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Hilbert's Paradox*

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Abstract

In diesem Aufsatz wird erstmals die Hilbertsche Antinomie publiziert. David Hilbert hat sie während seiner Auseinandersetzungen mit der Cantorschen Mengenlehre gefunden. Seinen Angaben zufolge wurde Ernst Zermelo durch sie zu seiner Version der Zermelo-Russellschen Antinomie angeregt. Es handelt sich um die Antinomie der Menge aller durch Addition (Vereinigung) und Selbstbelegung erzeugbaren Mengen. Sie ähnelt der Cantorschen Antinomie der Menge aller Kardinalzahlen, ist aber, so Hilbert, "rein mathematisch", da in ihr ein offensichtlicher Bezug zur Cantorschen Kardinal- und Ordinalzahlarithmetik vermieden wird.

In this paper Hilbert's paradox is published for the first time. It was discovered by David Hilbert while tackling Cantor's set theory. According to Hilbert, it initiated Ernst Zermelo's version of the Zermelo-Russell paradox. It is the paradox of all sets derived from addition (union) and self-mapping. It is similar to Cantor's paradox of the set of all cardinals, but, following Hilbert, of "purely mathematical nature", because an open reference to Cantor's cardinal and ordinal arithmetic is avoided.

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1 Introduction

In 1903 Gottlob Frege published the second volume of his *Grundgesetze der Arithmetik* [Frege 1903] containing the admission that the logical system

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used there for the foundation of arithmetic had proved to be inconsistent. He sent a copy of this volume to David Hilbert, who thanked in a letter dated 7 November 1903. In this letter Hilbert referred to Frege's description of Russell's paradox in the postscript, and wrote that "this example" was already known in Göttingen. In a footnote he added "I believe Dr Zermelo discovered it three or four years ago after I had communicated my examples to him" and continued

> I found other even more convincing contradictions as long as four or five years ago; they led me to the conviction that traditional logic is inadequate and that the theory of concept formation needs to be sharpened and refined.[1]

Hence, Hilbert maintained that he had formulated logical paradoxes around 1898 or 1899 which he communicated to Zermelo, thereby initiating Zermelo's independent discovery of Russell's paradox which took place around 1899 or 1900.

Zermelo's part in this story is well-known, Hilbert's role, however, almost completely in the dark. Hilbert never published a new paradox. There is no paradox associated to Hilbert in standard catalogues of paradoxes. What could it be? What could be more convincing than Russell's paradox?

In this paper we are going to present a candidate for Hilbert's paradox. In the first part we will give evidence for our suggestion and provide the historical context. In the second part Hilbert's paradox is described and its systematic significance is discussed.

Throughout the paper we use the term "paradox", bearing in mind, however, that as early as 1907 Ernst Zermelo had suggested to use "antinomy" instead. After having read the proof sheets of the paper "Bemerkungen zu den Paradoxieen von Russell und Burali-Forti" co-authored by his student Kurt Grelling and his philosophical colleague in Göttingen Leonard Nelson [Grelling/Nelson 1908] he criticized in a comment to Nelson the use of the term "paradox", "antinomy" being much more precise. "Paradox" means, he wrote, a statement contradicting the common opinion, it doesn't contain anything of an *inner contradiction* (as is the case for the paradoxes of Russell and Burali-Forti, and is expressed by the term "antinomy").[2]

[1] [Frege 1980, 51]. German original [Frege 1976, 79–80]: "Ihr Beispiel am Schlusse des Buches S. 253 ist uns hier bekannt* [footnote: "*Ich glaube vor 3–4 Jahren fand es Dr. Zermelo auf die Mitteilung meiner Beispiele hin."]; andere noch überzeugendere Widersprüche fand ich bereits vor 4–5 Jahren; sie führten mich zu der Ueberzeugung, dass die traditionelle Logik unzureichend ist, die Lehre von der Begriffsbildung vielmehr einer Verschärfung und Verfeinerung bedarf."

[2] Zermelo's postcard to Leonard Nelson, Glion (Switzerland), no date (postmark 22 December 1907): "Wollen Sie nicht auch lieber 'Antinomie' sagen, statt 'Paradoxie', da

2 Historical Context

2.1 Zermelo's Paradox

Let's turn to Zermelo's part in this story. Zermelo came to Göttingen in 1897 in order to work for his *Habilitation*. His special field of competence was mathematical physics, such as thermodynamics and hydrodynamics.[3] Under the influence of Hilbert he changed his focus of interests to set theory and foundations. He became Hilbert's collaborator in the philosophy of mathematics, a first member of Hilbert's school before it was established. Zermelo's first set-theoretical publication on the addition of transfinite cardinals dates from 1902 [Zermelo 1902], but as early as in the winter term 1900/1901 he gave a lecture course on set theory in Göttingen. It is possible that he found the paradox while preparing this course. He referred to it in the famous polemical paper "A New Proof of the Possibility of a Well-Ordering" of 1908 [Zermelo 1908a]. There Zermelo noted that he found the paradox independently of Russell, and that he had mentioned it to Hilbert and other people already before 1903, the year when it was first published by Frege and Russell ([Frege 1903], [Russell 1903]). And indeed, among the papers of Edmund Husserl, until 1916 professor of philosophy in Göttingen, a note from Husserl's hand was found, partially written in Gabelsberger shorthand, saying that Zermelo had informed him on 16 April 1902 that the assumption of a set M that contains all of its subsets m, m', ... as elements, is an inconsistent set, i. e., a set which, if treated as a set at all, leads to contradictions.[4] Zermelo's message was a comment on a review that Husserl had written on the first volume of Ernst Schröder's *Vorlesungen über die Algebra der Logik* [Schröder 1890]. Schröder had criticized George Boole's interpretation of the symbol 1 as the class of everything that can be subject of discourse (the universe of discourse, universal class).[5] Husserl had dismissed Schröder's argumentation as sophis-

der erstere Ausdruck sehr viel präziser ist." A month later Zermelo wrote to Nelson in a postcard, Glion, no date (postmark 20 January 1908): "Das Wort 'Paradoxie' scheint mir von Hessenberg [Gerhard Hessenberg, co-editor of the new series of the *Abhandlungen der Fries'schen Schule*, where the joint paper was published] weil es eben etwas *ganz anderes* bedeutet, nämlich eine Aussage, welche der *herkömmlichen Meinung* widerstreitet; von einem *inneren Widerspruch* enthält es gar nichts," Archiv der sozialen Demokratie, Bonn, Nelson papers.

[3] On Zermelo's activities in Göttingen cf. esp. [Moore 1982], [Peckhaus 1990a, 76–122], [Peckhaus 1990b].

[4] Critical edition in *Husserliana* XXII [Husserl 1979, 399]: "*Zermelo* teilt mit (16. April 1902) [...] Eine Menge M, welche *jede* ihrer Teilmengen m, m′ ... *als Element* enthält, ist eine inkonsistente Menge, d. h. eine solche Menge, wenn sie überhaupt als Menge behandelt wird, führt zu Widersprüchen." English translation in [Rang/Thomas 1981].

