

KRIPKE'S THEORY OF TRUTH

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1. INTRODUCTION

The purpose of this note is to give a simple, easily accessible proof of the existence of the minimal fixed point, and of various maximal fixed points, under the Strong Kleene valuation scheme.¹ We begin by recording a few facts about unions and intersections which are used throughout, and which cannot be expected to be familiar to all students.

Definition. Let A be a set. Then $\cup A$ is the union of all the sets contained in A ; $\cap A$ is their intersection. That is, $x \in \cup A$ if, and only if, $\exists y(y \in A \wedge x \in y)$ and $x \in \cap A$ if, and only if, $\forall y(y \in A \rightarrow x \in y)$.

Proposition 1.1. *Let A be a set of sets and let y be a set. Then,*

- (1) *If y is a subset of some member of A , then y is a subset of $\cup A$. I.e., $\exists z(z \in A \wedge y \subseteq z) \rightarrow y \subseteq \cup A$. A fortiori, if $z \in A$, then $z \subseteq \cup A$.*
- (2) *If y is a superset of every member of A , then y is a superset of $\cap A$. I.e., $\forall z(z \in A \rightarrow z \subseteq y) \rightarrow \cap A \subseteq y$. A fortiori, if $z \in A$, then $\cap A \subseteq z$.*
- (3) *If y is a subset of every member of A , then y is a subset of $\cap A$. I.e., $\forall z(z \in A \rightarrow y \subseteq z) \rightarrow y \subseteq \cap A$.*
- (4) *If y is a superset of some member of A , then y is a superset of $\cap A$. I.e., $\exists z(z \in A \wedge z \subseteq y) \rightarrow \cap A \subseteq y$.*

¹I therefore have striven to keep the set-theoretic machinery to a minimum. No reference is made to ordinals: The only principle of set-theory not likely to be familiar to a beginner is Zorn's Lemma, which I assume, rather than prove (from choice). The method of proof used here therefore has certain disadvantages, as compared to Kripke's. Because ordinals are not used, and fixed-points are not constructed as the limits of sequences of theories, it is not possible to define a notion of level in these terms. Furthermore, while one can show that some sentences do not have truth-values in the minimal fixed point (are ungrounded), namely, by showing that they have different truth-values in some fixed points (see section 5), the technique obviously does not work for sentences that have intrinsic truth-values.

In developing the proof given here, I have drawn heavily upon work by Melvin Fitting [1]. The version of the proof given here is somewhat simpler than Fitting's, in large part because I have eschewed generality in favor of perspicuity. I independently discovered a proof dual to that given below in about 1990.

Proof. We prove (1) and (2). For (1), suppose that y is a subset of z , which is a member of A . Then, since $z \in A$, $z \subseteq \cup A$. So $y \subseteq z \subseteq \cup A$, so $y \subseteq \cup A$. Since $z \subseteq z$, then of course $z \subseteq \cup A$.

For (2), suppose that y is a superset of every member of A . Let $x \in \cup A$. Then, by the definition of $\cup A$, there is some $w \in A$ such that $x \in w$. But $w \subseteq y$, so $x \in y$. And again, since $z \subseteq z$, of course $\cap A \subseteq z$. \square

2. ZORN'S LEMMA

The proof we are going to give below depends upon *Zorn's Lemma*, to state which we need a few definitions.

Definition. Let C be a set of sets. C is said to be a *chain* iff $C \neq \emptyset$ and, for any two members x and y of C , one is a subset of the other. Thus, C is a chain only if $\forall x \forall y (x \in C \wedge y \in C \rightarrow x \subseteq y \vee y \subseteq x)$.

Definition. Let D be a set of sets. D is said to be *closed under unions of chains* iff the union of any chain which is a subset of D is an element of D . That is, D is closed under unions of chains iff: $\forall C [C \subseteq D \wedge C \text{ is a chain} \rightarrow \cup C \in D]$.

Definition. Let D be a set of sets. An element x of D is said to be a *maximal element* of D if it is the only member of D of which it is a subset, i.e., if no superset of it is in D . Thus, x is maximal in D iff $\forall y (y \in D \wedge x \subseteq y \rightarrow x = y)$.

Lemma 2.1 (Zorn's Lemma). *Let D be a non-empty set which is closed under unions of chains and let $A \in D$. Then there is a maximal element of D of which A is a subset.*

Zorn's Lemma can be proven from the so-called Axiom of Choice (and the other axioms of set-theory), but we shall here simply take it as an axiom. (It is, in fact, equivalent to Choice, so this is reasonable.) Intuitively, the idea is this. Let A be an element of D and suppose, for *reductio*, that there is no superset of A that is a maximal element of D . If A had no proper superset, it would itself be maximal, so there is some bigger member of D of which A is a subset, call it A_1 . Similarly, A_1 must have a proper superset, call it A_2 ; which must in turn have a proper superset, A_3 ; and so on. Keep going in this way as long as you can; if you get through A_1, \dots, A_n, \dots , for all n , then take their union and keep going; etc. The sets A_i formed in this way will form a *chain* of elements of D , call it C : By construction, $A_i \subseteq A_{i+1}$.² Since D is closed under unions of chains, $\cup C \in D$. Moreover, $\cup C$ is a maximal element of D . For suppose not. Then $\cup C$ has some proper superset, call it y . But then $C \cup \{y\}$ is a chain of elements of D that is bigger than C , and in forming C we were supposed to keep going as long as we could. Contradiction.

