence}_{\mathbf{N}}\langle 3 \rangle \oplus \dots$

^{iv} $\text{Domain}_{\mathbf{N}}\langle\omega\rangle \equiv \text{Domain}_{\mathbf{N}}\langle 1 \rangle \oplus \text{Domain}_{\mathbf{N}}\langle 2 \rangle \oplus \text{Domain}_{\mathbf{N}}\langle 3 \rangle \oplus \dots$

where

$\text{Domain}_{\mathbf{N}}\langle 1 \rangle \equiv \mathbf{N}$

$\text{Domain}_{\mathbf{N}}\langle n+1 \rangle \equiv \text{Domain}_{\mathbf{N}}\langle n \rangle^{\mathbf{N}}$

Suppose to obtain a contradiction that

$$\vdash_{\mathbb{N}} \text{ProofsComputationallyEnumerable}_{\mathbb{N}}$$

Then there is a provable in \mathbb{N} computable total procedure $\text{ProofsEnumerator}_{\mathbb{N}}: [\mathbb{N}] \mapsto \text{Proof}_{\mathbb{N}}$ such that it is provable in \mathbb{N} that

$$\forall [p: \text{Proof}_{\mathbb{N}}] \mapsto \exists [i: \mathbb{N}] \mapsto \text{ProofsEnumerator}_{\mathbb{N}}[i] = p$$

$$\forall [i: \mathbb{N}] \mapsto \text{ProofsEnumerator}_{\mathbb{N}}[i]: ?\text{Proof}_{\mathbb{N}}$$

A subset of the proofs in \mathbb{N} are those proving that certain procedures $[\mathbb{N}] \mapsto \mathbb{N}$ are total. Consequently, there is a procedure

$$\text{ProvedTotalsEnumerator}_{\mathbb{N}}: [\mathbb{N}] \mapsto ([\mathbb{N}] \mapsto \mathbb{N})$$

that enumerates the provable in \mathbb{N} total computable procedures $[\mathbb{N}] \mapsto \mathbb{N}$ that can be used in the implementation of the following procedure:

$$\text{Diagonal}_{\mathbb{N}}[i: \mathbb{N}]: \mathbb{N} \equiv 1 + (\text{ProvedTotalsEnumerator}_{\mathbb{N}}[i])[i]$$

Consequently:

- Diagonal is a provable in \mathbb{N} total procedure because it is implemented using computable provable in \mathbb{N} total procedures.
- Diagonal is not a provable in \mathbb{N} total procedure because it differs from every other computable provable in \mathbb{N} total procedure.

The above contradiction completes the proof.

Note that the closed mathematical theory \mathbb{N} is inferentially undecidable²⁰ with respect to $\text{ProofsComputationallyEnumerable}_{\mathbb{N}}$ does not mean Mathematical *incompleteness* with respect to the information that can be inferred about theory \mathbb{N} because

- $\vdash_{\mathbb{N}} \text{ProofsComputationallyEnumerable}_{\mathbb{N}}$
- $\vdash \not\vdash_{\mathbb{N}} \text{ProofsComputationallyEnumerable}_{\mathbb{N}}$

Theorem $\vdash_{\mathbb{N}} \text{Consistent}_{\mathbb{N}}$

Proof: Suppose to derive an inconsistency that $\neg \text{Consistent}_{\mathbb{N}}$. By the definition of inconsistency for \mathbb{N} , there is some proposition of \mathbb{N} , Ψ such that $\vdash_{\mathbb{N}} (\Psi \wedge \neg \Psi)$. By Existential Elimination, there is some proposition Ψ_0 such that

$$\vdash_{\mathbb{N}} (\Psi_0 \wedge \neg \Psi_0) \text{ which can be used to infer in } \mathbb{N} \text{ that } (\Psi_0 \wedge \neg \Psi_0).$$

The above contradiction completes the proof.

Information Invarianceⁱ is a *fundamental* technical goal of logic consisting of the following:²¹

1. *Soundness of inference*: information is not increased by inferenceⁱⁱ
2. *Completeness of inference*: all information that necessarily holds can be inferred

ⁱ Closely related to conservation laws in physics

ⁱⁱ E.g. inconsistent information does not infer nonsense.

Overview

Contradiction	Outcome
Church discovered to his dismay that if theorems of mathematics are postulated to be computationally enumerable, then mathematics is inconsistent.	Proofs of mathematics cannot be computationally enumerated and mathematics is open and inexhaustible. But theorems of a particular theory can be postulated to be computationally enumerable.
Using \mathbf{Y} fixed points to construct a “self-referential” sentence for untyped mathematical sentences, [Gödel 1931] claimed that mathematics cannot prove its own consistency. However, it is pointed out in this paper that mathematics easily proves its own consistency.	The contradiction can be resolved by using types for sentences of mathematics so that of \mathbf{Y} fixed points do not exist.
Using \mathbf{Y} fixed points to construct a “self-referential” sentence using an untyped mathematical sentences, [Gödel 1931] claimed to prove inferential undecidability (sometimes called “incompleteness”) for mathematics. However, such “self-referential” sentences lead to inconsistency in mathematics.	In Classical Direct Logic, the sentence $\text{ProofsComputationallyEnumerable}_{\mathbf{N}}$ is true but unprovable in \mathbf{N} assuming that \mathbf{N} is consistent.
In Computer Science, it is important that the Natural Numbers (\mathbf{N}) be axiomatized in a way that does not allow integers (e.g. infinite ones) in models of the axioms. However, it is impossible to properly axiomatize \mathbf{N} using first-order logic.	Using Classical Direct Logic, \mathbf{N} can be axiomatized in such a way that all models are uniquely isomorphic to \mathbf{N} [Dedekind 1888, Peano 1889]. Consequently, there are no infinite integers in models of the axioms.
First-order logic is unsuitable as the foundation of mathematics for Computer Science: <ul style="list-style-type: none"> • Some theorems of ordinary classical mathematics cannot be proved. • Some ordinary theorems useful in Computer Science cannot be proved. • There are undesirable models of mathematical theories (see above). 	Classical Direct Logic is suitable as the foundation of mathematics for Computer Science: <ul style="list-style-type: none"> • All ordinary theorems of classical mathematics can be proved. • All ordinary theorems useful in Computer Science can be proved • There are no undesirable models of mathematical theories.

Conclusion

The problem is that today some knowledge still feels too dangerous because our times are not so different to Cantor or Boltzmann or Gödel's time. We too feel things we thought were solid being challenged; feel our certainties slipping away. And so, as then, we still desperately want to cling to a belief in certainty. It makes us feel safe. ...

Are we grown up enough to live with uncertainties or will we repeat the mistakes of the twentieth century and pledge blind allegiance to another certainty.

Malone [2007]

The world always needs heretics to challenge the prevailing orthodoxies. We are lucky that we can be heretics today without any danger of being burned at the stake. But unfortunately I am an old heretic. Old heretics do not cut much ice. When you hear an old heretic talking, you always say, "Too bad he has lost his marbles."

What the world needs is young heretics. I am hoping that one or two of you people in the audience may fill that role.

Dyson [2005]

The closed mathematical theory \mathbb{N} has the usual Peano/Dedekind axioms including the induction axiom. Consequently, the proposition $\text{ProofsComputationallyEnumerable}_{\mathbb{N}}$ is true but unprovable in \mathbb{N} .

Information Invariance is a fundamental technical goal of logic consisting of the following:

1. *Soundness of inference*: information is not increased by inference
2. *Completeness of inference*: all information that necessarily holds can be inferred.

That the closed mathematical theory \mathbb{N} is inferentially undecidableⁱ with respect to $\text{ProofsComputationallyEnumerable}_{\mathbb{N}}$ does not mean incompleteness with respect to the information that can be inferred because

- $\vdash \neg \text{ProofsComputationallyEnumerable}_{\mathbb{N}}$
- $\vdash \neg \neg \text{ProofsComputationallyEnumerable}_{\mathbb{N}}$

Computer Science needs a rigorous foundation for all of mathematics that enables computers to carry out all reasoning without human intervention.²² [Frege 1879] was a good start, but it foundered on the issue of being well-founded. [Russell 1925] attempted basing foundations entirely on types, but foundered on the issue of being expressive enough to carry to some common

ⁱ sometimes called "incomplete"

mathematical reasoning. [Church 1932, 1933] attempted basing foundations entirely on untyped higher-order functions, but foundered because it allowed “self-referential” propositions leading to contradictions [Kleene and Rosser 1935]. Presently, Isabelle [Paulson 1989] and Coq [Coquand and Huet 1986] are founded on types and do not allow theories to reason about themselves. Classical Direct Logic is a foundation for all of mathematical reasoning based on both sets (for well-founded structures) and types (to provide grounding for concepts) that allows general inference about reasoning.

[Gödel 1931] claimed inferential undecidabilityⁱ results for mathematics using a “self-referential” proposition constructed using \mathbf{Y} fixed points for untyped mathematical sentences. In opposition to Wittgenstein's correct argument that “self-referential” propositions lead to contradictions in mathematics, Gödel later claimed that his results were for a cut-down first-order theory of Peano numbers. However, first-order logic is not a suitable foundation for Computer Science because of the requirement that computer systems be able to carry out all reasoning without requiring human intervention (including reasoning about their own inference systems).

Following [Frege 1879, Russell 1925, and Church 1932-1933], Direct Logic was developed and then investigated “self-referential” propositions with the following results.

- Formalization of Wittgenstein's proof that Gödel's “self-referential” proposition leads to contradiction in mathematics. So the consistency of mathematics had to be rescued against Gödel's “self-referential” propositions. The “self-referential” proposition used in results of [Curry 1941] and [Löb 1955] also lead to inconsistency in mathematics. Consequently, mathematics had to be rescued against these “self-referential” propositions as well.

ⁱ sometimes called “incompleteness”

- Self-proof of the consistency of mathematics. Consequently, mathematics had to be rescued against the claim [Gödel 1931] that mathematics cannot prove its own consistency. Also, it became an open problem whether mathematics proves its own consistency, which was resolved by the author discovering an amazing simple proof.²³ A solution is to bar “self-referential” propositions using typed sentences of mathematics.²⁴ However, Establishment Philosophers have very reluctant to accept the solution.

According to [Dawson 2006]:²⁵

- *Gödel’s results altered the mathematical landscape, but they did **not** “produce a debacle”.*
- *There is **less** controversy today over mathematical foundations than there was **before** Gödel’s work.*

However, Gödel’s writings have produced a controversy of a very different kind from the one discussed by Dawson:

- Gödel’s claim that mathematics cannot prove its own consistencyⁱ has been disproved.
- Consequently, Gödel’s writings have led to increased controversy over mathematical foundations.

The development of Direct Logic has strengthened the position of working mathematicians as follows:ⁱⁱ

- Allowing freedom from the philosophical dogma of the First-Order Thesis
- Providing a usable type theory for all of Mathematics
- Allowing theories to freely reason about theories
- Providing Inconsistency Robust Direct Logic for safely reasoning about theories of practice that are (of necessity) pervasively inconsistent.

ⁱ Gödel’s writing was accepted doctrine by Establishment Philosophers for over eight decades

ⁱⁱ Of course, Direct Logic must preserve as much previous learning as possible.