[5] [Schröder 1890, 245]: "Es [ist] in der That unzulässig [...], unter 1 eine so umfassende, sozusagen ganz offene Klasse, wie das oben geschilderte 'Universum des Diskus-

tical [Husserl 1891, 272], and was now advised by Zermelo that Schröder was right concerning the matter, but not in his proof.

The document from the Husserl papers provides convincing evidence for Hilbert's assertion concerning Zermelo. It is furthermore confirmed by Zermelo's own recollections. In 1936, Heinrich Scholz was working on the papers of Gottlob Frege which he had acquired for his department at the University of Münster. He had found Hilbert's letter to Frege, mentioned above, and now asked Zermelo what paradoxes Hilbert referred to in this letter.[6] Zermelo answered that the set-theoretic paradoxes were often discussed in the Hilbert circle around 1900, and he himself had given at that time a precise formulation of the paradox of the biggest cardinality which was later named after Russell.[7]

2.2 Traces of Hilbert's Paradox

But what about Hilbert's own paradox? It left some traces in history. The most prominent one is Otto Blumenthal's hint in his biography of Hilbert published in the third volume of Hilbert's *Collected Works* [Blumenthal 1935]. There Blumenthal mentions the paradoxes of set theory and relates them to the second of Hilbert's problems presented in the famous Paris problems lecture in 1900 [Hilbert 1900a], i. e., the problem of proving the consistency of the axioms of arithmetic. According to Blumenthal the paradoxes showed that certain operations with the infinite, which everyone thought to be allowed, led unquestionably to contradictions. Blumenthal reports that Hilbert convinced himself of this fact by constructing the example of an inconsistent set of all sets resulting from combination and self-mapping, i. e., purely mathematical operations.[8]

Another trace can be found in the year 1907. The Göttingen philosopher Leonard Nelson and the student of mathematics and philosophy Kurt

sionsfähigen' (von *Boole*) zu verstehen." Schröder referred to Boole's definition of the universe of discourse and his interpretation of the symbol 1, cf. [Boole 1854, 42–43].

[6]Heinrich Scholz to Zermelo, dated Münster, 5 April 1936, University Archive Freiburg i. Br., Zermelo papers, C 129/106.

[7]Zermelo to Scholz, dated Freiburg i. Br., 10 April 1936, Institut für mathematische Logik und Grundlagenforschung, Münster, Scholz papers: "Über die mengentheoretischen Antinomien wurde um 1900 herum im Hilbert'schen Kreise viel diskutiert, und damals habe ich auch der Antinomie von der größten Mächtigkeit die später nach Russell benannte präzise Form (von der 'Menge aller Mengen, die sich nicht selbst enthalten') gegeben. Beim Erscheinen des Russellschen Werkes [...] war uns das schon geläufig."

[8][Blumenthal 1935, 421–422]: "Hilbert überzeugte sich davon [daß gewisse Operationen mit dem Unendlichen zu Widersprüchen führten] endgültig durch das von ihm aufgestellte, nirgends aus dem Gebiete der rein mathematischen Operationen heraustretende Beispiel der widerspruchsvollen Menge aller durch Vereinigung und Selbstbelegung entstehenden Mengen."

Grelling were working on one of the first philosophical papers discussing the paradoxes, here especially the ones of Russell and Burali-Forti [Grelling/Nelson 1908]. The joint paper contained a general formulation fitting for several paradoxes, among them the semantical "heterological paradox" or "Grelling's paradox" (cf. [Peckhaus 1990a, 168–195], [Peckhaus 1995]). From a letter of the Göttingen mathematician Ernst Hellinger to Leonard Nelson, dated 28 December 1907,[9] we learn that Hellinger had read a manuscript version of the paper. He suggested to add a note on Hilbert's paradox, because its appearance was more mathematical and perhaps more suitable for mathematicians not working in set theory. In the end Hilbert's paradox was not included, because Grelling failed to reduce it to the general formulation. Nevertheless we can state that, at least in Göttingen, Hilbert's paradox was generally known.

2.3 Hilbert and Cantor

Given the time period referred to by Hilbert, it can be assumed that Hilbert formulated the paradox during his discussions with Georg Cantor, documented in their correspondence between 1897 and 1900.[10] Main topic were Cantor's problems with the assumption of a set of all cardinals. Already in the first of Cantor's letters to Hilbert, dated 26 September 1897 [Cantor 1991, no. 156, 388–389], Cantor proves that the totality of alephs doesn't exist, i. e., that this totality is no well-defined, ready set [*fertige Menge*]. If it is taken to be a ready set, a certain larger aleph would follow on this totality. So this new aleph would at the same time belong to the totality of all alephs, and not belong to it, because of being larger than all alephs (ibid., 388). Cantor consequently distinguished sets from other kinds of multiplicities, i. e., "ready" sets from multiplicities which are no sets, like the totality of all cardinals. The latter multiplicities are "absolutely infinite", unlike the former ones, the "transfinite" sets. In a later letter Cantor gave the following characterization of a ready set: A set can be imagined as ready if it is consistently possible to imagine all of its elements as being gathered, the set itself therefore as *one* compound thing, i. e., if it is possible to imagine the totality of its elements as existing.[11] This is, however, impossible for the absolute infinite which he

[9]Hellinger to Nelson, dated Breslau, 28 December 1907, Archiv der sozialen Demokratie, Bonn, Nelson papers: "Es wäre vielleicht nicht unzweckmäßig, es [Hilbert's paradox] zu erwähnen, da es mathematischer aussieht als die andern, und vielleicht auch dem nichtmengentheoretischen Mathematiker sympathischer aussieht, als das W-Paradoxon [i. e., Burali-Forti's paradox of the set W of all ordinals]."

[10]For a comprehensive discussion of this correspondence cf. [Purkert/Ilgauds 1987, 147–166]. Extracts are published in [Cantor 1991]. For Cantor's reaction to the paradox see also [Ferreirós 1999, 290–296].

[11]Cantor's letter to Hilbert, dated 2 October 1897 [Cantor 1991, 390], also published in [Purkert/Ilgauds 1987, no. 44, 226–227]: "Ich sage von einer Menge, daß sie als *fertig*

identifies with God. The *absolute infinite* doesn't allow any determination [Cantor 1883, 556]. Realized in its highest perfection in God it has to be strictly opposed to the *actual infinite* which he calls the transfinite [Cantor 1887, 81–82].