²It is to prove that this is possible that the Axiom of Choice is needed.

3. K RIPKE'S CONSTRUCTION: INTERPRETATIONS

Definition. The T-rules are the following:

$$\begin{aligned} A &\vdash T(\ulcorner A \urcorner) \\ \neg A &\vdash \neg T(\ulcorner A \urcorner) \\ T(\ulcorner A \urcorner) &\vdash A \\ \neg T(\ulcorner A \urcorner) &\vdash \neg A \end{aligned}$$

Our goal here is to prove that the T-rules are consistent with arithmetic (a similar construction will work, however, for any consistent first-order theory). The language of our theory is thus the language of arithmetic, augmented by the single, additional one-place predicate letter ‘ T ’. We assume some fixed Gödel numbering of the sentences of our language, the details of which need not concern us.³ A sentence of the form ‘ $T(\mathbf{n})$ ’—here, we use ‘ \mathbf{n} ’ as a name of the numeral denoting n (that is, for: $\underbrace{S \dots S}_n 0$)—is intended to mean that the sentence with Gödel number n is true.⁴

We will construct an *interpretation* of our language that meets the following three desiderata:

- (1) all truths of arithmetic are true in that interpretation;
- (2) a sentence A is true under that interpretation if, and only if, $T(\ulcorner A \urcorner)$ is true under that interpretation;
- (3) a sentence A is false under that interpretation (i.e., its negation is true) if, and only if, $T(\ulcorner A \urcorner)$ is false under that interpretation (i.e., its negation is true).

Any such interpretation will be one in which all truths of arithmetic are true (by (1)) and in which the T-rules are *truth-preserving* (by (2) and (3)).

What is an interpretation of this language to be like, then? The key idea is that we can allow a sentence of the form $T(\mathbf{n})$ not to have a truth-value at all. If so, of course, we cannot then use the usual truth-tables to determine the values of negations, conjunctions, and the like, since the usual truth-tables assume that every sentence has a truth-value (either true or false).

Let us first discuss the logical constants. One can, in fact, proceed here in a variety of different ways. The simplest, however, is this. (This is called the Strong Kleene valuation scheme.) We want the truth-values

³For a simple presentation of the formal machinery needed here, see my “Formal Background for Theories of Truth”.

⁴Henceforth, we shall frequently omit quotation marks, to improve readability.

of complex sentences to agree with those given by the truth-tables *if* all the constituent sentences themselves have truth-values; and we want to preserve certain basic intuitions, such as that a disjunction is true if either disjunct is true. So we make the following stipulations. First, we say that $\neg A$ is true if A is false; false, if A is true; and has no truth-value if A has no truth-value. Secondly, we say that $A \vee B$ is true, if either A or B is true; false, if both A and B are false; and has no truth-value, otherwise. We thus have, in effect, the following ‘three-valued’ truth-tables, where ‘ X ’ means ‘has no truth-value’:

\vee	T	X	F
T	T	T	T
X	T	X	X
F	T	X	F

The interpretations of ‘ \wedge ’, ‘ \rightarrow ’, and ‘ \equiv ’ are then given by their usual definitions in terms of ‘ \neg ’ and ‘ \vee ’. So, $A \wedge B$ is true, if both A and B are true; false, if either A or B is false; and without truth-value, otherwise. $A \rightarrow B$ is true if either A is false or B is true; false, if A is true and B is false; and without truth-value, otherwise. And $A \equiv B$ is true if A and B have the same truth-value; false if they have different truth-values; and without truth-value if either of them is without truth-value.

The quantifiers are then interpreted, as usual, as being infinite conjunction and infinite disjunction: A sentence of the form $\forall x A(x)$ will be true if $A(x)$ is true for every assignment of an object to ‘ x ’; false, if $A(x)$ is false for some assignment to ‘ x ’; and without truth-value otherwise. Similarly, $\exists x A(x)$ is true if $A(x)$ is true for some assignment to ‘ x ’; false, if it is false for every assignment to ‘ x ’; and without truth-value, otherwise.

Since we are interested here in the language of arithmetic, we can simplify our treatment of the quantifiers. Every object in the domain is a natural number, and every natural number has a standard name, the numeral that denotes it. So $A(x)$ is true for every assignment of an object to ‘ x ’ iff $A(n)$ is true for every numeral n ; and $A(x)$ is false for some assignment to ‘ x ’ iff $A(n)$ is false for some numeral n . In the present context, then, we can characterize the truth of quantified sentences in terms of the *truth* of their instances, rather than having to talk, more generally, about satisfaction. The techniques used below can be applied to the case of satisfaction as well as truth, but doing so introduces complications that are not particularly enlightening.

We can now ensure that the first desideratum above will be satisfied simply by interpreting the arithmetical part of the language in the usual way. So the domain will be the set of natural numbers; ‘0’ will denote zero; ‘ S ’, succession; ‘+’, addition; and ‘ \times ’, multiplication. In any such interpretation, all the purely arithmetical sentences will be given their intended interpretation and so will be true in the interpretation just in

case they are (really) true.⁵ Thus, we need only consider, henceforth, what a particular interpretation does with the predicate T .