Sociology of Foundations

“Faced with the choice between changing one’s mind and proving that there is no need to do so, almost everyone gets busy on the proof.”
John Kenneth Galbraith [1971 pg. 50]

“Max Planck, surveying his own career in his Scientific Autobiography [Planck 1949], sadly remarked that ‘a new scientific truth does not triumph by convincing its opponents and making them see the light, but rather because its opponents eventually die, and a new generation grows up that is familiar with it.’ ”
[Kuhn 1962]

The inherently social nature of the processes by which principles and propositions in logic are produced, disseminated, and established is illustrated by the following issues with examples:²⁶

- **The formal presentation of a demonstration (proof) has not lead automatically to consensus.** Formal presentation in print and at several different professional meetings of the extraordinarily simple proof in this paper have not lead automatically to consensus about the theorem that “Mathematics is Consistent”. New results can sound crazy to those steeped in conventional thinking. Paradigm shifts often happen because conventional thought is making assumptions taken as dogma. As computer science continues to advance, such assumptions can get in the way and have to be discarded.
- **There has been an absence of universally recognized central logical principles.** Disputes over the validity of the Principle of Excluded Middle led to the development of Intuitionistic Logic, which is an alternative to Classical Logic.
- **There are many ways of doing logic.** One view of logic is that it is about *truth*; another view is that it is about *argumentation* (i.e. proofs).²⁷
- **Argumentation and propositions have be variously (re-)connected and both have been re-used.** Church's paradox is that assuming theorems of mathematics are computationally enumerable leads to contradiction. In this papers, the paradox is transformed into the fundamental principle that “Mathematics is Open” (*i.e.* it is a theorem of mathematics that the proofs of mathematics are not computationally enumerable) using the argument used in Church's paradox.

- **New technological developments have cast doubts on traditional logical principles.** The pervasive inconsistency of modern large-scale information systems has cast doubt on classical logical principles, *e.g.*, Excluded Middle.²⁸
- **Political actions have been taken against views differing from the Establishment Philosophers.** According to [Kline 1990, p. 32], Hippasus was literally thrown overboard by his fellow Pythagoreans “...for having produced an element in the universe which denied the...doctrine that all phenomena in the universe can be reduced to whole numbers and their ratios.” Fearing that he was dying and the influence that Brouwer might have after his death, Hilbert firedⁱ Brouwer as an associate editor of *Mathematische Annalen* because of “incompatibility of our views on fundamental matters”ⁱⁱ *e.g.*, Hilbert ridiculed Brouwer for challenging the validity of the Principle of Excluded Middle.

Some philosophers celebrated Gödel's writings because their jobs depended on adherence to the first-order dogma. Since philosophers couldn't prove anything significant about practical mathematical theories, they cut them down to unrealistic first-order theories where results could be proved (*e.g.* compactness) that did not hold for practical mathematical theories. In the famous words of Upton Sinclair:

*“It is difficult to get a man to understand something,
when his salary depends on his not understanding it.”*

Establishment Philosophers have often ridiculed dissenting views and attempted to limit their distribution by political means.²⁹

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ⁱ in an unlawful way (Einstein, a member of the editorial board, refused to support Hilbert's action)

ⁱⁱ Hilbert letter to Brouwer, October 1928

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ⁱ Please see section on Berry's Paradox in the historical appendix.

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Appendix 1. Notation of Classical Direct Logic

- *Type* i.e., a **Type** is a *discrimination* of the following:
 - τ :**Type** $\langle\tau\rangle$ ⁱ
 - **Boolean**:**Type** $\langle\text{Boolean}\rangle$ ³⁰ and \mathbf{N} ³¹:**Type** $\langle\mathbf{N}\rangle$
 - If order: \mathbf{N}_+ , then
Proposition $\langle\text{order}\rangle$:**Type** $\langle\text{Proposition}\langle\text{order}\rangle\rangle$ and
Sentence $\langle\text{order}\rangle$:**Type** $\langle\text{Sentence}\langle\text{order}\rangle\rangle$ ii
 - $\tau_1 \circ \tau_2$:**Type** $\langle\tau_1 \circ \tau_2\rangle$ ³², $[\tau_1, \tau_2]$:**Type** $\langle[\tau_1, \tau_2]\rangle$ ³³,
 $[\tau_1] \mapsto \tau_2$:**Type** $\langle[\tau_1] \mapsto \tau_2\rangle$ ⁱⁱⁱ and $\sigma_2^{\sigma_1}$:**Type** $\langle\tau_1 \circ \tau_2\rangle$ ^{iv}
 - **Set** $\langle\tau\rangle$:**Type** $\langle\text{Set}\langle\tau\rangle\rangle$
- *Propositions*, i.e., a **Proposition** is a *discrimination* of the following where order: \mathbf{N}_+ :
 - If Φ :**Proposition** $\langle\text{order}\rangle$, then $\neg\Phi$:**Proposition** $\langle\text{order}\rangle$.
 - If Φ, Ψ :**Proposition** $\langle\text{order}\rangle$, then
 $\Phi \wedge \Psi, \Phi \vee \Psi, \Phi \Rightarrow \Psi, \Phi \Leftrightarrow \Psi$:**Proposition** $\langle\text{order}\rangle$.
 - If p :**Boolean** and Φ, Ψ :**Proposition** $\langle\text{order}\rangle$, then
 $(p \diamond \text{True} \text{;} \Phi_1 \boxtimes \text{False} \text{;} \Phi_2)$:**Proposition** $\langle\text{order}\rangle$.³⁴
 - If x_1, x_2 : τ , then $x_1 = x_2, x_1 \sqsubseteq x_2, x_1 \subseteq x_2$:**Proposition** $\langle 1 \rangle$.
 - If x_1 : τ_1 and x_2 : τ_2 , then $x_1 \in x_2, x_1 ? x_2$:**Proposition** $\langle 1 \rangle$.
 - If x : τ and p :**Proposition** $\langle\text{order}\rangle$ ^{τ} , then
 $p[[x]]$:**Proposition** $\langle\text{order}+1\rangle$ ^v
 - If p :**Proof**, T :**Theory**, and Φ_1 to Φ_n :**Proposition** $\langle\text{order}\rangle$,
then $(\Phi_1, \dots, \Phi_k \vdash_T^p \Phi_{k+1}, \dots, \Phi_n)$:**Proposition** $\langle\text{order}\rangle$.³⁵
 - If s :**Sentence** $\langle\text{order}\rangle$ with no free variables, then
 $[s]$:**Proposition** $\langle\text{order}\rangle$.

ⁱ The type of τ means that “self-referential” types cannot be constructed in Direct Logic.

$$\tau_1 : ?\text{Type}\langle\tau_2\rangle \Rightarrow \tau_1 \sqsubseteq \tau_2$$

ⁱⁱ x :**Sentence** $\langle\text{order}\rangle \Leftrightarrow \exists[\text{order}:\mathbf{N}_+] \rightarrow x$:**Sentence** $\langle\text{order}\rangle$

If order1 \leq order2, then x :**Sentence** $\langle\text{order}1\rangle \Rightarrow x$:**Sentence** $\langle\text{order}2\rangle$

ⁱⁱⁱ Type of computable procedures from τ_1 into τ_2 .

If f : $([\tau_1] \mapsto \tau_2)$ and x : τ_1 , then $f.[x]$: τ_2 .

^{iv} Type of computable procedures from τ_1 into τ_2 .

If f : $\tau_2^{\sigma_1}$ and x : τ_1 , then $f[x]$: τ_2 .

^v The type of $p[[x]]$ means that “self-referential” propositions p cannot be constructed in Direct Logic.

Grammar trees (*i.e.* expressions and sentences) are defined as follows :

- **Expressions**, *i.e.*, an **Expression** $\langle\tau\rangle$ is a *discrimination* of the following:
 - **Constant** $\langle\tau\rangle$:**Type** \langle **Constant** $\langle\tau\rangle\rangle$.
 - **(Boolean)**:**Constant** \langle **Type** \langle **Boolean** $\rangle\rangle$ ³⁶,
 - **(N)**:**Constant** \langle **Type** \langle **N** $\rangle\rangle$ ³⁷,
 - **(Theory)**:**Constant** \langle **Type** \langle **Theory** $\rangle\rangle$ and
 - **(Proof)**:**Constant** \langle **Type** \langle **Proof** $\rangle\rangle$
 - If order:**N**₊, then
(Proposition \langle order \rangle):**Constant** \langle **Proposition** \langle order $\rangle\rangle$
 - If order:**N**₊, then
(Sentence \langle order \rangle):**Constant** \langle **Sentence** \langle order $\rangle\rangle$
 - If **x**:**Constant** $\langle\tau\rangle$, then **x**:**Expression** $\langle\tau\rangle$.
 - **Expression** $\langle\tau\rangle$:**Type** \langle **Expression** $\langle\tau\rangle\rangle$.
 - If **x**:**Variable** $\langle\tau\rangle$, then **x**:**Expression** $\langle\tau\rangle$.
 - If for **i** in **1** to **n**, **f_i**:**Variable** $\langle\sigma_1^{\tau_i}\rangle$ in **d_i** and **y**, **x_i**:**Variable** $\langle\tau_i\rangle$ in **d_i**, **d_i**:**Expression** $\langle\sigma_i\rangle$, and **y**:**Expression** $\langle\tau\rangle$, then
(Let f₁[x₁:τ₁]:σ₁≡d₁, ... , f_n[x_n:τ_n]:σ_n≡d_n³⁸. y):Expression** $\langle\tau\rangle$.**
 - If for **i** in **1** to **n**, **x_i**:**Variable** $\langle\tau_i\rangle$ in **d_i** and **y**, **d_i**:**Expression** $\langle\sigma_i\rangle$, and **y**:**Expression** $\langle\tau\rangle$, then
(Let x₁:τ₁≡d₁, ... , x_n≡d_n³⁹. y):Expression** $\langle\tau\rangle$.**
 - If **e₁**:**Expression** $\langle\tau_1\rangle$ and **e₂**:**Expression** $\langle\tau_2\rangle$, then
(e₁⊙e₂):Expression**** $\langle\tau_1\odot\tau_2\rangle$, **([e₁, e₂]):**Expression**** $\langle[\tau_1, \tau_2]\rangle$,
 - **([e₁]→e₂):**Expression**** \langle **Type** \langle **[τ₁]→τ₂** $\rangle\rangle$ and
(e₂^{e₁}):Expression**** \langle **Type** \langle **σ₂^{σ_{e₁}}** $\rangle\rangle$.
 - If **t₁**:**Expression** \langle **Boolean** \rangle , **t₂**, **t₃**:**Expression** $\langle\tau\rangle$, then
(t₁⊕True: t₂⊖False: t₃):Expression**** $\langle\tau\rangle$.⁴⁰
 - If **t**:**Expression** $\langle\tau_2\rangle$ and **x**:**Variable** $\langle\tau_1\rangle$ in **t**⁴¹, then
(λ[x:τ₁]:t):Expression**** $\langle\sigma_2^{\sigma_1}\rangle$.
 - If **e**:**Expression** $\langle\sigma_2^{\sigma_1}\rangle$ and **x**:**Expression** $\langle\tau_1\rangle$, then
(e[x]):Expression**** $\langle\tau_2\rangle$.
 - If **e**:**Expression** \langle **[τ₁]→τ₂** \rangle and **x**:**Expression** $\langle\tau_1\rangle$, then
(e.[x]):Expression**** $\langle\tau_2\rangle$.
 - If **e**:**Expression** $\langle\tau\rangle$ with no free variables, then **[e]:τ**.