It is well-known that Cantor later changed his terminology. In May 1899 he wrote to Hilbert that he got used to substitute what he formerly had called "ready" with the expression "consistent". The notion "sets" stood now for "consistent multiplicities".[12]

Cantor disproves the existence of the totality of all cardinals by showing that the assumption of its existence contradicts his definition of a set as a comprehension of certain well distinguished objects of our intuition or our thinking in a whole.[13] The totality of all cardinals (and of all ordinals) cannot be thought of as *one* such thing, contrary to actual infinite objects like transfinite sets. He is therefore not really concerned with paradoxes and their solution, but with negative existence proofs using *reductio-ad-absurdum* arguments.[14]

From these passages we learn that Hilbert was concerned with what was later called "Cantor's paradox", i. e., the paradox of the greatest cardinal, or of the set of all cardinals. It is clear, however, that the contradiction discussed by Cantor served only as a paradigmatic example for other inconsistent multiplicities, i. e., totalities resulting from unrestricted comprehension. Nevertheless, there is no evidence that Cantor and Hilbert discussed the contradiction resulting from the assumption of a greatest ordinal, today known as "Burali-Forti's paradox", although this had been claimed by several authors.[15] Usually Cantor's letter to Philip E. B. Jourdain of 4 November 1903 is taken as evidence for Cantor having known the paradox of the greatest ordinal before its publication by Cesare Burali-Forti [Burali-Forti 1897], and

gedacht werden kann, und nenne solche Menge, wenn sie unendlich viele Elemente enthält, 'transfinit' oder 'überendlich', wenn es ohne Widerspruch möglich ist (wie dies bei den endlichen Mengen der Fall), *alle ihre Elemente als zusammenseiend*, die Menge selbst daher als *ein* zusammengesetztes *Ding für sich* zu denken; oder auch, (in anderen Worten) wenn es *möglich ist*, sich die Menge mit der Totalität ihrer Elemente als *actuell existirend* zu *denken*." A similar definition can be found in Cantor's letter to Hilbert, Halle, 10 October 1898 [Cantor 1991, no. 158, 396–397, definition on p. 396].

[12] Cantor's letter to Hilbert, Halle, 9 May 1899 [Cantor 1991, no. 160, p. 399]: "Ich habe mich jetzt daran gewöhnt, das was ich früher 'fertig' genannt, durch den Ausdruck 'consistent' zu ersetzen [...]. 'Mengen' würden darnach 'consistente Vielheiten' sein."

[13] [Cantor 1895/97], quoted in [Cantor 1932, 282]: "Unter einer 'Menge' verstehen wir jede Zusammenfassung M von bestimmten wohlunterschiedenen Objekten m unsrer Anschauung oder unseres Denkens (welche die 'Elemente' von M genannt werden) zu einem Ganzen."

[14] We follow in this evaluation [Moore/Garciadiego 1981], [Garciadiego Dantan 1992].

[15] E. g., [Fraenkel 1930, 261], [Meschkowski 1983, 144].

that he had communicated this paradox to Hilbert as early as 1896.[16] In fact Cantor showed in this letter to Jourdain that the assumption of a system of all ordinals leads to a contradiction. In his communication with Hilbert, however, he only referred to the assumption of a greatest cardinal.[17] Purkert and Ilgauds made it furthermore plausible [Purkert/Ilgauds 1987, 151] that Cantor's recollections were erroneous. He most probably referred to his letter to Hilbert of 26 September 1897, mentioned above. The notion of the greatest ordinal was also topic in the letter Cantor wrote to Dedekind on 3 August 1899. There he proved that the system Ω of all numbers is an inconsistent, absolutely infinite multiplicity.[18] In this letter Cantor also referred to the totality of everything imaginable ("Inbegriff alles Denkbaren"), i. e., Dedekind's own assumption in *Was sind und was sollen die Zahlen?* [Dedekind 1888], needed to prove that there are infinite systems (sets).[19] Cantor showed that his negative existence proofs also hold for this assumption.

Hilbert's responses in correspondence have not been passed on,[20] but he published his opinion at prominent places. In the paper "On the Concept of Number" from 1900 [Hilbert 1900b], Hilbert's first paper on the foundations of arithmetic, he gave a set of axioms for arithmetic, and claimed that only a suitable modification of known methods of inference is needed for proving the consistency of the axioms. If this proof was successful, the existence of the totality of real numbers would be shown at the same time. In this context he referred to Cantor's problem whether the system of real numbers is a consistent or ready set. He stressed:

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[16]The letter was quoted by Jourdain [Jourdain 1904] and mentioned by Felix Bernstein [Bernstein 1905, 187]. Gerhard Hessenberg referred to Bernstein when maintaining Cantor's priority [Hessenberg 1906, § 98, p. 631]. From there it became standard folklore. Cf. [Grattan-Guinness 2000, 117–119].

[17]Cantor's letter to Philip E. B. Jourdain, dated Halle 4 November 1903 [Cantor 1991, no. 172, pp. 433–434, quote p. 433]: "Den unzweifelhaft richtigen Satz, daß es außer den Alephs keine anderen transfiniten Cardinalzahlen giebt, habe ich vor über 20 Jahren (bei der Entdeckung der Alephs selbst) intuitiv erkannt. [...] Schon vor 7 Jahren machte ich Herrn Hilbert, vor 4 Jahren Herrn Dedekind darauf bezügliche briefliche Mitteilung." The extensive correspondence between Cantor and Jourdain is published in [Grattan-Guinness 1972–73].

[18]Cantor to Dedekind, dated Halle, 3 August 1899, [Cantor 1991, no. 163, pp. 407–411]. It is one of the best known of Cantor's letters, published already in Zermelo's edition of Cantor's collected works [Cantor 1932, 443–447]. Ivor Grattan-Guinness has shown, however, that Zermelo combined this letter with the one of 28 July 1899 and even changed the original wording at some places [Grattan-Guinness 1974–75].

[19][Dedekind 1888, 14]: "Meine Gedankenwelt, d. h. die Gesamtheit S aller Dinge, welche Gegenstand meines Denkens sein können, ist unendlich."

[20]In his letter to Hilbert of 2 October 1897 Cantor referred to some of Hilbert's objections, quoted in [Purkert/Ilgauds 1987, 226–227].

> Under the conception above, the doubts which have been raised against the existence of the totality of all real numbers (and against the existence of infinite sets in general) lose all justification; for by the set of real numbers we do not have to imagine the totality of all possible laws according to which the elements of a fundamental sequence can proceed, but rather—as just described—a system of things whose internal relations are given by a *finite and closed* set of axioms [...], and about which new statements are valid only if one can derive them from the axioms by means of a finite number of logical inferences.[21]

He also claimed that the existence of the totality of all powers or of all Cantorian alephs could be disproved, in Cantor's terminology, that the system of all powers is an inconsistent (not ready) set (ibid.).

Hilbert took up this topic again in his famous Paris lecture on "Mathematical Problems".[22] In the context of his commentary on the second problem concerning the consistency of the arithmetical axioms he used the same examples from Cantorian set theory and the continuum problem as in the earlier lecture. "If contradicting attributes be assigned to a concept," he wrote, "I say, that mathematically the concept does not exist" [Hilbert 1996a, 1105].