How are we to allow that a sentence of the form $T(n)$ might not have a truth-value? One standard way to treat predicates in a three-valued setting is to take them to have an *extension* and an *anti-extension*, where the extension is the set of objects of which the predicate is true, and the anti-extension is the set of objects of which it is false.⁶ This is how Kripke proceeds. But in the present case, there is a simpler method. We still assign just an extension to T , and we say that $T(n)$ is true if n is in the extension of T ; but we say that $T(n)$ is *false*—not if n is not in the extension of T , but—if n is the Gödel number of some sentence A and the Gödel number of its *negation* is in the extension of T : That is, $T(\ulcorner A \urcorner)$ is false iff $T(\ulcorner \neg A \urcorner)$ is true.⁷

We place one restriction upon the extensions assigned to T : They may not contain any number which is not the Gödel number of a sentence. Thus, if n is not the Gödel number of a sentence, then it will never be in the extension of T , so $T(n)$ will always be without truth-value. (This is different from how Kripke does it: He insists that the Gödel numbers of non-sentences should be in the anti-extension.)

Given how we have interpreted T , the third desideratum on the interpretation we are seeking will follow from the second. These were:

2. a sentence A is true under a given interpretation if, and only if, $T(\ulcorner A \urcorner)$ is true under that interpretation;
3. a sentence A is false under the interpretation (i.e., its negation is true) if, and only if, $T(\ulcorner A \urcorner)$ is false under that interpretation (i.e., its negation is true).

Suppose that (2) holds, and let A be a sentence. Then $\neg A$ is true iff (by (2)) $T(\ulcorner \neg A \urcorner)$ is true iff (by the rules for interpreting T) $T(\ulcorner A \urcorner)$ is false iff (by the rules for negation) $\neg T(\ulcorner A \urcorner)$ is true. So $\neg A$ is true iff $\neg T(\ulcorner A \urcorner)$ is true, and we need not worry any more about (3).

Suppose we have an interpretation which assigns to T , as its extension, some set S . Some sentences come out true under this interpretation. Let $\mathbf{T}(S)$ be the set whose members are exactly the Gödel numbers of those sentences that come out true under this interpretation. Thus, $\mathbf{T}(x)$ is a function on sets.

⁵This depends, of course, upon the fact that the three-valued truth-tables agree with the classical tables when everything has a truth-value.

⁶More generally still, in a many-valued setting, one can take the semantic value of a predicate to be a function from objects to truth-values. In the present case, one could adopt that strategy or one could take there to be just the two truth-values, true and false, and allow the function to be partial.

⁷I owe this trick to George Boolos.

Instead of saying, all the time, “ A is true under the interpretation that assigns the set S as extension of ‘ T ’ and is otherwise as said above”, we shall say simply: A is true $_S$. Thus, $n \in \mathbf{T}(S)$ iff the sentence with Gödel number n is true $_S$. When we speak of a sentence’s being true *simpliciter*, we mean sentences which really are true, such as ‘ $0 = 0$ ’.

Example. Consider the interpretation which assigns to T , as its extension, the empty set, \emptyset . What sentences will come out true under this interpretation? Well, certainly every true ‘purely arithmetical’ sentence—i.e., every true sentence not containing T —will be true $_{\emptyset}$, since the arithmetical part of the language is given its intended interpretation. There will be some sentences containing T that are true $_{\emptyset}$, as well, for example, $0 = 0 \vee T(\ulcorner 0 = 1 \urcorner)$, since $0 = 0$ is true $_{\emptyset}$, and so the disjunction of this sentence with any other sentence is true $_{\emptyset}$, as well. But no sentence of the form $T(\mathbf{n})$ is true $_{\emptyset}$, since the extension of T is empty. $\mathbf{T}(\emptyset)$ thus contains the Gödel numbers of all true purely arithmetical sentences, and some other numbers besides.

Example. Consider the interpretation which assigns to T , as its extension, the set of all Gödel numbers of sentences—call it $Sent$. What sentences come out true under this interpretation? Well, all true purely arithmetical sentences, again. And, if n is the Gödel number of a sentence, then $T(\mathbf{n})$ is true $_{Sent}$. So, in particular, both $T(\ulcorner 0 = 0 \urcorner)$ and $T(\ulcorner \neg 0 = 0 \urcorner)$ are true $_{Sent}$, which means that $T(\ulcorner 0 = 0 \urcorner)$ is also false $_{Sent}$ —since $T(\ulcorner 0 = 0 \urcorner)$ is false $_{Sent}$ iff $T(\ulcorner \neg 0 = 0 \urcorner)$ is true $_{Sent}$. So the interpretation that assigns the set of all Gödel numbers of sentences to S is, in an obvious sense, *inconsistent*: It makes some sentences come out both true and false.

Obviously, inconsistent interpretations are not going to do us much good. So we need to restrict our attention to consistent ones. Say that a set S is a *consistent set* if it does not contain both the Gödel number of A and that of $\ulcorner \neg A \urcorner$, for any sentence A .

Definition. Con is the set of all consistent sets of Gödel numbers of sentences.

Lemma 3.1. *If S is a consistent set, then the interpretation that makes S the extension of T is a consistent interpretation. That is, if $S \in Con$, then no sentence is both true $_S$ and false $_S$.*

Proof. The proof is by induction on the complexity of formulas. We show, first, that no atomic sentence can be both true $_S$ and false $_S$; and then we show that, if A and B are not both true $_S$ and false $_S$, then neither are ‘ $\neg A$ ’, ‘ $A \vee B$ ’, ‘ $A \wedge B$ ’, ‘ $A \rightarrow B$ ’, and ‘ $A \equiv B$ ’; and, that if no sentence of the form $A(\mathbf{n})$ is both true $_S$ and false $_S$, then neither is $\forall xA(x)$ or $\exists xA(x)$.