- **Sentences**, i.e., a **Sentence** is a *discrimination* of the following where order: \mathbb{N}_+ :
 - If x :**Variable** \langle **Sentence** \langle order $\rangle\rangle$, then (x) :**Sentence** \langle order+1 \rangle .ⁱ
 - If s_1 :**Sentence** \langle order \rangle , then $(\neg s_1)$:**Sentence** \langle order \rangle .
 - If s_1, s_2 :**Sentence** \langle order \rangle , then $(s_1 \wedge s_2), (s_1 \vee s_2), (s_1 \Rightarrow s_2), (s_1 \Leftrightarrow s_2)$:**Sentence** \langle order \rangle .
 - If t :**Expression** \langle **Boolean** \rangle , s_1, s_2 :**Sentence** \langle order \rangle , then $(t \spadesuit \text{True} \textcircled{\ast} s_1 \boxtimes \text{False} \textcircled{\ast} s_2)$:**Sentence** \langle order \rangle .⁴²
 - If t_1 :**Expression** \langle τ \rangle and t_2 :**Expression** \langle τ \rangle , then $(t_1 = t_2), (t_1 \sqsubseteq t_2), (t_1 \sqsubseteq\!\!\sqsubseteq t_2)$:**Sentence** \langle 1 \rangle .
 - If t_1 :**Expression** \langle τ_1 \rangle and t_2 :**Expression** \langle τ_2 \rangle , then $(t_1 \in t_2), (t_1 : ? t_2)$:**Sentence** \langle 1 \rangle .
 - If x :**Variable** \langle τ_1 \rangle in s^{43} and s :**Sentence** \langle order \rangle , then $(\forall [x:\tau_1] \rightarrow s), (\exists [x:\tau_1] \rightarrow s)$:**Sentence** \langle order \rangle .
 - If x :**Expression** \langle τ \rangle and p :**Sentence** \langle order \rangle^{τ} , then $(p[[x]])$:**Sentence** \langle order+1 \rangle .ⁱⁱ
 - If T :**Expression** \langle **Theory** \rangle , s_1 to s_n :**Sentence** \langle order \rangle and p :**Expression** \langle **Proof** \rangle , then $(s_1, \dots, s_k \vdash_{\frac{p}{T}} s_{k+1}, \dots, s_n)$:**Sentence** \langle order \rangle .

ⁱ The type of (x) means that “self-referential” sentences cannot be constructed in Direct Logic.

ⁱⁱ The type of $(p[[x]])$ means that “self-referential” sentences cannot be constructed in Direct Logic.

Foundations with strong parameterized types

Everyone is free to elaborate [their] own foundations. All that is required of [a] Foundation of Mathematics is that its discussion embody absolute rigor, transparency, philosophical coherence, and addresses fundamental methodological issues.

[Nielsen 2014]

Classical Direct Logic develops foundations for mathematics by deriving sets⁴⁴ from types⁴⁵ and the Peano/Dedekind axioms for the integers to encompass all of standard mathematics including the reals, analysis, geometry, *etc.*⁴⁶

For each order: \mathbf{N}_+ and $P:\mathbf{Proposition}\langle\text{order}\rangle^{\mathbf{N}}$, the following categorical Peano/Dedekind induction axiom holds:

$$(P[0] \wedge \forall[i:\mathbf{N}] \rightarrow P[i] \Rightarrow P[i+1]) \Leftrightarrow \forall[i:\mathbf{N}] \rightarrow P[i]$$

Type Choice

$$\forall[f:\sigma^{\tau}] \rightarrow \exists[\text{choice}:\sigma^{\tau}] \rightarrow \forall[x:\tau] \rightarrow (\exists[y:\sigma] \rightarrow f[x]:?\sigma) \Leftrightarrow \text{choice}[x]:?\sigma$$

Natural Numbers and Real Numbers are Unique up to Isomorphismⁱ

“If the mathematical community at some stage in the development of mathematics has succeeded in becoming (informally) clear about a particular mathematical structure, this clarity can be made mathematically exact. . . usually by means of a full second-order language. Why must there be such a characterisation? Answer: if the clarity is genuine, there must be a way to articulate it precisely. If there is no such way, the seeming clarity must be illusory. Such a claim is of the character as the Church-Turing thesis, . . . for every particular structure developed in the practice of mathematics, there is [a] categorical characterization of it.”

[Isaacson 2007]

ⁱ and the isomorphism is unique

Theoremⁱ (Categoricity of \mathbb{N}):⁴⁷

If \mathbf{X} be a type satisfying the Dedekind/Peano categorical axioms for the natural numbers, then \mathbf{X} is isomorphic to \mathbb{N} ⁴⁸ which is more powerful than the cut-down first-order theory of the natural numbers.⁴⁹



Giuseppe Peano

Theorem (Categoricity of \mathbb{R}):

If \mathbf{X} is a type satisfying the Dedekind categorical axioms for the real numbers⁵⁰, then \mathbf{X} is isomorphic to \mathbb{R} , which is strictly more powerful than cut-down first-order theory.⁵¹

Classical Direct Logic is much stronger than first-order axiomatizations⁵² of set theory in that it provides categoricity for \mathbb{N} . Categoricity is very important in Computer Science so that there are no nonstandard elements in models of computational systems, *e.g.*, infinite integers and infinitesimal reals.⁵³



Richard Dedekind

Theorem (Model Soundness of \mathbb{N}): $(\vdash_{\mathbb{N}}\Psi) \Rightarrow \models_{\mathbb{N}}\Psi$

Proof: Suppose $\vdash_{\mathbb{N}}\Psi$. The conclusion immediately follows because the axioms for the theory \mathbb{N} hold in the model \mathbb{N} .

Sets defined using strong parameterized types

The type $\mathbf{Set}\langle\tau\rangle$ can be defined as follows:

$$\mathbf{Set}\langle\tau\rangle \equiv \mathbf{Boolean}^{\tau}$$

Of course set membership is defined as follows:

$$\forall [x:\tau, s:\mathbf{Set}\langle\tau\rangle] \rightarrow x \in s \Leftrightarrow s[x] = \mathbf{True}$$

ⁱ [Dedekind 1888, Peano 1889]

Theorem. $\text{Set}\langle\mathbb{N}\rangle$ is categorical via a (unique) isomorphism.

Proof: Suppose that \mathbf{Y} satisfies the axioms for sets of type \mathbb{N} . Then there some such \mathbf{X} that $\mathbf{Y}=\text{Set}\langle\mathbf{X}\rangle$ and \mathbf{X} is isomorphic to \mathbb{N} via the isomorphism $\text{Ix}:\mathbf{X}^{\mathbb{N}}$. Define the isomorphism $\text{ISet}\langle\mathbf{X}\rangle:\text{Set}\langle\mathbf{X}\rangle^{\text{Set}\langle\mathbb{N}\rangle}$ as follows for $s:\text{Set}\langle\mathbb{N}\rangle$:

$$\text{ISet}\langle\mathbf{X}\rangle[s:\text{Set}\langle\mathbb{N}\rangle]:\text{Set}\langle\mathbf{X}\rangle \equiv [j:\mathbb{N}] \rightarrow \text{Ix}[j]$$

$\text{ISet}\langle\mathbf{X}\rangle$ is a unique isomorphism:

- $\text{ISet}\langle\mathbf{X}\rangle$ is 1-1
- The range of $\text{ISet}\langle\mathbf{X}\rangle$ is $\text{Set}\langle\mathbf{X}\rangle$
- $\text{ISet}\langle\mathbf{X}\rangle$ is a homomorphism:
 - $\text{ISet}\langle\mathbf{X}\rangle[\{ \}] = \{ \} \mathbf{x}$
 - $\forall [s1,s2:\text{Set}\langle\mathbb{N}\rangle] \rightarrow \text{ISet}\langle\mathbf{X}\rangle[s1 \cup s2] = \text{ISet}\langle\mathbf{X}\rangle[s1] \cup \mathbf{x} \text{ISet}\langle\mathbf{X}\rangle[s2]$
 - $\forall [s1,s2:\text{Set}\langle\mathbb{N}\rangle] \rightarrow \text{ISet}\langle\mathbf{X}\rangle[s1 \cap s2] = \text{ISet}\langle\mathbf{X}\rangle[s1] \cap \mathbf{x} \text{ISet}\langle\mathbf{X}\rangle[s2]$
 - $\forall [s:\text{Set}\langle\mathbb{N}\rangle] \rightarrow \text{ISet}\langle\mathbf{X}\rangle[\mathbb{N} - s] = \mathbf{X} - \mathbf{x} \text{ISet}\langle\mathbf{X}\rangle[s]$
- $\text{I}^{-1}\text{Set}\langle\mathbf{X}\rangle:\text{Set}\langle\mathbf{X}\rangle^{\text{Set}\langle\mathbf{X}\rangle}$ is a homomorphism:
 - $\text{I}^{-1}\text{Set}\langle\mathbf{X}\rangle[\{ \} \mathbf{x}] = \{ \}$
 - $\forall [s1,s2:\text{Set}\langle\mathbf{X}\rangle] \rightarrow \text{I}^{-1}\text{Set}\langle\mathbf{X}\rangle[s1 \cup \mathbf{x} s2] = \text{ISet}\langle\mathbf{X}\rangle[s1] \cup \text{ISet}\langle\mathbf{X}\rangle[s2]$
 - $\forall [s1,s2:\text{Set}\langle\mathbf{X}\rangle] \rightarrow \text{I}^{-1}\text{Set}\langle\mathbf{X}\rangle[s1 \cap \mathbf{x} s2] = \text{ISet}\langle\mathbf{X}\rangle[s1] \cap \text{ISet}\langle\mathbf{X}\rangle[s2]$
 - $\forall [s:\text{Set}\langle\mathbf{X}\rangle] \rightarrow \text{I}^{-1}\text{Set}\langle\mathbf{X}\rangle[\mathbf{X} - \mathbf{x} s] = \mathbb{N} - \text{I}^{-1}\text{Set}\langle\mathbf{X}\rangle[s]$
- $\text{ISet}\langle\mathbf{X}\rangle$ is a unique isomorphism: If $g:\text{Set}\langle\mathbf{X}\rangle^{\text{Set}\langle\mathbb{N}\rangle}$ is an isomorphism, then $g = \text{ISet}\langle\mathbf{X}\rangle$

Function sets can be defined as follows:

$$\begin{aligned} \forall [f:\text{Set}\langle[\tau_1, \tau_2]\rangle] \rightarrow \\ f:?\text{FunctionSet}\langle\tau_1, \tau_2\rangle \\ \Leftrightarrow \forall [x:\tau_1; y1,y2:\tau_2] \rightarrow [x, y1] \in f \wedge [x, y2] \in f \Leftrightarrow y1=y2 \end{aligned}$$

Set Choice Theorem.

$$\begin{aligned} \forall [f:\text{FunctionSet}\langle\tau, \text{Set}\langle\tau\rangle\rangle] \rightarrow \\ \exists [\text{choice}:\text{FunctionSet}\langle\tau, \tau\rangle] \rightarrow \forall [x:\tau] \rightarrow f[x] \neq \{ \} \Leftrightarrow \text{choice}[x] \in x \end{aligned}$$