According to Hilbert a suitable axiomatization would be able to avoid the contradictions resulting from the attempt to comprehend absolute infinite multiplicities as a unit, because only those concepts had to be accepted which could be derived from an axiomatic base.

2.4 The 1905 lecture

Although it is evident that Hilbert was at that time deeply concerned with the problems of set theory, we didn't find any direct evidence that Hilbert had formulated contradictions in this context, or even a paradox of his own. Indirect evidence can be found, however, in documents dating from a few years later.

Only after the publication of the paradoxes by Russell and Frege, and especially through Frege's reaction, the logical significance of this kind of

[21][Hilbert 1996b, 1095]. German original [Hilbert 1900b, 184]: "Die Bedenken, welche gegen die Existenz des Inbegriffs aller reellen Zahlen und unendlicher Mengen überhaupt geltend gemacht worden sind, verlieren bei der oben gekennzeichneten Auffassung jede Berechtigung: unter der Menge der reellen Zahlen haben wir uns hiernach nicht etwa die Gesamtheit aller möglichen Gesetze zu denken, nach denen die Elemente einer Fundamentalreihe fortschreiten können, sondern vielmehr — wie eben dargelegt — ein System von Dingen, deren gegenseitige Beziehungen durch das obige *endliche und abgeschlossene* System von Axiomen [...] gegeben sind, und über welche neue Aussagen nur Gültigkeit haben, falls man sie mittels einer endlichen Anzahl von logischen Schlüssen aus jenen Axiomen ableiten kann."

[22][Hilbert 1900a], English translations [Hilbert 1902], [Hilbert 1996a].

contradictions became evident.[23] Now the mathematicians understood that these paradoxes were no simple contradictions they were familiar with in their everyday *reductio ad absurdum* arguments. As logical paradoxes they seriously affected Hilbert's axiomatic programme, especially the demanded consistency proof for arithmetic. It is a matter of course that a consistency proof could not be given on the base of a logic proved to be inconsistent. Hilbert first expressed this new insight in a talk delivered at the Third International Congress of Mathematicians in Heidelberg in August 1904 [Hilbert 1905c]. In this lecture "On the Foundations of Logic and Arithmetic" he demanded a "partly simultaneous development of the laws of logic and arithmetic."[24] Following Blumenthal [Blumenthal 1935, 422], this lecture remained completely misunderstood and several of its ideas proved to be defective. Nevertheless it was the first step to build up a foundational system of mathematics avoiding the paradoxes. The next step was taken in a lecture course on the "Logical Principles of Mathematical Thinking" which Hilbert gave in Göttingen in the summer term of 1905. Two sets of notes of this lecture course were passed on. The "official" notes are from Ernst Hellinger, then student of mathematics. They contain marginal notes by Hilbert's hand [Hilbert 1905a]. An additional set was produced by the student of mathematics and physics Max Born [Hilbert 1905b]. Part B of these notes on "The Logical Foundations" starts with a comprehensive discussion of the paradoxes of set theory. It is opened with metaphorical considerations on the general development of science:

> It has, indeed, been usual practice in the historical development of science that we began cultivating a discipline without many scruples, pressing onwards as far as possible, that we thereby, however, then run into difficulties (often only after a long time) that forced us to turn back and reflect on the foundations of the discipline. The house of knowledge is not erected like a dwelling where the foundation is first well laid-out before the erection of the living quarters begins. Science prefers to obtain comfortable rooms as quickly as possible in which it can rule, and only subsequently, when it becomes clear that, here and there, the loosely joined foundations are unable to support the completion of the rooms, science proceeds in propping up and securing them. This is no shortcoming but rather a correct and healthy development.[25]

[23]Cf. [Moore/Garciadiego 1981], [Garciadiego Dantan 1992].

[24][Hilbert 1905c, p. 176]: "Wir geraten so [because of the interrelatedness of logic and arithmetic] in eine Zwickmühle und zur Vermeidung von Paradoxien ist daher eine teilweise gleichzeitige Entwicklung der Gesetze der Logik und der Arithmetik erforderlich."

[25][Hilbert 1905b, 122]: "Es ist in der Entwicklungsgeschichte der Wissenschaft wohl immer so gewesen, dass man ohne viele Scrupel eine Disciplin zu bearbeiten begann

Although contradictions are quite common in science, Hilbert continued, in the case of set theory they seem to be different, because there they have a tendency towards the side of theoretical philosophy. In set theory the common Aristotelian logic and its standard methods of concept formation were used without hesitation. And these standard tools of purely logical operations, especially the subsumption of concepts under a general concept, proved to be responsible for the new contradictions.

Hilbert elucidated these considerations by presenting three examples. The first paradox discussed is the Liar paradox. The third one is "Zermelo's paradox," as the Russell-Zermelo paradox was called in Göttingen at that time. Hilbert described this paradox as purely logical, assuming that it might be more convincing for non-mathematicians. He stressed, however, that it was derived from his own paradox, the second one in his list of examples, and this second paradox was, according to Hilbert, of purely mathematical nature.[26] Hilbert expressed his opinion that this paradox

> appears to be especially important; when I found it, I thought in the beginning that it causes invincible problems for set theory that would finally lead to its failing; now I firmly believe, however, that everything essential can be kept after a revision of the foundations, as always in science up to now. I haven't published this contradiction, but it is known to set theorists, especially to G. Cantor.[27]

This paradox, arising from uniting sets and mapping them to themselves is exactly the one Blumenthal referred to in his biography. It is most likely the one Hilbert himself referred to in his letter to Frege.

und soweit vordrang wie möglich, dass man dabei aber, oft erst nach langer Zeit, auf Schwierigkeiten stieß, durch die man gezwungen wurde, umzukehren und sich auf die Grundlagen der Disciplin zu besinnen. Das Gebäude der Wissenschaft wird nicht aufgerichtet wie ein Wohnhaus, wo zuerst die Grundmauern fest fundamentiert werden und man dann erst zum Auf- und Ausbau der Wohnräume schreitet; die Wissenschaft zieht es vor, sich möglichst schnell wohnliche Räume zu verschaffen, in denen sie schalten kann, und erst nachträglich, wenn es sich zeigt, dass hier und da die locker gefügten Fundamente den Ausbau der Wohnräume nicht zu tragen vermögen, geht sie daran, dieselben zu stützen und zu befestigen. Das ist kein Mangel, sondern die richtige und gesunde Entwicklung." The manuscripts differ in this passage, cf. [Hilbert 1905a, 192].

[26] [Hilbert 1905a, 210]: "Als drittes Beispiel dieser Widersprüche stelle ich neben diesen meinen rein mathematischen noch einen rein logischen, den Dr. *Zermelo* aus jenem herausgezogen hat [...]."