If A is atomic, then it is either purely arithmetical or of the form $T(t)$, for some term t . If the former, it certainly cannot be both true_S and false_S , since it will have whatever truth-value it has in the intended interpretation of the language of arithmetic. If the latter, suppose that t denotes the number n . If $T(t)$ is true_S , $n \in S$; and if it is false_S , then the Gödel number of the negation of the sentence whose Gödel number is $n \in S$. But then S is not consistent, *contra* our supposition.

Suppose then that both A and B are not both true_S and false_S . If $\neg A$ is both true_S and false_S , then A itself must be both false_S and true_S . Similarly, if $A \wedge B$ is both true_S and false_S , both A and B must be true_S , and at least one of A and B must be false_S . Similarly for the conditional and biconditional.

So suppose that no sentence of the form $A(n)$ is both true_S and false_S . If $\forall x A(x)$ is both true_S and false_S , then, first, $A(n)$ must be true_S for every n . But ' $A(n)$ ' must also be false_S for some n . But then some sentence ' $A(n)$ ' must be both true_S and false_S . Similarly for $\exists x A(x)$. \square

Corollary 3.2. *If S is consistent, so is $\mathbf{T}(S)$.*

Proof. Suppose $\mathbf{T}(S)$ is not consistent. Then, for some sentence A , $\mathbf{T}(S)$ must contain both the Gödel number of A and that of $\neg A$. Now, $\mathbf{T}(S)$ contains the Gödel numbers of sentences which are true_S . So both A and ' $\neg A$ ' must be true_S , i.e., A must be both true_S and false_S . But then, by 3.1, S is not consistent. \square

4. KRIPKE'S CONSTRUCTION: FIXED POINT MODELS

We are looking for an interpretation satisfying conditions (1)–(3), and to give such an interpretation we need only specify an appropriate set S as the extension of ' T '. Using our function $\mathbf{T}(x)$, it is easy to characterize the sets S that will do the trick.

Definition. S is a *fixed-point* of $\mathbf{T}(x)$ iff S is a consistent set and $S = \mathbf{T}(S)$.

Proposition 4.1. *If S is a fixed point of $\mathbf{T}(x)$, then the interpretation that makes S the extension of T satisfies (1)–(3).*

Proof. As argued earlier, desideratum (3) is satisfied if (2) is. And (1) is satisfied by *any* interpretation of the sort we are considering. So we need only check that (2) is satisfied:

2. A is true_S if, and only if, $T(\ulcorner A \urcorner)$ is true_S .

But A is true_S iff (by the definition of \mathbf{T}) the Gödel number of A is in $\mathbf{T}(S)$ iff (since S is a fixed point) the Gödel number of A is in S iff (by the rules for determining the truth-value of $T(t)$) $T(\ulcorner A \urcorner)$ is true_S . \square

So all we now need to do is to show that there is a fixed point of $T(x)$. We will in fact show two things: That $T(x)$ has *maximal* fixed points and that $T(x)$ has a *minimal* fixed point. By the definition given earlier, a fixed point is maximal if there is no other fixed point of which it is a subset. Such a fixed point will, as Kripke puts it, assign as many truth-values as is consistently possible. A fixed point is *minimal* if there is no other fixed point of which it is a superset. In fact, we shall see that there is a *unique* minimal fixed point that is a subset of every fixed point. Thus, the minimal fixed point is the one that contains the Gödel numbers of those sentences whose Gödel numbers must be in *any* fixed point.

Before giving the proofs, we need a couple preliminary results.

Lemma 4.2. *Let $S \subseteq R$. Then, if A is true_S, it is true_R. Moreover, if A is false_S, then it is false_R.*

Proof. By induction on the complexity of expressions. Certainly this holds if A is a purely arithmetical atomic sentence, since the truth of purely arithmetical sentences is not affected by what is assigned to T . Suppose that A is of the form $T(t)$ and that t denotes n . If $T(t)$ is true_S, then $n \in S$, but $S \subseteq R$, so $n \in R$, so $T(t)$ is true_R. And if $T(t)$ is false_S, then there must be some sentence B such that n is the Gödel number of B and the Gödel number of $\ulcorner \neg B \urcorner$, say m , is in S . But $S \subseteq R$, so $m \in R$, whence $T(t)$ is false_R, too.

Suppose now that A is logically complex, i.e., of one of the forms: $\neg B$, $B \vee C$, etc., $\forall xB(x)$, etc. We want to show that if B and C satisfy the lemma, then so do $\neg B$, $B \vee C$, etc., and that if all sentences of the form $B(n)$ do, then so do $\forall xB(x)$, etc.⁸ The proof is straightforward but tedious.

If A is $\neg B$ and A is true_S, then B must be false_S. But then, by the induction hypothesis, B must also be false_R, so $\ulcorner \neg B \urcorner$, i.e., A must be true_R. And if $\ulcorner \neg B \urcorner$ is false_S, then B is true_S, whence B is true_R, whence $\ulcorner \neg B \urcorner$ is false_R.