Theorem The usual axioms of Zermelo-Fraenkel-Choice (ZFC) hold in $\text{Set}\langle\tau\rangle$:⁵⁴

- Foundation: There are no downward infinite membership chains.⁵⁵
- Infinity: \mathbb{N} is infinite.
- Powerset: $\forall [s:\text{Set}\langle\tau\rangle] \rightarrow \text{Boolean}^S:?\text{Set}\langle\text{Set}\langle\tau\rangle\rangle$
- Union: $\forall [s:\text{Set}\langle\text{Set}\langle\tau\rangle\rangle] \rightarrow \cup s:?\text{Set}\langle\tau\rangle$
- Replacement: The image of any set under any set function is also a set, *i.e.*:
 $\forall [s:\text{Set}\langle\tau_1\rangle, f:\text{FunctionSet}\langle\text{Set}\langle\tau_1\rangle, \tau_2\rangle] \rightarrow$
 $(\text{Elementwise}[f])[s]:?\text{Set}\langle\tau_2\rangle$
- Choice: Every set has a choice function set, *i.e.*,
 $\forall [s:\text{Set}\langle\tau\rangle] \rightarrow \exists [f:\text{FunctionSet}\langle\text{Set}\langle\tau\rangle, \tau\rangle] \rightarrow \forall [t \subseteq s] \rightarrow t \neq \{\} \Rightarrow f[t] \in t$

Appendix 2. Historical Background

The powerful (try to) insist that their statements are literal depictions of a single reality. 'It really is that way', they tell us. 'There is no alternative.' But those on the receiving end of such homilies learn to read them allegorically, these are techniques used by subordinates to read through the words of the powerful to the concealed realities that have produced them.
 Law [2004]

Gödel was certain

"Certainty" is far from being a sign of success; it is only a symptom of lack of imagination and conceptual poverty. It produces smug satisfaction and prevents the growth of knowledge.
 [Lakatos 1976]

Paul Cohen [2006] wrote as follows of his interaction with Gödel:

His [Gödel's] main interest seemed to lie in discussing the "truth" or "falsity" of these questions, not merely in their undecidability. He struck me as having an almost unshakable belief in this "realist" position, which I found difficult to share. His ideas were grounded in a deep philosophical belief as to what the human mind could achieve. I greatly admired this faith in the power and beauty of Western Culture, as he put it, and would have liked to understand more deeply what were the sources of his strongly held beliefs. Through our discussions, I came closer to his point of view, although I never shared completely his "realist" point of view, that all questions of Set Theory were in the final analysis, either true or false.



Kurt Gödel

Chaitin [2007] famously complained about the triviality of basing something as important as incompleteness on such a ridiculous solipsistic sentence saying:

Gödel's proof of inferential undecidability [incompleteness] *was too superficial. It didn't get at the real heart of what was going on. It was more tantalizing than anything else. It was not a good reason for something so devastating and fundamental. It was too clever by half. It was too superficial.* [It was based on the clever construction] *"I'm unprovable."* So what? This doesn't give any insight how serious the problem is.ⁱ

The thesis of Chaitin's criticism above is that incompleteness is a fundamental issue for formal systems that is not adequately addressed by Gödel's proof based on his sentence "*I'm unprovable.*"⁵⁶

Gödel's alleged Mathematical sentence "*I'm unprovable.*" comes from a nonexistent **Y** fixed point (sometimes called the Diagonal Lemma) that doesn't exist because of types. His results were for Principia Mathematica, which was intended as the foundation of all of Mathematics. Unfortunately, Principia Mathematica had some defects in its types that have been corrected in Direct Logic. However, the sentence "*I'm unprovable.*" is very dubious as a sentence of mathematics because it is not a sentence grounded on standard mathematical objects such as numbers, triangles, groups, etc.

Church/Turing correctly proved inferential incompleteness (sometimes called the "First Incompleteness Theorem") without using a nonexistent "self-referential" proposition. The Church/Turing theorem and its proof are very robust.

After Church[1935] and Turing[1936] proved inferential undecidability of closed mathematical theories using computational undecidability, Gödel claimed more generality and that his results applied to all consistent mathematical systems that incorporate Peano axioms. However, when he learned of Wittgenstein's devastating proof of inconsistency,⁵⁷ Gödel retreated to claiming that his results applied to the very weak first-order theory of natural numbers.⁵⁸ The upshot is that Gödel never acknowledged that his "self-referential" propositionⁱⁱ implies inconsistency in mathematics. See further discussion below in this article.

ⁱ According to [Chaitin 2007]: "You see, the real problem with Gödel's proof is that it gives no idea how serious incompleteness is."

ⁱⁱ constructed using **Y** fixed points exploiting an untyped notation for mathematics

Also, the ultimate criteria for correctness in the theory of natural numbers is provability using categorical induction [Dedekind 1888, Peano 1889]. In this sense, Wittgenstein was correct in his identification of “truth” with provability. On the other hand, Gödel obfuscated the important identification of provability as the touchstone of ultimate correctness in mathematics.

von Neumann [1961] had a very different view from Gödel:

*It is **not** necessarily true that the mathematical method is something absolute, which was revealed from on high, or which somehow, after we got hold of it, was evidently right and has stayed evidently right ever since.*



John von Neumann

Provability Logic

One kind of Provability Logic (called $\mathcal{P}L$) is a cut-down theory of deduction that has been used to investigate provability predicates for languages that allow “self-referential” propositions [Verbrugge 2010]. $\mathcal{P}L$ is very weak; even for proving theorems about integers because $\mathcal{P}L$ is first-order.

[Löb 1955] proposed the following conditions that became the basis of Provability Logic:ⁱ

1. $(\vdash_{\mathcal{P}L}\Phi) \Rightarrow \vdash_{\mathcal{P}L}\vdash_{\mathcal{P}L}\Phi$ ⁵⁹
2. $\vdash_{\mathcal{P}L}((\vdash_{\mathcal{P}L}(\Phi \Rightarrow \Psi)) \Rightarrow ((\vdash_{\mathcal{P}L}\Phi) \Rightarrow \vdash_{\mathcal{P}L}\Psi))$ ⁶⁰
3. $\vdash_{\mathcal{P}L}((\vdash_{\mathcal{P}L}\Phi) \Rightarrow \vdash_{\mathcal{P}L}\vdash_{\mathcal{P}L}\Phi)$ ⁶¹

ⁱ His formulation actually used a convoluted coding of propositions into integers.

Gödel's construction of the sentence *I'm unprovable in PL*ⁱ using fixed points can be carried out in Provability logic as a proposition about the natural numbers with the following results:

- $\not\vdash_{\mathcal{PL}} I'mUnprovableInPL$ ⁱⁱ
- $\not\vdash_{\mathcal{PL}} \neg I'mUnprovableInPL$ ⁱⁱⁱ
- $\text{Consistent}[\mathcal{PL}] \Rightarrow \vdash_{\mathbb{N}} I'mUnprovableInPL$ ^{iv}
- $\text{Consistent}[\mathcal{PL}] \Rightarrow \vDash_{\mathbb{N}} I'mUnprovableInPL$ ^v

However, \mathcal{PL} is a weak theory. For example, the principle of natural deduction below called “Soundness” in Direct Logic that allows theorems to be used in subarguments is *not* allowed in \mathcal{PL} .⁶²

$$(\vdash \Phi) \Rightarrow \Phi$$

Soundness is highly desirable in order that computer systems be able to reason about the mathematical foundations of Classical Direct Logic using Classical Direct Logic.

In summary, Provability Logic (although a useful historical development step) is too weak and fragile to serve in the mathematical foundation of Computer Science.

Limitations of first-order logic

By this it appears how necessary it is for nay man that aspires to true knowledge to examine the definitions of former authors; and either to correct them, where they are negligently set down, or to make them himself. For the errors of definitions multiply themselves, according as the reckoning proceeds, and lead men into absurdities, which at last they see, but cannot avoid, without reckoning anew from the beginning; in which lies the foundation of their errors...

[Hobbes *Leviathan*, Chapter 4]⁶³

It is very important not to confuse Mathematics with first-order logic, which was invented by philosophers for their own purposes. It turns out that first-order logic is amazing weak. For example, first-order logic is incapable of

ⁱ $I'mUnprovableInPL \equiv \not\vdash_{\mathcal{PL}} I'mUnprovableInPL$

ⁱⁱ Proof by contradiction in \mathcal{PL}

ⁱⁱⁱ Proof by contradiction in \mathcal{PL}

^{iv} Proof by contradiction in theory \mathbb{N}

^v If $\text{Consistent}[\mathcal{PL}]$, then $I'mUnprovableInPL$ is true in the model \mathbb{N} by proof above in theory \mathbb{N} .

characterizing even the Peano numbers, *i.e.*, there are infinite integers in models of every first-order axiomatization of the Peano numbers. Furthermore, there are infinitesimal real numbers in models of every first-order axiomatization of the real numbers.ⁱ Of course, infinite integers and infinitesimal reals are monsters that must be banned from the mathematical foundations of Computer Science.

However, some philosophers have found first-order logic to be useful for their careers because it is weak enough that they can prove theorems about first-order axiomatizations whereas they cannot prove such theorems about stronger practical systems, *e.g.*, Classical Direct Logic. For example, there is a famous theorem that first-order set theory is too weak to decide ContinuumHypothesis⁶⁴, *i.e.*, $\not\vdash_{\text{FirstOrderSetAxioms}} \text{ContinuumHypothesis}$ and $\not\vdash_{\text{FirstOrderSetAxioms}} \neg \text{ContinuumHypothesis}$.⁶⁵ However, ContinuumHypothesis is still an open problem in Mathematics. That ContinuumHypothesis is an open problem is not so important for Computer Science because for subsets of reals that are computableⁱⁱ, the ComputationalContinuumTheoremⁱⁱⁱ holds.⁶⁶



Ernst Zermelo

Zermelo considered the First-Order Thesis to be a mathematical “hoax” because it necessarily allowed unintended models of axioms.⁶⁷

ⁱ Likewise, first-order set theory (e.g. ZFC) is very weak. See discussion immediately below.

ⁱⁱ A real number is computable if and only if its digits are computable.

ⁱⁱⁱ \mathbb{R} has no subset of computable reals whose cardinality is strictly between \aleph_1 and \aleph_2 .

[Barwise 1985] critiqued the First-Order Thesisⁱ as follows:

*The reasons for the widespread, often uncritical acceptance of the first-order thesis are numerous. The first-order thesis ... confuses the subject matter of logic with one of its tools. First-order language is just an artificial language structured to help investigate logic, much as a telescope is a tool constructed to help study heavenly bodies. From the perspective of the mathematics in the street, the first-order thesis is like the claim that astronomy is the study of the telescope.*⁶⁸



Jon Barwise

Computer Science is making increasing use of Model Analysisⁱⁱ in the sense of analyzing relationships among the following:

- concurrent programs and their Actor Model denotations
- axiom systems and their models

Having infinite integers and infinitesimal reals in models of axioms can cause problems in practical Model Analysis because a computer system can easily prove that there are no infinite integers and no infinitesimal reals. Consequently, infinite integers and infinitesimal reals are modeling monsters. Fortunately, these modeling monsters do not exist in Classical Direct Logic.