[27] [Hilbert 1905a, 204]: "Der erste [of the last two], der rein mathematischer Natur ist, scheint mir besonders bedeutsam; als ich ihn fand, glaubte ich zuerst, dass er der Mengentheorie unüberwindliche Schwierigkeiten in den Weg legte, an denen sie scheitern müsste; ich glaube jedoch jetzt sicher, dass[,] wie stets bisher in der Wissenschaft, nach der Revision der Grundlagen alles Wesentliche erhalten bleiben wird. Ich habe diesen Widerspruch nicht publiciert; er ist aber den Mengentheoretikern, insbesondere G. Cantor bekannt."

3 Hilbert's Paradox

3.1 Hilbert's Presentation

The full text of Hilbert's paradox is given in the appendices, both in English translation (appendix I) and in the German original (appendix II). Here, we reconstruct the main steps of Hilbert's argumentation.

The paradox is based on a special notion of set which Hilbert introduces by means of two set formation principles starting from the natural numbers. The first principle is the *addition principle*. In analogy to the finite case, Hilbert argued that the principle can be used for uniting two sets together "into a new conceptual unit [...], a new set that contains each element of both sets." This operation can be extended: "In the same way, we are able to unite several sets and even infinitely many into a unit set." The second principle is called *mapping principle*. Given a set $\mathcal{M}$, he introduces the set $\mathcal{M}^{\mathcal{M}}$ of so-called *self-mappings* of $\mathcal{M}$ to itself. A self-mapping is just a total function which maps the elements of $\mathcal{M}$ to elements of $\mathcal{M}$.[28]

Now, he considers all sets which result from the natural numbers "by applying the operations of addition and self-mapping an arbitrary number of times." By use of the addition principle which allows to build the union of arbitrary sets one can "unite them all into a summative set $\mathcal{U}$ which is well-defined." In the next step the mapping principle is applied to $\mathcal{U}$, and we get $\mathcal{F} = \mathcal{U}^{\mathcal{U}}$ as the set of all self-mappings of $\mathcal{U}$. Since $\mathcal{F}$ was built from the natural numbers by using the two principles only, Hilbert concludes that it has to be contained in $\mathcal{U}$. From this fact he derives a contradiction.

Since "there are 'not more' elements" in $\mathcal{F}$ than in $\mathcal{U}$ there is an assignment of the elements u_i of $\mathcal{U}$ to elements f_i of $\mathcal{F}$ such that all elements of f_i are used. Now one can define a self-mapping g of $\mathcal{U}$ which differs from all f_i. Thus, g is not contained in $\mathcal{F}$. Since $\mathcal{F}$ was assumed to contain all self-mappings we have a contradiction. In order to define g Hilbert used Cantor's diagonalization method. If f_i is a mapping u_i to $f_i(u_i) = u_{f_i^{(i)}}$ he chooses an element $u_{g^{(i)}}$ different from $u_{f_i^{(i)}}$ as the image of u_i under g. Thus, we have $g(u_i) = u_{g^{(i)}} \neq u_{f_i^{(i)}}$ and g "is distinct from any mapping f_k of $\mathcal{F}$ in at least one assignment."[29]

Hilbert finishes his argument with the following observation:

> We could also formulate this contradiction in a way that, according

[28]Hilbert used the German term "*Selbstbelegung*" which is translated here by "self-mapping". The term "*Belegung*" was already used by Cantor [Cantor 1895/97]. In his edition of Georg Cantor's collected works Zermelo explained *Belegung* as a function with explicitly given domain and (potential) range [Cantor 1932, footnote [3], p. 352].

[29]Hilbert's notation $u_{g^{(i)}}$ is somewhat clumsy. In fact, it is enough to say that $g(u_i) = v_i$ for any element v_i of $\mathcal{U}$ with $v_i \neq f_i(u_i)$.

to the last consideration, the set $\mathcal{U}^{\mathcal{U}}$ is always bigger [of greater cardinality][30] than $\mathcal{U}$ but, according to the former, is contained in $\mathcal{U}$.

3.2 Brief Reconstruction

In order to make the argument more comprehensible the paradox can be presented in the following way. First we define a notion of set:

Definition 1 *We define inductively:*

1. *The natural numbers as a whole are a set.*[31]
2. Addition principle*: If we have an arbitrary, possibly infinite collection of sets, the union of all these sets is a set.*
3. Mapping principle*: The totality of all total functions from a given set into itself is a set.*

Now we take the closure of all sets defined according to this definition:

Definition 2 *Let $\mathcal{U}$ be the union of all sets defined according to definition 1.*

This union is well defined according to the addition principle. Thus we can apply the mapping principle to it.

Definition 3 *Let $\mathcal{F}$ be the set $\mathcal{U}^{\mathcal{U}}$.*

Obviously $\mathcal{F}$ is built according to our definition of sets. We have used the addition principle to define $\mathcal{U}$ and than the mapping principle to define $\mathcal{F}$. But that means, $\mathcal{F}$ has to be contained in $\mathcal{U}$ because $\mathcal{U}$ was the union of all sets built according to the definition of sets. Thus, we get the following

Lemma 4 $\mathcal{F} \subset \mathcal{U}$.

From this lemma it follows that there exists a function of $\mathcal{U}$ in $\mathcal{F}$ whose range is the whole set $\mathcal{F}$. Therefore, we can apply Cantor's diagonalization method to define a function from $\mathcal{U}$ to $\mathcal{U}$ which is distinct from each element of $\mathcal{F}$.

Proposition 5 *There exists a total function g from $\mathcal{U}$ to $\mathcal{U}$ such that $g \notin \mathcal{F}$.*

But by definition of $\mathcal{F}$, this set contains *all* total function from $\mathcal{U}$ to $\mathcal{U}$. Thus, we get as a

Corollary 6 *The system of sets defined by 1 is contradictory.*

[30] Added in Hellinger's lecture notes by Hilbert's hand.

[31] Hilbert even argues that the natural numbers can be defined from finite sets using the addition principle.

3.3 Analysis of the Paradox

The reconstruction given above reveals the source of the paradox. Obviously the addition principle is too vague. Hilbert allows "to unite several sets and even infinitely many into a unit set," he even allows to "unite them all," i. e., all sets defined by addition and self-mapping. He doesn't determine, however, the domain of the universal quantifier. The definition of the set $\mathcal{U}$ is, thus, based on an *impredicative construction*, because $\mathcal{U}$ itself has to belong to this domain. In short: The definition of $\mathcal{U}$ depends on a totality containing $\mathcal{U}$ itself.