Similarly, if A is $\ulcorner B \vee C \urcorner$ and is true_S, at least one of B and C must be true_S; but that sentence must also be true_R, by the induction hypothesis, whence $\ulcorner B \vee C \urcorner$ must also be true_R. And if $\ulcorner B \vee C \urcorner$ is false_S, both B and C must be false_S, whence they must both be false_R, whence $\ulcorner B \vee C \urcorner$ is false_R.

If A is $\ulcorner \forall xB(x) \urcorner$ and is true_S, then $B(n)$ must be true_S for every numeral n ; so all such sentences must be true_R; but then $\ulcorner \forall xB(x) \urcorner$ is true_R, too.

⁸Strictly speaking, of course, we can simply take the elided formulae to be defined in terms of the rest, so we do not really need to check them.

And if $\ulcorner \forall x B(x) \urcorner$ is false_S , $B(n)$ must be false_S for some numeral n and so false_R , $\ulcorner \forall x B(x) \urcorner$ is false_R .

The other propositional connectives and the existential quantifier are left as Exercise 14. \square

Corollary 4.3. *If $S \subseteq T$, then $\mathbf{T}(S) \subseteq \mathbf{T}(T)$. That is, $\mathbf{T}(x)$ is ‘monotonic’.*

Proof. Suppose that $S \subseteq T$ and that $n \in \mathbf{T}(S)$. $\mathbf{T}(S)$ contains the Gödel numbers of sentences that are true_S . But any such sentence is, by 4.2, also true_T . So $n \in \mathbf{T}(T)$. \square

This is the crucial fact for all that follows. As a close examination of the proofs will show, the only fact about \mathbf{T} upon which they rely is that \mathbf{T} is monotonic. Hence, our choice of the Strong Kleene valuation scheme is, in a certain sense, arbitrary: Other ways of handling the logical constants will also work, so long as the (analogous) operator \mathbf{T} defined in terms of them is monotonic.⁹

Lemma 4.4. *Con is closed under intersections and also under unions of chains. That is, if $B \subseteq \text{Con}$ and $B \neq \emptyset$, then $\cap B \in \text{Con}$ and, if B is a (non-empty) chain, then $\cup B \in \text{Con}$.*

Proof. Suppose $B \subseteq \text{Con}$, $B \neq \emptyset$. Then $\cap B$ is certainly a set of Gödel numbers of sentences. And it is consistent, since, if it contained both the Gödel number of some sentence A and that of its negation, every element of B would also contain these. But every element of B is consistent.

Suppose now that B is a chain. Then again, $\cup B$ is a set of Gödel numbers of sentences. Suppose, for *reductio*, that it is not consistent. Then there is some sentence A such that $\cup B$ contains both the Gödel number of A , say n , and that of $\ulcorner \neg A \urcorner$, say m . Since $n \in \cup B$, there must be some $D \in B$ such that $n \in D$. Similarly, for some $E \in B$, $m \in E$. Since B is a chain, either $D \subseteq E$ or $E \subseteq D$. If the former, then $n \in D \subseteq E$, so $n \in E$. But then E contains both n and m , i.e., both the Gödel number of A and that of $\ulcorner \neg A \urcorner$ and is therefore not consistent. Similarly, if $E \subseteq D$, then D is not consistent. So $\cup B$ is consistent. \square

Sets S for which $S \subseteq \mathbf{T}(S)$ are of special interest. Such sets are often called ‘sound’, for this reason: Suppose that $S \not\subseteq \mathbf{T}(S)$. Then there is a sentence $A \in S$ such that $A \notin \mathbf{T}(S)$, i.e., such that A is not true_S . Thus, in the interpretation that treats S as the extension of the truth-predicate, $\mathbf{T}(\ulcorner A \urcorner)$ is true—that is, it is true_S —and yet A itself is *not* true in this interpretation—it is not true_S . On the other hand, if $S \subseteq \mathbf{T}(S)$, then any sentence $A \in S$ is true_S . So, in that sense, S is ‘sound’: The sentences

⁹See my “Truth and Inductive Definability” for an examination of the sense in which this is so.

that S 'says' are true are true _{S} . What the following theorem says is thus that every sound set can be extended to a maximal fixed point.¹⁰

Theorem 4.5 (Fixed Point Theorem). *Suppose that $S \in \text{Con}$ and that S is sound, i.e., that $S \subseteq \mathbf{T}(S)$. Then $\mathbf{T}(x)$ has a maximal fixed point of which S is a subset.*

Proof. Let $B = \{X \in \text{Con} : X \subseteq \mathbf{T}(X)\}$. B is non-empty, since $S \in B$. We want to show that B is closed under unions of chains. So let $C \subseteq B$ be a (non-empty) chain. We must show that $\cup C \in \text{Con}$ and that $\cup C \subseteq \mathbf{T}(\cup C)$.

Now $B \subseteq \text{Con}$, so since $C \subseteq B$, $C \subseteq \text{Con}$. By 4.4, Con is closed under unions of chains. So $\cup C \in \text{Con}$.