The cut-down-first-order theory *FirstOrderPeanoDedekind*ⁱⁱⁱ is too limited for Computer Science because of the following:

- $(\vdash_{\text{FirstOrderPeanoDedekind}} \Psi) \Leftrightarrow \vdash_{\mathbb{N}} \Psi$
- There are some Ψ_0 that are important in Computer Science (see immediately below) such that:
 - $\vdash_{\mathbb{N}} \Psi_0$
 - $\not\vdash_{\text{FirstOrderPeanoDedekind}} \Psi_0$

In Computer Science, it is important that the Natural Numbers (\mathbb{N}) be axiomatized in a way that does not allow non-numbers (*e.g.* infinite ones) in models of the axioms. Unfortunately, every consistent first-order axiomatization of \mathbb{N} has a model with an infinite integer:

ⁱ The “First-Order Thesis” is that mathematical foundations should be restricted to first-order logic.

ⁱⁱ a restricted form of Model Checking in which the properties checked are limited to those that can be expressed in Linear-time Temporal Logic has been studied [Clarke, Emerson, Sifakis, *etc.* ACM 2007 Turing Award].

ⁱⁱⁱ with cut-down first-order Peano axioms

Theorem: If \mathbb{N} is a model of a first-order axiomatization \mathcal{T} , then \mathcal{T} has a model \mathbb{M} with an infinite integer.

Proof: The model \mathbb{M} is constructed as an extension of \mathbb{N} by adding a new element ∞ with the following atomic relationships:

$$\{\neg\infty < \infty\} \cup (\text{Elementwise}[[m] \rightarrow m < \infty])(\mathbb{N})^i$$

It can be shown that \mathbb{M} is a model of \mathcal{T} with an infinite integer ∞ .

The infinite integer ∞ is a monster that must be banned from the mathematical foundations of Computer Science.

A similar result holds for the standard theory \mathbb{R} of real numbers [Dedekind 1888] compared to a cut-down, first-order theory⁶⁹, which has models with infinitesimals:

Theorem: If \mathbb{R} is a model of a first-order axiomatization \mathcal{T} , then \mathcal{T} has a model \mathbb{M} with an infinitesimal.

Proof: The model \mathbb{M} is constructed as an extension of \mathbb{R} by adding a new element ∞ with the following atomic relationships:

$$\{\neg\infty < \infty\} \cup (\text{Elementwise}[[m] \rightarrow m < \infty])(\mathbb{N})^{ii}$$

Defining ε to be $\frac{1}{\infty}$, it follows that $\forall [r:\mathbb{R}] \rightarrow 0 < \varepsilon < \frac{1}{r}$. It can be shown that \mathbb{M} is a model of \mathcal{T} with an infinitesimal ε , which is a monster that must be banned from the mathematical foundations of Computer Science.

On the other hand, since it is not limited to first-order logic, Classical Direct Logic characterizes structures such as natural numbers and real numbers up to isomorphism.ⁱⁱⁱ

ⁱ $\text{Elementwise}[f] = [s] \rightarrow \{f[x] \mid x \in s\}$

ⁱⁱ $\text{Elementwise}[f] = [s] \rightarrow \{f[x] \mid x \in s\}$

ⁱⁱⁱ proving that software developers and computer systems are using the same structures

Of greater practical import, that a computer provides service *i.e.*
 $\exists [i:\mathbb{N}] \rightarrow \text{ResponseBefore}[i]$ cannot be proved in a first-order theory.

Proof: In order to obtain a contradiction, suppose that it is possible to prove the theorem that computer server provides serviceⁱ in a first-order theory \mathcal{T} .

Therefore the following infinite set of propositions is inconsistent:ⁱⁱ

$$(\text{Elementwise}[\lambda[i:\mathbb{N}] \rightarrow \neg \text{ResponseBefore}[i]])[\mathbb{N}].$$

By the compactness theorem of first-order logic, it follows that there is finite subset of the set of propositions that is inconsistent. But this is a contradiction, because all the finite subsets are consistent since the amount of time before a server responds is unbounded, *i.e.*,

$$(\nexists [i:\mathbb{N}] \rightarrow \vdash_{\mathcal{T}} \text{ResponseBefore}[i]).$$

The above examples illustrate the following fundamental limitation of first-order theories:

In a first-order theory \mathcal{T} , it is impossible to have both of the following for a predicate P:

- $\nexists [i:\mathbb{N}] \rightarrow \vdash_{\mathcal{T}} P[i]$ ⁱⁱⁱ
- $\vdash_{\mathcal{T}} \exists [i:\mathbb{N}] \rightarrow P[i]$

Proof: Suppose that it is possible for both of the above to hold in a first-order theory \mathcal{T} . Therefore the following infinite set of propositions is inconsistent:⁷⁰

$$(\text{Elementwise}[\lambda[m:\mathbb{N}] \rightarrow \neg P[m]])[\mathbb{N}]$$

By the compactness theorem of first-order logic, it follows that there is finite subset of the set of propositions that is inconsistent. But this is a contradiction, because all the finite subsets are consistent.

As a foundation of mathematics for Computer Science, Classical Direct Logic provides categorical⁷¹ numbers (integer and real), sets, lists, trees, graphs, etc. which can be used in arbitrary mathematical theories including theories for categories, large cardinals, first-order axiomatizations, etc. These various theories might have “monsters” of various kinds. However, these monsters are not imported into the foundations of Computer Science.

ⁱ $\exists [i:\mathbb{N}] \rightarrow \text{ResponseBefore}[i]$

ⁱⁱ *i.e.* in classical notation: $\{ \neg \text{ResponseBefore}[i] \mid i:\mathbb{N} \}$

ⁱⁱⁱ *i.e.* $\forall [i:\mathbb{N}] \rightarrow \nvdash_{\mathcal{T}} P[i]$

Computer Science needs *stronger* systems than provided by first-order logic in order to weed out unwanted models. In this regard, Computer Science doesn't have a problem computing with "infinite" objects (*i.e.* Actors) such as π and uncountable sets such as the real numbers \mathbb{R} .⁷²

Of course some problems are theoretically not computable. However, even in these cases, it is often possible to compute approximations and cases of practical interest.ⁱ

The mathematical foundation of Computer Science is very different from the general philosophy of mathematics in which infinite integers and infinitesimal reals may be of some interest. Of course, it is always possible to have special theories with infinite integers, infinitesimal reals, unicorns, *etc.*

Church's Paradox

in the case of any system of symbolic logic, the set of all provable theorems is [computationally] enumerable... any system of symbolic logic not hopelessly inadequate ... would contain the formal theorem that this same system ... was either insufficient [theorems are not computationally enumerable] or over-sufficient [that theorems are computationally enumerable means that the system is inconsistent]...

This, of course, is a deplorable state of affairs...

Indeed, if there is no formalization of logic as a whole, then there is no exact description of what logic is, for it in the very nature of an exact description that it implies a formalization. And if there no exact description of logic, then there is no sound basis for supposing that there is such a thing as logic.

[Church 1934]⁷³

[Church 1932, 1933] attempted basing foundations entirely on untyped higher-order functions, but foundered because contradictions emerged because

1. His system allowed "self-referential" propositions [Kleene and Rosser 1935]
2. He believed that theorems must be computationally enumerable.

ⁱ *e.g.* see Terminator [Knies 2006], which practically solves the halting problem for device drivers

The above issues can be addressed as follows:

1. Disallowing construction of “self-referential” propositions in Mathematics
2. Mathematics self proves that it is “open” in the sense that proofs are not computationally enumerable (*i.e.* not “closed”).ⁱ

Gödel, Curry, and Löb Paradoxes

Allowing construction of “self-referential” propositionsⁱⁱ results in contradictions [Wittgenstein 1937].⁷⁴

For example, consider the diagonal construction used in [Gödel 1931]:

The “self-referential” proposition “*I'm unprovable.*” that was used by Gödel *cannot* be constructed as follows:⁷⁵

Gödel:Nonexistent $\equiv \not\vdash$ **Gödel**

// illegal definition because $\not\vdash$ **Gödel** is of

// type of **Proposition** order greater than **Gödel**

Gödel $\Leftrightarrow \not\vdash$ **Gödel** // definition of **Gödel**

By the following argument, Wittgenstein derived a contradiction in Mathematics from Gödel’s result:

Gödel thought that he demonstrated $\vdash \not\vdash$ **Gödel**. Therefore \vdash **Gödel** using **Gödel** $\Leftrightarrow \not\vdash$ **Gödel**. $\vdash \vdash$ **Gödel** follows using adequacy. But the contradiction $\vdash \neg$ **Gödel** follows using **Gödel** $\Leftrightarrow \not\vdash$ **Gödel**.

ⁱ In other words, the paradox that concerned Church (because he thought that it could mean the demise of formal mathematical logic) has been transformed into fundamental theorem of foundations!

ⁱⁱ using **Y** fixed point operators exploiting an untyped sentences for mathematics

Also, the following paradoxes cannot prove *every* proposition because “self-referential” propositions do not exist in a strongly typed logic.⁷⁶

- **Curry’s Paradox** [Curry 1941] Suppose Ψ :**Proposition** \langle order: \mathbb{N}_+ \rangle .

Curry $_{\Psi}$:**Nonexistent** \equiv **Curry** $_{\Psi} \vdash \Psi$

// illegal definition because **Curry** $_{\Psi}$ is not a **Proposition** of any order

// because the type of **Curry** $_{\Psi} \vdash \Psi$ is a **Proposition** of higher

// order than **Curry** $_{\Psi}$

- 1) **Curry** $_{\Psi} \vdash \Psi \Leftrightarrow (\text{Curry}_{\Psi} \vdash \Psi \vdash \Psi)$ // definition of **Curry** $_{\Psi}$
- 2) $\vdash (\text{Curry}_{\Psi} \vdash \text{Curry}_{\Psi})$ // idempotency
- 3) $\vdash (\text{Curry}_{\Psi} \vdash (\text{Curry}_{\Psi} \vdash \Psi))$ // substituting 1) into 2)
- 4) $\vdash (\text{Curry}_{\Psi} \vdash \Psi)$ // contraction
- 5) $\vdash \text{Curry}_{\Psi}$ // substituting 1) into 4)
- 6) $\vdash \Psi$ // chaining 4) and 5)

- **Löb’s Paradox** [Löb 1955]⁷⁷ Suppose Ψ :**Proposition** \langle anOrder: \mathbb{N}_+ \rangle .

Löb $_{\Psi}$:**Nonexistent** $\equiv (\vdash \text{Löb}_{\Psi}) \vdash \Psi$

// illegal definition because **Löb** $_{\Psi}$ is not a **Proposition** of any order

// because the type of $(\vdash \text{Löb}_{\Psi}) \vdash \Psi$ is a **Proposition** of higher

// order than **Löb** $_{\Psi}$

- 1) **Löb** $_{\Psi} \Leftrightarrow ((\vdash \text{Löb}_{\Psi}) \vdash \Psi)$ // definition of **Löb** $_{\Psi}$
- 2) $\vdash ((\vdash \text{Löb}_{\Psi}) \vdash \text{Löb}_{\Psi})$ // soundness
- 3) $\vdash ((\vdash \text{Löb}_{\Psi}) \vdash ((\vdash \text{Löb}_{\Psi}) \vdash \Psi))$ // substituting 1) into 2)
- 4) $\vdash ((\vdash \text{Löb}_{\Psi}) \vdash \Psi)$ // contraction
- 5) $\vdash \text{Löb}_{\Psi}$ // substituting 1) into 4)
- 6) Ψ // chaining 4) and 5)

Of course, it is completely unacceptable for every proposition to be provable and so measures must be taken to prevent this.