These problems can be mastered by restricting the addition principle. It has to be demanded that the sets united have to be subsets of another set already established. And this is, in fact, the way in which Zermelo proceeded in his axiomatization of set theory. This axiomatic system, refined by Fraenkel and Skolem and called ZFC, is still today generally accepted as *the* basis of mathematics. In ZFC we have a *union axiom* corresponding to the addition principle. But in contrast to the addition principle, a *family of sets T being itself a set* is demanded which can be regarded as an *index set* giving some control over the sets gathered in the union.[32] Nowadays, the union axiom is stated as:

$$\forall T \exists S \forall x (x \in S \leftrightarrow \exists U (x \in U \wedge U \in T))$$

Abraham A. Fraenkel correctly saw that an unrestricted union axiom within axiomatized set theory led to the same problems as the ones connected with Russell's paradox. He saw the reason for these problems in an unconcerned use of the notion "arbitrarily many." Fraenkel referred directly to the union axiom, so his analysis reads like a diagnosis of the cause of Hilbert's paradox.[33]

Although Hilbert worked only in a restricted domain of sets, containing only those sets formed by addition and self-mapping, his addition principle was itself too vague, so that it resulted in similar effects as Cantor's com-

[32][Zermelo 1908b, 265]: "**Axiom V.** Jeder Menge T entspricht eine Menge $\mathfrak{S}T$ (die '*Vereinigungsmenge*' von T), welche alle Elemente der Elemente von T und nur solche als Elemente enthält. (Axiom der Vereinigung.)"

[33][Fraenkel 1927, 71]: "Will man [...] zu etwas allgemeineren Prozessen [of set formation] fortschreiten, so muß man [...] auch die Zusammenfassung der *Elemente verschiedener Mengen* anstreben. Einen Fingerzeig, wie dies zu erfolgen hat, liefert uns die Bildung der Vereinigungsmenge in der CANTORschen Mengenlehre, wo die sämtlichen Elemente beliebig vieler Mengen zu einer neuen Menge, der Vereinigungsmenge, vereinigt werden können [...]. Hinsichtlich der gefahrdrohenden Folgen eines unbekümmerten Gebrauchs des Begriffs 'beliebig viele' sind wir freilich, z. B. durch das RUSSELLsche Paradoxon, hinlänglich gewitzigt; wir gehen daher nicht wie früher von beliebig vielen Mengen aus, sondern setzen voraus, daß diese Mengen als die Elemente einer bereits als legitim erkannten Menge säuberlich gegeben sind."

prehension.[34] From another perspective the lack of a proper quantification theory is conspicuous. Hilbert's formulation is therefore affected by the general problems of impredicativity.

Zermelo's axiomatization of set theory can thus be read as an answer to two different paradoxes. His strategy was to avoid unrestricted comprehension leading to Cantor's paradox (and also to the Zermelo-Russell paradox), and furthermore unrestricted union leading to Hilbert's paradox. He could easily prevent the formulation of Hilbert's paradox by introducing the family set T in the union axiom (axiom V). The paradoxes resulting from unrestricted comprehension could be avoided by introducing the separation axiom (axiom III) which assures that each set M has at least one subset M_0 not being element of M [Zermelo 1908b, 264].

Contrary to the addition principle, the mapping principle is "innocent" of the emergence of Hilbert's paradox. If we replace the total functions from $\mathcal{M}$ to $\mathcal{M}$ by total functions from $\mathcal{M}$ to the set $\{0,1\}$ we get the set of charateristic functions of all subsets of $\mathcal{M}$. Thus, the mapping principle is closely related with the power set axiom as it is used in modern set theory. Hilbert demanded for the mapping principle that the set of all self-mappings is obtained over *sets* already established, a restriction also valid for the modern power set axiom.

4 Conclusion

Hilbert's paradox is closely related to Cantor's own paradox. Both, Cantor and Hilbert, construct "sets" which lead to contradictions being proved with the help of Cantor's diagonalization argument. However, the ways in which these "sets" are constructed differ essentially. According to Cantor ([Cantor 1883, § 11], cf. [Cantor 1932, 195–197]), there are three principles for the generation of cardinals. The first principle ("erstes Erzeugungsprinzip") concerns the generation of real whole numbers [*reale ganze Zahlen*] by adding a unit to a given, already generated number. The second principle allows the formation of a new number, if a certain succession of whole numbers with no greatest number is given. This new number is imagined as the limit of

[34] This is also the conclusion of Paul Bernays who reported in 1971, obviously referring to Hilbert's paradox: "Der Gedanke der Beschränkung auf solche Mengen, die man, beginnend mit einer Ausgangsmenge (etwa der Menge der natürlichen Zahlen) durch Potenzmengenbildungen, Vereinigungsprozesse und Aussonderungen bilden kann, wurde—wie ich aus Erzählungen von Hilbert weiß—seinerzeit auch erwogen; er führte aber zunächst gerade zu einer Verschärfung der Paradoxien, da man die Vereinigungsprozesse nicht genügend deutlich normierte, vielmehr die Zusammenfassung der durch die angegebenen Prozesse gewinnbaren Mengen zu einer Menge ihrerseits als einen zulässigen Vereinigungsprozeß ansah" [Bernays 1971/1976, 199]. We would like to thank José F. Ruiz, Madrid, for bringing this quote to our attention.

this succession. Cantor adds a third principle, the inhibition or restriction principle ("Hemmungs- oder Beschränkungsprinzip") which grants that the second number class has not only a higher cardinality than the first number class, but exactly the next higher cardinality. Considering Cantor's general definition of a set as the comprehension of certain well-distinguished objects of our intuition or our thinking as a whole ([Cantor 1895/97], [Cantor 1932, 282]), one can justly ask whether the sets of all cardinals, of all ordinals or the universal set of all sets are sets according to this definition, i. e., whether an unrestricted comprehension is possible. Cantor denies this, justifying his opinion with the help of a *reductio ad absurdum* argument, but he doesn't exclude the possibility of forming the paradoxes by provisions in his formalism.

Hilbert, on the other hand, introduces two alternative set formation principles, the addition principle and the mapping principle, but they lead to paradoxes as well. In avoiding concepts from transfinite arithmetic Hilbert believes to guarantee the purely mathematical nature of his paradox. For him, this paradox appears to be much more serious for mathematics than Cantor's, because it concerns an operation being part of everyday practice of working mathematicians.

The significance of Hilbert's paradox for the history of mathematics should have become obvious. The paradox shows the importance of the end 19th century discussion on universal sets and classes, e. g., Cantor's absolutely infinite totalities, Dedekind's infinite totality of all things which might become objects of our thinking, and Boole's universe of discourse. From the beginning the limitation of size argument played a role (cf. [Hallett 1984]). This discussion marks a latent foundational crisis in mathematics. Mathematicians involved were dealing with contradictions, i. e., paradoxes they hoped to get rid of. The foundational crisis became manifest in 1903, when Bertrand Russell and Gottlob Frege published the insight that "Russell's paradox" could be derived from Frege's system of the *Grundgesetze*. Now mathematicians were dealing with antinomies, i. e., intrinsic contradictions which could not easily be solved. Even this new move was closely connected to the earlier discussion because Russell found his own paradox while struggling with Cantor's set theory (cf. [Garciadiego Dantan 1992], [Grattan-Guinness 1978], [Grattan-Guinness 2000, 310–315]).