To show that $\cup C \subseteq \mathbf{T}(\cup C)$, it suffices, by part (2) of proposition 1.1, to show that every member of C is a subset of $\mathbf{T}(\cup C)$. So suppose that $X \in C$. Then $X \subseteq \cup C$, trivially, so, since $\mathbf{T}(x)$ is monotonic, $\mathbf{T}(X) \subseteq \mathbf{T}(\cup C)$. Since $X \in C \subseteq B$, $X \in B$, so $X \subseteq \mathbf{T}(X)$. So $X \subseteq \mathbf{T}(X) \subseteq \mathbf{T}(\cup C)$, for any $X \in C$. So $\cup C \subseteq \mathbf{T}(\cup C)$.

So B is closed under unions of chains. By Zorn's Lemma, there is a maximal member of B of which S is a subset—call it M_S . We now show that M_S is a maximal fixed point of $\mathbf{T}(x)$. $M_S \in B$, so $M_S \subseteq \mathbf{T}(M_S)$. Since $\mathbf{T}(x)$ is monotonic, $\mathbf{T}(M_S) \subseteq \mathbf{T}(\mathbf{T}(M_S))$. And since M_S is consistent, $\mathbf{T}(M_S)$ is also consistent, by 3.1. Thus, $\mathbf{T}(M_S) \in \text{Con}$ and $\mathbf{T}(M_S) \subseteq \mathbf{T}(\mathbf{T}(M_S))$. So $\mathbf{T}(M_S) \in B$. But M_S is a maximal element of B , so, since $M_S \subseteq \mathbf{T}(M_S)$, we have $M_S = \mathbf{T}(M_S)$, and so M_S is a fixed point of $\mathbf{T}(x)$.

Finally, M_S is a maximal fixed point. For let F be a fixed point other than M_S . So $F \in \text{Con}$ and $F = \mathbf{T}(F)$. But then, obviously, $F \subseteq \mathbf{T}(F)$, whence $F \in B$. But M_S is maximal in B , so F is not a superset of M_S . \square

Corollary 4.6. $\mathbf{T}(x)$ has at least one maximal fixed point.

Proof. Obviously, $\emptyset \subseteq \mathbf{T}(\emptyset)$. So, by 4.5, $\mathbf{T}(x)$ has a maximal fixed point of which \emptyset is a subset. \square

Theorem 4.7 (Kripke). $\mathbf{T}(x)$ has a unique minimal fixed point.

Proof. Let $B = \{X \in \text{Con} : \mathbf{T}(X) \subseteq X\}$. Let M be a maximal fixed point of $\mathbf{T}(x)$. Then $M \in \text{Con}$ and $M = \mathbf{T}(M)$. So B is non-empty.

We now show that $\cap B$ is a fixed point of $\mathbf{T}(x)$. Certainly, $\cap B \in \text{Con}$, since Con is closed under intersections, by 4.4.

To show that $\cap B = \mathbf{T}(\cap B)$, we show both that $\mathbf{T}(\cap B) \subseteq \cap B$ and that $\cap B \subseteq \mathbf{T}(\cap B)$.

¹⁰For this reason, Michael Kremer calls sound sets 'fixable'.

To prove the former, it is enough to show, by part (3) of 1.1, that $\mathbf{T}(\cap B)$ is a subset of every member of B . So assume $X \in B$. Then $\cap B \subseteq X$, so since $\mathbf{T}(x)$ is monotonic, $\mathbf{T}(\cap B) \subseteq \mathbf{T}(X)$. But since $X \in B$, $\mathbf{T}(X) \subseteq X$, so $\mathbf{T}(\cap B) \subseteq X$.

To prove the latter, it is enough to show that $\mathbf{T}(\cap B) \in B$. For then certainly $\cap B \subseteq \mathbf{T}(\cap B)$, since $\cap B$ is a subset of every member of B , by proposition 1.1. Now, $\cap B \in \text{Con}$, so $\mathbf{T}(\cap B) \in \text{Con}$, by 3.2. Since, by the argument of the last paragraph, $\mathbf{T}(\cap B) \subseteq \cap B$. But $\mathbf{T}(x)$ is monotonic, so $\mathbf{T}(\mathbf{T}(\cap B)) \subseteq \mathbf{T}(\cap B)$. Thus, $\mathbf{T}(\cap B) \in \text{Con}$ and $\mathbf{T}(\mathbf{T}(\cap B)) \subseteq \mathbf{T}(\cap B)$, so $\mathbf{T}(\cap B) \in B$. So $\cap B = \mathbf{T}(\cap B)$, and $\cap B$ is a fixed point.

Let F be any fixed point of $\mathbf{T}(x)$. Then $F \in \text{Con}$ and $\mathbf{T}(F) = F$, so certainly $\mathbf{T}(F) \subseteq F$. Hence $F \in B$, whence $\cap B \subseteq F$. So $\cap B$ is minimal. \square

Note that the minimal fixed point is *not* the intersection of all *maximal* fixed points. In fact, it is not obvious that the intersection of all maximal fixed points is a fixed point at all, or even a sound set.

5. APPLICATIONS

We know from Tarski's Theorem that not all instances of ' $A \equiv T(\ulcorner A \urcorner)$ ' can be true. But we can say a bit more about their status in Kripke's construction.

Remark 5.1. No instance of ' $A \equiv T(\ulcorner A \urcorner)$ ' is false in any fixed point.