Berry's Paradox

Berry's construction [Russell 1906] can be formalized using:

- Terminals[e] is the number of terminals of the expression e
- Characterize[[s:String<Expression<Proposition< $\omega+1$ >^N>>]
k:N]:Proposition< $\omega+1$ > \equiv

$$\forall [x:N] \rightarrow \lfloor \text{Parse} \langle \text{Expression} \langle \text{Proposition} \langle \omega+1 \rangle^N \rangle \cdot [s] \rfloor \llbracket x \rrbracket \Leftrightarrow x=k$$

Consider the following definition:

$$\text{BString}:\text{String} \langle \text{Expression} \langle \text{Proposition} \langle \omega+1 \rangle^N \rangle \rangle \equiv$$

$$\text{“}(\lambda [n:N] \rightarrow (\forall [s:\text{String} \langle \text{Expression} \langle \text{Proposition} \langle \omega+1 \rangle^N \rangle \rangle] \\ \text{Length}[s] < 100 \Leftrightarrow \neg \text{Characterize} \llbracket s, n \rrbracket \text{”}$$

$$\text{BExpression}:\text{Expression} \langle \text{Proposition} \langle \omega+1 \rangle^N \rangle \equiv$$

$$\text{Parse} \langle \text{Expression} \langle \text{Proposition} \langle \omega+1 \rangle^N \rangle \cdot [\text{BString}]$$

Note that

- Length[BString] < 100.
- {s:String<Expression<Proposition< $\omega+1$ >^N>> | \models_N Length[s] < 100} is finite.
- Therefore the following set is finite:

$$\{n:N_+ \mid \models_N \exists [s:\text{String} \langle \text{Expression} \langle \text{Proposition} \langle \omega+1 \rangle^N \rangle \rangle] \\ \text{Length}[s] < 100 \wedge \text{Characterize} \llbracket s, n \rrbracket \}$$

$$\text{BSet}:\text{Set} \langle N \rangle \equiv \{n:N_+ \mid \models_N \lfloor \text{BExpression} \rfloor \llbracket n \rrbracket \}$$

BSet \neq { } because is {n:N | n \geq 1} is infinite.

1. BNumber:N \equiv Least[BSet]
2. $\models_N \lfloor \text{BExpression} \rfloor \llbracket \text{BNumber} \rrbracket$ ⁷⁸
3. $\models_N \lfloor (\lambda [n:N] \rightarrow (\forall [s:\text{String} \langle \text{Expression} \langle \text{Proposition} \langle \omega+1 \rangle^N \rangle \rangle] \rightarrow \\ \text{Length}[s] < 100 \Leftrightarrow \neg \text{Characterize} \llbracket s, n \rrbracket \text{”}) \rfloor \llbracket \text{BNumber} \rrbracket$ ⁷⁹
4. $\models_N \forall [s:\text{String} \langle \text{Expression} \langle \text{Proposition} \langle \omega+1 \rangle^N \rangle \rangle] \rightarrow \\ \text{Length}[s] < 100 \Leftrightarrow \neg \text{Characterize} \llbracket s, \text{BNumber} \rrbracket$ ⁸⁰
5. $\models_N \text{Length}[\text{BString}] < 100 \Leftrightarrow \neg \text{Characterize} \llbracket \text{BString}, \text{BNumber} \rrbracket$
// above is invalid because of attempted substitution of
// BString:String<Expression<Proposition< $\omega+1$ >^N>> for
// s:String<Expression<Proposition< $\omega+1$ >^N>>

Appendix 3. Classical Natural Deduction

Below are schemas for nested-box-style Natural Deductionⁱ for Classical Mathematics:

\Rightarrow Introduction	\Rightarrow Elimination
Ψ ① hypothesis \dots Φ ① inference $\Psi \Rightarrow \Phi$ ① conclusion	Ψ ① premise \dots $\Psi \Rightarrow \Phi$ ① premise \dots Φ ① conclusion
$(\Psi \vdash \Phi) \vdash (\Psi \Rightarrow \Phi)$	$\Psi, (\Psi \Rightarrow \Phi) \vdash \Phi$
\wedge Introduction	\wedge Elimination
Ψ ① premise \dots Φ ① premise $\Psi \wedge \Phi$ ① conclusion	$\Psi \wedge \Phi$ ① premise Ψ ① conclusion \dots Φ ① conclusion
$\Psi, \Phi \vdash (\Psi \wedge \Phi)$	$(\Psi \wedge \Phi) \vdash \Psi, \Phi$
\vee Introduction	\vee Elimination
Ψ ① premise \dots $\Psi \vee \Phi$ ① conclusion	$\neg \Psi$ ① premise \dots $\Psi \vee \Phi$ ① premise \dots Φ ① conclusion
$\Psi \vdash (\Psi \vee \Phi)$	$\neg \Psi, (\Psi \vee \Phi) \vdash \Phi$
Proof by Contradiction	\vee Cases
Ψ ① hypothesis \dots $\Phi \wedge \neg \Phi$ ① inference $\neg \Psi$ ① conclusion	$\Psi \vee \Phi$ ① premise $\Psi \vdash \Theta$ ① premise \dots $\Phi \vdash \Theta$ ① premise \dots Θ ① conclusion
$(\Psi \vdash (\Phi \wedge \neg \Phi)) \vdash \neg \Psi$	$(\Psi \vee \Phi), (\Psi \vdash \Theta), (\Phi \vdash \Theta) \vdash \Theta$
Soundness	Adequacy
$(\vdash \Psi) \Rightarrow \Psi$	$(\Phi \vdash \Psi) \Leftrightarrow (\vdash (\Phi \vdash \Psi))$

ⁱ Evolved from classical natural deduction [Jaśkowski 1934]. See history in Pelletier [1999].

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End Notes

¹ [White 1956, Wilder 1968, Rosental 2008]

² The principle of soundness is fundamental to Mathematics going back at least to Euclid.

³ There seem to be no practical uses for “self-referential” propositions in the mathematical foundations of Computer Science.

⁴ Mathematical foundations of Computer Science must be general, rigorous, realistic, and as simple as possible. There are a large number of highly technical aspects with complicated interdependencies and trade-offs. Foundations will be used by humans and computer systems. Contradictions in the mathematical foundations of Computer Science cannot be allowed and if found must be repaired.

Classical mathematics is the subject of this article. In a more general context:

- Inconsistency Robust Direct Logic is for pervasively inconsistent theories of practice, e.g., theories for climate modeling and for modeling the human brain.
- Classical Direct Logic can be freely used in theories of Inconsistency Robust Direct Logic. See [Hewitt 2010] for discussion of Inconsistency Robust Direct Logic. Classical Direct Logic for mathematics used in inconsistency robust theories.

⁵ Soundness means:

- A theorem of Mathematics can be used *anywhere* including in inconsistency robust inference
- A theorem of Mathematics can be used in a step of a sub-proof to prove a theorem in Mathematics *regardless* of the assumptions of the sub-proof.

⁶ Note that this theorem is very different from the result [Kleene 1938], that mathematics can be extended with a proposition asserting its own consistency.

⁷ Many of today's most prominent philosophers and logicians have cast doubt on the correctness of the proof.

⁸ The definition of inconsistency, *i.e.*, $\text{Consistent} \Leftrightarrow \neg \exists [\Psi] \rightarrow \vdash (\Psi \wedge \neg \Psi)$ is not per set about numbers. Consistent with the general practice in Computer Science, there is no way to identify propositions with integers.

⁹ A prominent logician referee of this article suggested that if the proof is accepted then consistency should be made an explicit premise of every theorem of classical mathematics!

¹⁰ As shown above, there is a simple proof in Classical Direct Logic that Mathematics (\vdash) is consistent. If Classical Direct Logic has a bug, then there might also be a proof that Mathematics is inconsistent. Of course, if a such bug is found, then it must be repaired.

Fortunately, Classical Direct Logic is simple in the sense that it has just *one* fundamental axiom, namely the Peano/Dedekind categorical induction axioms for each order: \mathbb{N}_+ and P : **Proposition** $\langle \text{order} \rangle \mathbb{N}$:

$$(P[0] \wedge \forall[i:\mathbb{N}] \rightarrow P[i] \Rightarrow P[i+1]) \Leftrightarrow \forall[i:\mathbb{N}] \rightarrow P[i]$$

Of course, Classical Direct Logic has machinery in addition the above axiom that could also have bugs.

The Classical Direct Logic proof that Mathematics (\vdash) is consistent is very robust. One explanation is that consistency is built in to the very architecture of classical mathematics because it was designed to be consistent. Consequently, it is not absurd that there is a simple proof of the consistency of Mathematics (\vdash) that does not use all of the machinery of Classical Direct Logic.

In reaction to paradoxes, philosophers developed the dogma of the necessity of strict separation of “object theories” (theories about basic mathematical entities such as numbers) and “meta theories” (theories about theories). This linguistic separation can be very awkward in Computer Science. Consequently, Direct Logic does not have the separation in order that some propositions can be more “directly” expressed. For example, Direct Logic can use $\vdash \vdash \Psi$ to express that it is provable that P is provable in Mathematics. It turns out in Classical Direct Logic that $\vdash \vdash \Psi$ holds if and only if $\vdash \Psi$ holds. By using such expressions, Direct Logic contravenes the philosophical dogma that the proposition $\vdash \vdash \Psi$ must be expressed using Gödel numbers.

¹¹ Classical Direct Logic is different from [Willard 2007], which developed sufficiently weak systems that “self-referential” sentences do not exist.

¹² Subsequent further discussion of Wittgenstein's criticism of Gödel's writings has unfortunately misunderstood Wittgenstein.

For example, [Berto 2009] granted that proof theoretically if $P \Leftrightarrow \nabla P$, then:

1) $\vdash \nabla P$

However, the above has proof consequences as follows:

2) $\vdash P$ because $(\nabla P) \Leftrightarrow P$ in 1) above

3) $\vdash \vdash P$ because of 2) above

4) $\vdash \neg P$ because $(\vdash P) \Leftrightarrow \neg P$ in 3) above

Of course, 2) and 4) are a manifest contradiction in mathematics that has been obtained without any additional “semantic story” that [Berto 2009] claimed is required for Wittgenstein's argument that

contradiction in mathematics “*is what comes of making up such* [“self-referential”] *sentences.*” [Wittgenstein 1956, p. 51e]

¹³ specified by axioms [Dedekind 1888, Peano 1889] that characterize them up to a unique isomorphism

¹⁴ Consequently there is no need to introduce a special kind of set called a “class” that was introduced as a patch for set theory by von Neumann.

¹⁵ The *Computational Representation Theorem* [Clinger 1981; Hewitt 2006] characterizes computation for systems which are closed in the sense that they do not receive communications from outside:

The denotation Denote_S of a closed system S represents all the possible behaviors of S as¹⁵

$$\text{Denote}_S = \lim_{i \rightarrow \infty} \text{Progressions}_S^i$$

where $\text{Progressions}_S^i \rightarrow \text{Progressions}_S^{i+1}$

In this way, S can be mathematically characterized in terms of all its possible behaviors (including those involving unbounded nondeterminism).