Appendix I: Hilbert's Paradox (English Translation)

[Marginal note: 18th lecture, 10 July] [. . .] |204 In addition, I now come to two examples of contradictions which are much more convincing, the first, being of purely mathematical nature, appears to be especially important; when I found it, I thought in the beginning that it causes invincible problems for set theory that would finally lead to its failing; now I firmly believe, however, that everything essential can be kept after a revision of the foundations, as always in science up to now. I haven't published this contradiction, but it is known to set theorists, especially to G. Cantor. Anyhow, we regard finite sets, represented by finitely many numbers, as a permitted operational basis, and also the countable infinite set $1, 2, 3\ldots$ of all natural numbers. Furthermore, it seems to be allowed to unite two such sets $(1, 2, 3\ldots)$ and $(a_1, a_2, a_3\ldots)$ into a new conceptual unit $(1, 2, 3\ldots, a_1, a_2, a_3\ldots)$, i.e., a new set that contains each element of both sets. In the same way, we are able to unite several sets and even infinitely many into a unit set. We designate this as *addition principle*, and write |[205] in short for the set derived from $\mathcal{M}_1, \mathcal{M}_2\ldots$,

$$\mathcal{M}_1 + \mathcal{M}_2 + \cdots$$

These unions are operations, generally applied in logic in even much more complicated cases without any hesitation. Therefore, it seems to be possible to apply them here without further ado. Besides this addition principle, we use a further consideration for forming new sets. Let $y = f(x)$ be a number theoretic function which maps to every integer value x an integer y; in a sense immediately to be understood, we can designate such a function as a *mapping* [*Belegung*] of the number sequence to itself, by imagining for instance a scheme:

$$\begin{aligned} x &= 1, 2, 3, 4\ldots \\ y &= 2, 3, 6, 9\ldots \end{aligned}$$

The system of all these number theoretic functions $f(x)$, or of all possible mappings of the number sequence to elements of its own, forms a new set "resulting from the number sequence $\mathcal{M}$ by *self-mapping*," we write it $\mathcal{M}^{\mathcal{M}}$.|[206] As a principle following from the laws of uniting in common logic and, according to it, completely unobjectionable, we can now look upon the opinion that in every case well-defined sets arise from well-defined sets by self-mapping (*mapping principle*). For instance, by using this principle, the set of all real functions results from the continuum of all real numbers. We want to use only these two principles unobjectionable according to all previous mathematics and logic.

We start with all finite sets of numbers and the infinite series $1, 2, 3\ldots$ of natural numbers already derived from it by addition, and take all sets resulting from them by applying the operations of addition and self-mapping an arbitrary number of times; these sets form again a well-defined unit, for according to the addition principle I unite them all into a summative set $\mathcal{U}$ which is well-defined. If I form now the set $\mathcal{F} = \mathcal{U}^{\mathcal{U}}$ of self-mappings of

$\mathcal{U}$, this set arises from the original number sequence via the two operations of addition and |[207] self-mapping only; it, therefore, also belongs to the sets from whose addition $\mathcal{U}$ just resulted and, therefore, must be a part of $\mathcal{U}$:

$$(1) \qquad \mathcal{F} \text{ is contained in } \mathcal{U}.$$

[Marginal note: 19th lecture, 11 July] I will now show that this leads to a contradiction. Let $u_1, u_2, u_3 \ldots$ be the elements of $\mathcal{U}$; then, each element f of $\mathcal{F} = \mathcal{U}^{\mathcal{U}}$ represents a mapping of $\mathcal{U}$ to itself, i. e., in a way a function, which assigns to each element u_i of $\mathcal{U}$ another $u_{f(i)}$, where it is not at all necessary that the $u_{f(i)}$ have to be distinct from one another; we, therefore, best present this element f by a scheme:

$$f(u_1) = u_{f(1)}, f(u_2) = u_{f(2)}, f(u_3) = u_{f(3)} \ldots$$

Our result (1), that $\mathcal{F}$ is contained in $\mathcal{U}$, can now be expressed more closely in the following way: we can definitely assign to each single element u_i of $\mathcal{U}$ a f_i of $\mathcal{F}$ so that all f_i will thereby be used, maybe even repeatedly, but that, in any case, to each u_i only corresponds *exactly one single* f_i; this means, obviously, nothing else than that there are "not more" elements f_i than u_i. Let's now regard such an assignment:|[208]

$$u_1|f_1, u_2|f_2, u_3|f_3 \ldots,$$

and from this I will form a new mapping g of $\mathcal{U}$ to itself that differs from all f_i, i. e., it is not contained in $\mathcal{F}$ because, in our assignment, all elements of $\mathcal{F}$ had to be applied; but since $\mathcal{F}$ includes all possible mappings, we have, thus, derived the contradiction. We again apply the principle of Cantor's diagonalization method. In the mapping f_1, let the element u_1 correspond to the $u_{f_1^{(1)}}$:

$$f_1(u_1) = u_{f_1^{(1)}};$$

if $u_{g^{(1)}}$ is an element different from $u_{f_1^{(1)}}$, then we construct the new mapping g which assigns u_1 to it:

$$g(u_1) = u_{g^{(1)}} \neq u_{f_1^{(1)}}.$$

We proceed further according to this principle; by the way, the designation of elements of $\mathcal{U}$ and $\mathcal{F}$ by number indices is not essential, and it should by no means insinuate that these sets are countable which is, in no way, the case. If u_2 is some element of $\mathcal{U}$, a mapping [*Belegung*] f_2 |[209] belongs to it in the mapping [*Abbildung*] of f to u; we look for the element $f_2(u_2) = u_{f_2^{(2)}}$, which it [the mapping f_2] assigns to u_2, choose $u_{g^{(2)}} \neq u_{f_2^{(2)}}$ and define a mapping g which assigns it to u_2:

$$g(u_2) = u_{g^{(2)}} \neq u_{f_2^{(2)}}$$

The mapping g which we obtain in this way has the scheme

$$g(u_1) = u_{g^{(1)}} \neq u_{f_1^{(1)}}, g(u_2) = u_{g^{(2)}} \neq u_{f_2^{(2)}}, g(u_3) = u_{g^{(3)}} \neq u_{f_3^{(3)}} \dots$$

It is distinct from any mapping f_k of $\mathcal{F}$ in at least one assignment; namely, if u_k is the element (or one of these) corresponding to f_k in the mapping [*Abbildung*] of $\mathcal{F}$ to $\mathcal{U}$, then it follows from the definition of g that:

$$f_k(u_k) = u_{f_k^{(k)}} \qquad g(u_k) = u_{g^{(k)}} \neq u_{f_k^{(k)}}.$$

By this, we indeed have the contradiction that the well-defined mapping g cannot be contained in the set of all mappings. We could also formulate this contradiction in a way that, according to the last consideration, the set $\mathcal{U}^{\mathcal{U}}$ is always bigger [note by Hilbert's hand: "of greater cardinality"] than $\mathcal{U}$ but, according to the former, is contained in $\mathcal{U}$. This contradiction is not at all yet solved; anyway, one can see that it must depend upon the fact that the operations of uniting arbitrary sets or objects into $|^{210}$ new sets or universalities, respectively, is, nevertheless, not allowed, although it is always used in traditional logic, and although we have carefully applied it only on natural numbers and sets arising from them, i. e., on purely mathematical objects.