Proof. Suppose ' $A \equiv T(\ulcorner A \urcorner)$ ' is false _{S} , where S is a fixed point. Then either A is true _{S} and $T(\ulcorner A \urcorner)$ is false _{S} or conversely. But if A is true _{S} , then, since fixed points satisfy the T-rules, $T(\ulcorner A \urcorner)$ must also be true _{S} , so S is not consistent. Similarly, if A is false _{S} , then $T(\ulcorner A \urcorner)$ must also be false _{S} . \square

Definition. A sentence is *grounded* if it has a truth-value in the interpretation that assigns as extension of T the minimal fixed point: That is, if either its Gödel number or that of its negation is in the minimal fixed point.

Proposition 5.2. *Let A be a grounded sentence. Then $A \equiv T(\ulcorner A \urcorner)$ is true in the minimal fixed point.*

Proof. Since A is grounded, it has a truth-value in the minimal fixed point: Either it is true, or it is false. If it is true, then $T(\ulcorner A \urcorner)$ is also true; if it is false, then $T(\ulcorner A \urcorner)$ is false. Either way, A and $T(\ulcorner A \urcorner)$ have the same truth-value. So $A \equiv T(\ulcorner A \urcorner)$ is true. \square

It is important to note that the diagonal lemma *does not hold in its classical form in this framework*. According to Gödel's version of the diagonal lemma, and that usually employed, for any formula $A(x)$, there is a sentence G such that

$$\vdash G \equiv A(\ulcorner G \urcorner)$$

But, in the logic in which we are working, it might be that both G and $A(\ulcorner G \urcorner)$ are without truth-value, whence $G \equiv A(\ulcorner G \urcorner)$ will be without truth-value, too. The diagonal lemma does, however, hold in a modified form.

Lemma 5.3 (Modified Diagonal Lemma). *There is a Gödel numbering of the formulae of the language of arithmetic which is such that, if $A(x)$ is any formula, then there is a term t such that:*

$$Q \vdash t = \ulcorner A(t) \urcorner$$

Moreover, there is a sentence G , namely, $A(t)$, such that:

$$\begin{aligned} G &\dashv\vdash A(\ulcorner G \urcorner) \\ \neg G &\dashv\vdash \neg A(\ulcorner G \urcorner) \end{aligned}$$

where the double turnstile means that the inference is valid in both directions.

We shall not prove this version of the diagonal lemma here.¹¹

Consider now the formula $\neg T(x)$. There is, by the modified diagonal lemma, a sentence λ such that:

$$\begin{aligned} \lambda &\dashv\vdash \neg T(\ulcorner \lambda \urcorner) \\ \neg \lambda &\dashv\vdash \neg T(\ulcorner \neg \lambda \urcorner) \end{aligned}$$

Thus, λ is a liar sentence.

Definition. A sentence is *paradoxical* if it has no truth-value in any interpretation that assigns some fixed point as extension of T : That is, if neither its Gödel number nor that of its negation is in any fixed point.

Proposition 5.4. *λ is paradoxical: Neither the Gödel number of λ nor that of its negation belongs to any fixed point.*

Proof. Suppose that F is a fixed point and that the Gödel number of λ is in F . Then $T(\ulcorner \lambda \urcorner)$ is true_F . But then, since F is a fixed point, λ must be true_F , as well. But by construction, λ implies $\neg T(\ulcorner \lambda \urcorner)$, so $\neg T(\ulcorner \lambda \urcorner)$ is also true_F . But then F is not consistent, by 3.1. Similarly, if $\ulcorner \neg \lambda \urcorner$ is in F ,

¹¹Such a result for the case of a language more expressive than that of arithmetic—in particular, for the language of primitive recursive arithmetic—is originally due to Jeroslow [3]. The present form is mentioned by Kripke [4] and is proven in detail in my “Self-reference and the Languages of Arithmetic” [2].

then $T(\ulcorner \neg \lambda \urcorner)$ is true_F , so $\neg T(\ulcorner \lambda \urcorner)$ is false_F ; but $\neg T(\ulcorner \lambda \urcorner)$ implies λ , and again F is not consistent. \square

Proposition 5.5. *Let A be a paradoxical sentence. Then $A \equiv T(\ulcorner A \urcorner)$ is also paradoxical. In particular, $\lambda \equiv T(\ulcorner \lambda \urcorner)$ is paradoxical.*

Proof. Suppose $A \equiv T(\ulcorner A \urcorner)$ has a truth-value in some fixed point F . Then A and $T(\ulcorner A \urcorner)$ must have the same truth-value in F . But then A has a truth-value in F and so is not paradoxical. \square

Now consider the formula $T(x)$. There is, by the modified diagonal lemma, a term τ such that $Q \vdash \tau = \ulcorner T(\tau) \urcorner$. So τ is a truth-teller.

Proposition 5.6. *There are fixed points that contain $\ulcorner T(\tau) \urcorner$ and there are fixed points that contain $\ulcorner \neg T(\tau) \urcorner$.*

Proof. Consider the set $\{\tau\}$. This set is obviously consistent. Moreover, $\{\tau\} \subseteq \mathbf{T}(\{\tau\})$. For $\tau \in \mathbf{T}(\{\tau\})$ just in case the sentence with Gödel number τ is $\text{true}_{\{\tau\}}$. But since, obviously, $\tau \in \{\tau\}$, we have that $T(\tau)$ is $\text{true}_{\{\tau\}}$; but $T(\tau)$ is the sentence Gödel number τ . So $\{\tau\}$ is both sound and consistent. By 4.5, then, there is a (maximal) fixed point M of which $\{\tau\}$ is a subset, that is, of which τ is a member.