The denotations of the Computational Representation Theorem form the basis of procedurally checking programs against all their possible executions.

¹⁶ According to [Gödel correspondence with Ernst Zermelo October 30, 1931 in *Kurt Gödel Collected Works Volume V Correspondence H-Z*, Oxford University Press, 2003.

pp. 420-431.]: Without Gödel's restriction “you obtain an uncountable system of possible statements, among which only a countable subset are ‘provable’, and there must certainly be ‘undecidable’ statements.”

¹⁷ e.g. [Shulman 2012, nLab 2014]

¹⁸ [cf. Church 1934, Kleene 1936]

¹⁹ [Church 1936, Turing 1936]

²⁰ sometimes called “incomplete”

²¹ That the closed mathematical theory \mathbf{N} is inferentially undecidable²¹ with respect to $\text{ProofsComputationallyEnumerable}_{\mathbf{N}}$ does not mean incompleteness with respect to the information that can be inferred because

- $\vdash \not\vdash_{\mathbf{N}} \text{ProofsComputationallyEnumerable}_{\mathbf{N}}$
- $\vdash \not\vdash_{\mathbf{N}} \neg \text{ProofsComputationallyEnumerable}_{\mathbf{N}}$

²² Consequently, there can cannot be any escape hatch into an unformalized “meta-theory.”

²³ The claim also relied on Gödel's “self-referential” proposition.

²⁴ Formal syntax was invented long after [Gödel 1931].

²⁵ emphasis in original

²⁶ cf. [Rosental 2008]

²⁷ According to [Concoran 2001]:

“after first-order logic had been isolated and had been assimilated by the logic community, people emerged who could not accept the idea that first-order logic was not comprehensive. These logicians can be viewed not as conservatives who want to reinstate an outmoded tradition but rather as radicals who want to overthrow an established tradition.”

²⁸ for discussion see [Hewitt 2010]

²⁹ For example:

From: Harvey Friedman
Sent: Wednesday, April 20, 2016 10:53
To: Carl Hewitt
Cc: Martin Davis @cs.nyu; Dana Scott @cmu; Eric Astor @uconn; Mario Carneiro @osu; Dave Mcallester @ttic; Joe Shipman
Subject: Re: Parameterized types in the foundations of mathematics

Not if I have anything to say about it!

Harvey

On Wed, Apr 20, 2016 at 11:25 AM, Carl Hewitt wrote:

> Hi Martin,
>
> Please post the message below to FOM [Foundations of Mathematics forum].
>
> Thanks!
>
> Carl
>
> According to Harvey Friedman on the FOM Wiki: "I have not yet seen any seriously alternative foundational setup that tries to be better than ZFC in this [categoricity of models] and other respects that isn't far far worse than ZFC in other even more important respects."
>
> Of course, ZFC is a trivial consequence of parameterized types with the following definition for set of type τ :
>
> $\text{Set}\langle\tau\rangle \equiv \text{Boolean}^\tau$
>
> Also of course, classical mathematics can be naturally formalized using parameterized types. For example, see "Inconsistency Robustness in Foundations: Mathematics self proves its own Consistency and Other Matters" in HAL Archives.
>
> Regards,
> Carl

³⁰ **True \neq False**

$\forall[x:\text{Boolean}] \rightarrow x=\text{True} \vee x=\text{False}$

³¹ The natural numbers are axiomatised as follows where Successor is the successor function:

- $0:\mathbb{N}$
- Successor: $\mathbb{N}^{\mathbb{N}}$
- $\forall[i:\mathbb{N}] \rightarrow \text{Successor}[i] \neq 0$
- $\forall[i, j:\mathbb{N}] \rightarrow \text{Successor}[i] = \text{Successor}[j] \Rightarrow i=j$
- For each order: \mathbb{N}_+ and $P:\text{Proposition}\langle\text{order}\rangle^{\mathbb{N}}$:
 $(P[0] \wedge \forall[i:\mathbb{N}] \rightarrow P[i]) \Rightarrow P[\text{Successor}[i]] \Leftrightarrow \forall[i:\mathbb{N}] \rightarrow P[i]$

³² For $i=1,2$

- If $x:\tau_1$, then $((\tau_1 \circ \tau_2)[x]):?(\tau_1 \circ \tau_2)$ and $x=((\tau_1 \circ \tau_2)[x]) \downarrow \tau_1$.
- $\forall[z:\tau] \rightarrow z:?\tau_1 \circ \tau_2 \Leftrightarrow \exists[x:\tau_1] \rightarrow z=(\tau_1 \circ \tau_2)[x]$

³³ type of 2-element list with first element of type τ_1 and with second element of type τ_2

³⁴ *if t then Φ_1 else Φ_2*

³⁵ Φ_1, \dots and Φ_k infer $\Psi_1, \dots,$ and Ψ_n

³⁶ **(True),(False):Constant<Boolean>**

³⁷ **(0),(1):Constant<N>**

³⁸ mutually recursive definitions of functions f_1 to n

³⁹ mutually recursive definitions of variables x_1 to n

⁴⁰ *if t_1 then t_2 else t_3*

⁴¹ if present

⁴² *if t then s_1 else s_1*

⁴³ if present

⁴⁴ According to [Scott 1967]: “As long as an idealistic manner of speaking about abstract objects is popular in mathematics, people will speak about collections of objects, and then collections of collections of ... of collections. In other words set theory is inevitable.” [emphasis in original]

⁴⁵ According to [Scott 1967]: “there is only one satisfactory way of avoiding the paradoxes: namely, the use of some form of the *theory of types*... the best way to regard Zermelo's theory is as a simplification and extension of Russell's ...*simple* theory of types. Now Russell made his types *explicit* in his notation and Zermelo left them *implicit*. It is a mistake to leave something so important invisible...”

⁴⁶ [Church 1956; Boolos 1975; Corcoran 1973, 1980]. Also, Classical Direct Logic is *not* a univalent homotopy type theory [Awodey, Pelayo, and Warren 2013].

⁴⁷ [Dedekind 1888, Peano 1889] According to [Isaacson]:

Second-order quantification is significant for philosophy of mathematics since it is the means by which mathematical structures may be characterized. But it is also significant for mathematics itself. It is the means by which the significant distinction can be made between the independence of Euclid's Fifth postulate from the other postulates of geometry and the independence of Cantor's Continuum hypothesis from the axioms of set theory. The independence of the Fifth postulate rejects the fact, which can be expressed and established using second-order logic, that there are different geometries, in one of which the Fifth postulate holds (is true), in others of which it is false.

⁴⁸ For each type \mathbf{X} that satisfies the Dedekind/Peano axioms there is a (unique) isomorphism $I: \mathbf{X}^{\mathbf{N}}$ and inductively defined as follows:

1. $I[0] = 0_{\mathbf{X}}$
2. $I[S[j]] = S_{\mathbf{X}}[I[j]]$

Using proofs by induction on \mathbf{N} and \mathbf{X} , the following follow:

1. I is defined for every \mathbf{N}

2. I is one-to-one: $\forall [k, j: \mathbf{N}] \rightarrow I[k] = I[j] \Rightarrow k = j$

First show **Lemma** by induction on k : $\forall [k: \mathbf{N}] \rightarrow I[k] = 0_{\mathbf{X}} \Rightarrow k = 0$

Base: Suppose $k = 0$. QED.

Induction: Suppose $I[k] = 0_{\mathbf{X}} \Rightarrow k = 0$

To show: $I[S[k]] = 0_{\mathbf{X}} \Rightarrow S[k] = 0_{\mathbf{X}}$

$I[S[k]] = S_{\mathbf{X}}[I[k]]$ Therefore if $I[S[k]] = 0_{\mathbf{X}}$ then $0_{\mathbf{X}} = S_{\mathbf{X}}[I[k]]$
which is a contradiction

To show: $\forall [k, j: \mathbf{N}] \rightarrow I[k] = I[j] \Rightarrow k = j$

Proof: Induction on $P[m: \mathbf{N}]$: Proposition <1> \equiv

$\forall [k, j \leq m: \mathbf{N}] \rightarrow I[k] = I[j] \Rightarrow k = j$

Base: Suppose $m = k = j = 0$. QED.

Induction: Suppose $\forall [k, j \leq m: \mathbf{N}] \rightarrow I[k] = I[j] \Rightarrow k = j$

To show: $\forall [0 < k, j < S[m]] \rightarrow I[k] = I[j] \Rightarrow k = j$

$\exists [k_0, j_0 \leq m: \mathbf{N}] \rightarrow k = S[k_0] \wedge j = S[j_0]$ because $0 < k, j \leq m$

$k_0 = j_0$ since $k_0, j_0 \leq m$, $k, j < S[m]$ and

$I[k_0] = I[j_0] \Rightarrow k_0 = j_0$ by induction hypothesis

$S[k_0] = S[j_0]$ and therefore $k = j$

3. the range of I is all of \mathbf{X} : $\forall [y: \mathbf{X}] \rightarrow \exists [k: \mathbf{N}] \rightarrow I[k] = y$

Proof: Induction on $P[y: \mathbf{X}]$: Proposition <1> $\equiv \exists [k: \mathbf{N}] \rightarrow I[k] = y$

Base: Suppose $y = 0_{\mathbf{X}}$. To show $\exists [k: \mathbf{N}] \rightarrow I[k] = 0_{\mathbf{X}}$. Clearly $I[0] = 0_{\mathbf{X}}$

Induction: Suppose $y > 0_{\mathbf{X}}$ and $\exists [k: \mathbf{N}] \rightarrow I[k] = y$. Let $I[k_0] = y$.

To show $\exists [k: \mathbf{N}] \rightarrow I[k] = S_{\mathbf{X}}[y]$.

It follows from $I[S[k_0]] = S_{\mathbf{X}}[I[k_0]] = S_{\mathbf{X}}[y]$

3. I is a homomorphism: $I[0]=0_{\mathbf{x}}$ and $\forall [j:\mathbf{N}] \rightarrow I[S[j]]=S_{\mathbf{x}}[I[j]]$

Proof: Induction on $P[j:\mathbf{N}]$: Proposition <1> $\equiv I[S[j]]=S_{\mathbf{x}}[I[j]]$

Base: $I[S[0]]=S_{\mathbf{x}}[I[0]]$ by definition of I

Induction: Suppose $\forall [i:\mathbf{N}] \rightarrow I[S[i]]=S_{\mathbf{x}}[I[i]]$

To show: $\forall [j:\mathbf{N}] \rightarrow I[S[S[j]]]=S_{\mathbf{x}}[I[S[j]]]$

$I[S[S[j]]]=S_{\mathbf{x}}[I[S[j]]]$ by definition of I

4. $I^{-1}:\mathbf{N}^{\mathbf{X}}$ is a homomorphism:

$I^{-1}[0_{\mathbf{x}}]=0$ and $\forall [y:\mathbf{X}] \rightarrow I^{-1}[S_{\mathbf{x}}[y]]=S[I^{-1}[y]]$

Proof:

To Show: $I^{-1}[0_{\mathbf{x}}]=0$.