Consider now the set $\{\text{neg}(\tau)\}$, where $\text{neg}(\tau)$ is the Gödel number of the negation of the sentence with Gödel number τ , i.e., that of $\ulcorner \neg T(\tau) \urcorner$. This set too is obviously consistent. Moreover, $\{\text{neg}(\tau)\} \subseteq \mathbf{T}(\{\text{neg}(\tau)\})$. For $\text{neg}(\tau) \in \mathbf{T}(\{\text{neg}(\tau)\})$ just in case the sentence with Gödel number $\text{neg}(\tau)$ is $\text{true}_{\{\text{neg}(\tau)\}}$. But since, obviously, $\text{neg}(\tau) \in \{\text{neg}(\tau)\}$, we have that $T(\text{neg}(\tau))$ is $\text{true}_{\{\text{neg}(\tau)\}}$; so $T(\tau)$ is $\text{false}_{\{\text{neg}(\tau)\}}$, whence $\neg T(\tau)$ is $\text{true}_{\{\text{neg}(\tau)\}}$; but, as noted, $\text{neg}(\tau) = \ulcorner \neg T(\tau) \urcorner$, so $\text{neg}(\tau)$ is indeed $\text{true}_{\{\text{neg}(\tau)\}}$. So $\{\text{neg}(\tau)\}$ is both sound and consistent. By 4.5, there is a (maximal) fixed point M of which it is a subset, that is, of which $\text{neg}(\tau)$ is a member. \square

Proposition 5.7. *τ is ungrounded: Neither its Gödel number nor that of its negation is in the minimal fixed point.*

Proof. The minimal fixed point is a subset of every maximal fixed point. If τ were in the minimal fixed point, then, it would have to be in every fixed point. But, as we just saw, there are fixed points that contain $\text{neg}(\tau)$. Such a fixed point cannot contain $\ulcorner \tau \urcorner$, on pain of its not being consistent. Similarly, $\text{neg}(\tau)$ cannot be in the minimal fixed point either. \square

Proposition 5.8. *$T(\ulcorner T(\ulcorner \tau \urcorner) \urcorner) \equiv T(\ulcorner \tau \urcorner)$ is ungrounded. But there is a fixed point F such that it is true_F .*

Proof. The mentioned sentence will be without truth-value whenever $T(\ulcorner \tau \urcorner)$ is, and $T(\ulcorner \tau \urcorner)$ is without truth-value in the minimal fixed point. But there is a fixed point F in which $T(\ulcorner \tau \urcorner)$ is true_F , whence $T(\ulcorner T(\ulcorner \tau \urcorner) \urcorner)$ is true_F , and then so is $T(\ulcorner T(\ulcorner \tau \urcorner) \urcorner) \equiv T(\ulcorner \tau \urcorner)$. \square

Proposition 5.9 (Adapted from Vann McGee [5]). *Let A be any sentence. Then there is a sentence G such that, for every fixed point F , if $G \equiv T(\ulcorner G \urcorner)$ is true_F , then A is true_F .*

Proof. Consider the formula $T(x) \equiv A$. By the modified diagonal lemma, there is a sentence G such that:

$$\begin{aligned} G &\dashv\vdash T(\ulcorner G \urcorner) \equiv A \\ \neg G &\dashv\vdash \neg(T(\ulcorner G \urcorner) \equiv A) \end{aligned}$$

Now, let F be a fixed point and suppose that $G \equiv T(\ulcorner G \urcorner)$ is true_F . Then both G and $T(\ulcorner G \urcorner)$ have a truth-value $_F$, and they have the same one.

Suppose that G is true_F . By the T-rules, $T(\ulcorner G \urcorner)$ is also true_F . But then, by the first of the displayed rules, $T(\ulcorner G \urcorner) \equiv A$ must also be true_F , and so A must be true_F .

Suppose, then, that $\ulcorner \neg G \urcorner$ is true_F . By the T-rules, $T(\ulcorner \neg G \urcorner)$ is also true_F ; so $T(\ulcorner G \urcorner)$ is false_F . But then, by the second of the displayed rules, $\neg(T(\ulcorner G \urcorner) \equiv A)$ is true_F , so $T(\ulcorner G \urcorner) \equiv A$ is false_F . So $T(\ulcorner G \urcorner)$ and A must both have truth-values $_F$, and these must be different. Since $T(\ulcorner G \urcorner)$ is false_F , A must be true_F .

Either way, then, A is true_F , as claimed. \square

Thus, every sentence follows from some instance of the T-schema, if the T-rules hold (and if the biconditional works as it does in the Strong Kleene scheme).

6. EXERCISES

Exercise 6.1. Prove parts (3) and (4) of 1.1.

Exercise 6.2. Prove that no classical interpretation meets all three of the conditions mentioned on page 3. Prove, that is, that, no matter what set we assign as extension of T , if we determine the truth-values of complex sentences in the usual way, the interpretation cannot satisfy all of (1)–(3).

Exercise 6.3. Do the cases of Lemma 4.2 that we omitted.

Exercise 6.4. (Optional) Is the intersection of all maximal fixed points a sound set? Is it a fixed point? (*Warning:* I do not actually know the answer to this question!)

Exercise 6.5. Show that a sentence is grounded if it has the same truth-value in every fixed point and, equivalently, if it has *some* truth-value in every fixed point.

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