Let $i=I^{-1}[0_{\mathbf{x}}]$. Therefore $I[i]=0_{\mathbf{x}}$ and $k=0$.

To Show: $\forall [y:\mathbf{X}] \rightarrow I^{-1}[S_{\mathbf{x}}[y]]=S[I^{-1}[y]]$

Induction on $P[y:\mathbf{X}]$: Proposition <1> $\equiv I^{-1}[S_{\mathbf{x}}[y]]=S[I^{-1}[y]]$

Base: To show: $I^{-1}[S_{\mathbf{x}}[0]]=S[I^{-1}[0_{\mathbf{x}}]]=S[0]$

Let $k=I^{-1}[S_{\mathbf{x}}[0]]$. Therefore $I[k]=S_{\mathbf{x}}[0]$ and $k=S[0]$.

Induction: Suppose $\forall [j:\mathbf{N}] \rightarrow I[S[j]]=S_{\mathbf{x}}[I[j]]$

To show: $\forall [i:\mathbf{N}] \rightarrow I[S[S[i]]]=S_{\mathbf{x}}[I[S[i]]]$

$I[S[S[i]]]=S_{\mathbf{x}}[I[S[i]]]$ by definition of I

5. I is the unique isomorphism: If $g:\mathbf{X}^{\mathbf{N}}$ is an isomorphism then $g=I$

Proof: Induction on $P[j:\mathbf{N}]$: Proposition <1> $\equiv I[j]=g[j]$

Base: $I[0]=0_{\mathbf{x}}$. $g[0]=0_{\mathbf{x}}$ because g is an isomorphism.

Therefore $I[0]=g[0]$

Induction: Suppose $I[j]=g[j]$.

To show: $I[S[j]]=g[S[j]]$

$I[S[j]]=S_{\mathbf{x}}[I[j]]=S_{\mathbf{x}}[g[j]]=g[S[j]]$

⁴⁹ For example, there are nondeterministic Turing machines that the theory \mathbf{N} proves always halt that cannot be proved to halt in the cut-down first-order theory.

⁵⁰ [Dedekind 1888]

The following can be used to characterize the real numbers (\mathbb{R} ⁵⁰) up to isomorphism with a unique isomorphism:

$\forall [S:\mathbf{Set}\langle\mathbb{R}\rangle] \rightarrow S \neq \{ \} \wedge \text{Bounded}[S] \Leftrightarrow \text{HasLeastUpperBound}[S]$

where

$\text{Bounded}[S:\mathbf{Set}\langle\mathbb{R}\rangle] \Leftrightarrow \exists [b:\mathbb{R}] \rightarrow \text{UpperBound}[b, S]$

$\text{UpperBound}[b:\mathbb{R}, S:\mathbf{Set}\langle\mathbb{R}\rangle] \Leftrightarrow b \in S \wedge \forall [x \in S] \rightarrow x \leq b$

$\text{HasLeastUpperBound}[S:\mathbf{Set}\langle\mathbb{R}\rangle] \Leftrightarrow \exists [b:\mathbb{R}] \rightarrow \text{LeastUpperBound}[b, S]$

$\text{LeastUpperBound}[b:\mathbb{R}, S:\mathbf{Set}\langle\mathbb{R}\rangle]$

$\Leftrightarrow \text{UpperBound}[b, S] \wedge \forall [x \in S] \rightarrow \text{UpperBound}[x, S] \Leftrightarrow x \leq b$

⁵¹ Robinson [1961]

⁵² The Continuum Hypothesis remains an open problem for Direct Logic because its set theory is very powerful. The forcing technique used to prove the independence of the Continuum Hypothesis for first-order set theory [Cohen 1963] does not apply to Direct Logic because of the strong

induction axiom [Dedekind 1888, Peano 1889] used in formalizing the natural numbers \mathbb{N} .

Of course, trivially, either:

- $(\models_{\mathbb{N}} \text{ContinuumHypothesis})$

or

- $(\models_{\mathbb{N}} \neg \text{ContinuumHypothesis})$

According to [Isaacson 2008]:

“In a sense made precise and established by the use of second-order logic [Dedekind 1888], there is only one set theory of the continuum. It remains an open question whether in that set theory [the continuum hypothesis holds or not].”

⁵³ According to Maybary [2000]:

“Why has the standard definition of real number become standard? There is a straightforward logical reason; we can write down a set of axioms, the axioms for a complete ordered field, that, on the one hand, strike us as truisms about the real numbers, and, on the other, are categorical in the sense that all structures satisfying the axioms are mutually isomorphic. This means that for any proposition in the standard theory of real numbers, either it or its negation is a logical consequence of the axioms, that is to say, the axioms are complete. Of course, these axioms are of second order, [formal proofs which would allow us to prove all truths and refute all falsehoods. But the categoricity does guarantee that the basic notions of real analysis are well defined and its propositions have definite meanings. Real analysis pursued in this standard way is thus a definite, and determinate, particular theory.”

⁵⁴ According to Isaacson 2008]: “The ZF axioms for pure sets with second-order Replacement determine every-thing about the cumulative hierarchy of sets except its height.”

⁵⁵ This implies, for example, that no set is an element of itself.

⁵⁶ Chaitin's criticism is partially supported by the fact that even Gödel himself agreed that the subsequent proof of incompleteness by Church/Turing based on computational undecidability was fundamental in proving that there is no total recursive procedure that can decide provability of a proposition of the Peano/Dedekind theory \mathbb{N} of natural numbers. There must be an inferentially undecidable proposition for \mathbb{N} because otherwise provability of any proposition could be computationally decided by enumerating all theorems until the proposition or its negation occurs. However, Gödel, Church, Turing, and many other logicians continued for a long time to believe in the importance of Gödel's proof based on his sentence “*I'm unprovable.*”

⁵⁷ [Wittgenstein in 1937 published in Wittgenstein 1956, p. 50e and p. 51e]

⁵⁸ [Wang 1997] pg. 197.

⁵⁹ In Direct Logic, 1) can be inferred from 3) within \mathcal{PL} .

⁶⁰ In Classical Direct Logic, $(\Phi \vdash_{\mathcal{P}L} \Psi) \Leftrightarrow \vdash_{\mathcal{P}L} (\Phi \Rightarrow \Psi)$.

⁶¹ In Direct Logic, 3) can be inferred from 1) within $\mathcal{P}L$.

⁶² Note that the rule of Soundness [*i.e.* $(\vdash \Phi) \Rightarrow \Phi$] does not involve any coding of propositions as integers. If the soundness were allowed in $\mathcal{P}L$, then it would be inconsistent because every sentence would be provable in $\mathcal{P}L$ by [Löb 1955] which is the following:⁶²

$$(\vdash_{\mathcal{P}L} ((\vdash_{\mathcal{P}L} \Phi) \Rightarrow \Phi)) \Rightarrow \vdash_{\mathcal{P}L} \Phi$$

⁶³ In 1666, England's House of Commons introduced a bill against atheism and blasphemy, singling out Hobbes' Leviathan. Oxford university condemned and burnt Leviathan four years after the death of Hobbes in 1679.

⁶⁴ There is no subset of \mathbb{R} whose cardinality is strictly between \mathbb{N} and \mathbb{R} .

⁶⁵ [Cohen 2006] Cohen's proof was a great achievement in spite of the weakness of his theorem.

⁶⁶ because the computable real numbers are enumerable.

⁶⁷ [Zermelo 1930, van Dalen 1998, Ebbinghaus 2007]

⁶⁸ First-order theories fall prey to paradoxes like the Löwenheim–Skolem theorems (*e.g.* any first-order theory of the real numbers has a countable model). First-order theorists have used the weakness of first-order logic to prove results that do not hold in stronger formalisms such as Direct Logic [Cohen 1963, Barwise 1985].

⁶⁹ *e.g.* the theory *RealClosedField* [Tarski 1951]

⁷⁰ *i.e.* in classical notation: $\{\neg P[m] \mid m:\mathbb{N}\}$

⁷¹ unique up to isomorphism via a unique isomorphism

⁷² Rejection of the First-Order Thesis resolves the seeming paradox between the formal proof in this article that Mathematics formally proves its own consistency and the formal proof that ‘Every “strong enough” formal system that admits a proof of its own consistency is actually inconsistent.’ [Paulson 2014]. Although Mathematics is “strong enough,” the absence of “self-referential” propositions (constructed using a **Y** fixed point on untyped sentences for Mathematics) blocks the proof of inconsistency to which Paulson referred.

⁷³ Statement of Church's Paradox

⁷⁴ See Historical Appendix. The Liar Paradox [Eubulides of Miletus] is an example of using untyped sentences to derive an inconsistency. However, strong typing prevents an inconsistency as follows:

Liar:Nonexistent $\equiv \neg$ **Liar**

// above definition is illegal because \neg **Liar** is of

// type **Proposition** order greater than **Liar**

1) **Liar** $\Leftrightarrow \neg$ **Liar**

// definition of **Liar**

2) \neg **Liar**

// proof by contradiction from 1)

3) **Liar**

// chaining 1) and 2)

⁷⁵In formalizing Gödel's proof, [Shankar 1994] and [O'Connor 2005] followed Gödel in using integers to code “self-referential” sentences using **Y** fixed points (using untyped sentences for mathematics).

⁷⁶In Direct Logic, **Y** fixed points on propositions or functions cannot be strongly typed and consequently are not valid for the following reasons:

- The **Y** fixed point functional operator cannot be defined using Direct Logic:

$$\mathbf{Helper}\langle\tau\rangle[f:\tau^\top]:\mathbf{Nonexistent} \equiv \lambda[x:\mathbf{Nonexistent}]:\tau \rightarrow f[x[x]]$$

$$\mathbf{Y}\langle\tau\rangle[f:\tau^\top]:\mathbf{Nonexistent} \equiv (\mathbf{Helper}\langle\tau\rangle[f])[\mathbf{Helper}\langle\tau\rangle[f]]$$

In the above, the expression $x[x]$ is illegal because it has no proper type.

- The **Y** fixed point logical operator cannot be defined using Direct Logic:

$$\mathbf{Helper}[f:\mathbf{Nonexistent}]:\mathbf{Nonexistent} \equiv$$

$$\lambda[x:\mathbf{Nonexistent}]:\mathbf{Nonexistent} \rightarrow f[x[x]]$$

$$\mathbf{Y}[f:\mathbf{Nonexistent}]:\mathbf{Nonexistent} \equiv (\mathbf{Helper}[f])[\mathbf{Helper}[f]]$$

In the above, the expression $x[x]$ is illegal because it has no proper type as a proposition.

⁷⁷Recently, [Yanofsky 2013 page 328] has expressed concern about Löb's paradox:

we must restrict the fixed-point machine in order to avoid proving false statements [using Löb's argument]. Such a restriction might seem strange because the proof that the fixed-point machine works seems applicable to all [functions on sentences in an untyped syntax of sentences]. But restrict we must.

Yanofsky solved the above problem posed by Löb's paradox using systems of logic that are so weak that they cannot abstract their own sentences. Unfortunately, such weak systems are inadequate for Computer Science. Instead of weakening, Direct Logic adopted the strategy of barring “self-referential” propositions by using a types for mathematics that does not allow the **Y** fixed-point machinery for sentences.

⁷⁸using definition of BSet

⁷⁹using definition of BExpression

⁸⁰substituting BNumber for n