Appendix II: Hilbert's Paradox (German Original)

[Marginalie: 18. Vorles. 10. VII.] [...] $|^{204}$ Ich komme nun noch zu 2 Beispielen für Widersprüche, die viel überzeugender sind, der erste, der rein mathematischer Natur ist, scheint mir besonders bedeutsam; als ich ihn fand, glaubte ich zuerst, daß er der Mengentheorie unüberwindliche Schwierigkeiten in den Weg legte, an denen sie scheitern müßte; ich glaube jedoch jetzt sicher, daß wie stets bisher in der Wissenschaft, nach der Revision der Grundlagen alles Wesentliche erhalten bleiben wird. Ich habe diesen Widerspruch nicht publiciert; er ist aber den Mengentheoretikern, insbesondere G. Cantor, bekannt. Wir sehen die endlichen Mengen, durch endliche viele Zahlen repräsentiert, jedenfalls als erlaubte Operationsbasis an, und ebenso die abzählbar unendliche Menge $1, 2, 3 \dots$ aller natürlichen Zahlen. Ferner erscheint es erlaubt, 2 solche Mengen $(1, 2, 3 \dots)$ und $(a_1, a_2, a_3 \dots)$ zu einer neuen Begriffseinheit $(1, 2, 3 \dots, a_1, a_2, a_3 \dots)$, einer neuen Menge, zusammenzufassen, die jedes Element der beiden Mengen enthält. Ebenso können wir auch mehrere Mengen und sogar unendlich viele zu einer Vereinigungsmenge zusammenfassen. Wir bezeichnen das als *Additionsprincip*, und schreiben $|^{205}$ die so aus $\mathcal{M}_1, \mathcal{M}_2 \dots$ hervorgehende Menge kurz

$$\mathcal{M}_1 + \mathcal{M}_2 + \cdots$$

Diese Zusammenfassungen sind Processe, die man in der Logik stets ohne jedes Bedenken in noch weit komplicierteren Fällen anwendet; es scheint also, daß man auch hier ohne weiteres davon Gebrauch machen könnte. Außer diesem Additionsprincip verwenden wir noch eine weitere Betrachtung zur Bildung neuer Mengen. Es sei $y = f(x)$ eine zahlentheoretische Funktion, die zu jedem ganzzahligen Wert x ein ganzzahliges y zuordnet; in sofort zu verstehendem Sinne können wir eine solche Funktion auch als eine *Belegung* der Zahlenreihe mit sich selbst bezeichnen, indem wir etwa an ein Schema denken:

$$\begin{aligned} x &= 1, 2, 3, 4 \dots \\ y &= 2, 3, 6, 9 \dots \end{aligned}$$

Das System aller solcher zahlentheoretischen Funktionen $f(x)$ oder aller möglichen Belegungen der Zahlenreihe mit Elementen ihrer selbst bildet eine neue Menge, die "durch *Selbstbelegung* aus der Zahlenreihe $\mathcal{M}$ entstehende," wir schreiben sie $\mathcal{M}^{\mathcal{M}}$. Als aus den |[206] Zusammenfassungsgesetzen der üblichen Logik folgendes und nach ihr gänzlich unbedenkliches Princip können wir nun das ansehen, daß aus wohldefinierten Mengen durch Selbstbelegung immer wieder wohldefinierte Mengen entstehen. (*Belegungsprincip*). Durch dies Princip entsteht aus dem Continuum aller reellen Zahlen beispielsweise die Menge aller reellen Funktionen. Allein mit diesen beiden nach aller bisherigen Mathematik und Logik unbedenklichen Principen wollen wir arbeiten.

Wir gehen von allen endlichen Mengen von Zahlen und der aus ihnen bereits durch Addition entstehenden unendlichen Reihe $1, 2, 3 \dots$ der natürli"-chen Zahlen aus, und fassen alle Mengen auf, die aus ihnen durch die beiden beliebig oft anzuwendenden Processe der Addition und Selbstbelegung entstehen; diese Mengen bilden wieder eine wohldefinierte Gesammtheit, nach dem Additionsprincip vereinige ich sie alle zu einer Summenmenge $\mathcal{U}$, die wohldefiniert ist. Bilde ich nun die Menge $\mathcal{F} = \mathcal{U}^{\mathcal{U}}$ der Selbstbelegungen von $\mathcal{U}$, so entsteht diese auch aus der ursprünglichen Zahlenreihe lediglich durch die beiden Processe der Addition und |[207] Selbstbelegung; sie gehört also auch zu den Mengen, aus deren Addition erst $\mathcal{U}$ entstand, und muß daher ein Teil von $\mathcal{U}$ sein:

(1) $\mathcal{F}$ ist in $\mathcal{U}$ enthalten.

Ich zeige nun, dass dies zu einem Widerspruch führt. Es seien $u_1, u_2, u_3 \dots$ die Elemente von $\mathcal{U}$; jedes Element f von $\mathcal{F} = \mathcal{U}^{\mathcal{U}}$ repräsentiert dann eine Belegung von $\mathcal{U}$ mit sich selbst, d. h. eine Funktion gewissermaßen, die jedem Elemente u_i von $\mathcal{U}$ ein anderes $u_{f(i)}$ zuordnet, wobei die $u_{f(i)}$ keineswegs untereinander verschieden zu sein brauchen; wir stellen dies Element f am besten also durch ein Schema dar:

$$f(u_1) = u_{f^{(1)}}, f(u_2) = u_{f^{(2)}}, f(u_3) = u_{f^{(3)}} \dots$$

Unser Resultat (1), daß $\mathcal{F}$ in $\mathcal{U}$ enthalten ist, kann man nun näher so aussprechen: Man kann jedem Elemente u_i von $\mathcal{U}$ eines f_i von $\mathcal{F}$ eindeutig zuordnen, so daß alle f_i dabei verwendet werden, eventuell sogar mehrfach, aber immer jedem u_i nur *genau ein* f_i entspricht; das heißt ja offenbar nichts anderes, als daß es "nicht mehr" Elemente f_i gibt, als u_i. Eine solche Zuordnung betrachten wir nun: |[208]

$$u_1|f_1, u_2|f_2, u_3|f_3 \dots,$$

und daraus werde ich eine neue Belegung g von $\mathcal{U}$ mit sich selbst bilden, die von allen f_i verschieden ist, also gar nicht in $\mathcal{F}$ enthalten wäre, da ja bei unserer Zuordnung alle Elemente von $\mathcal{F}$ zur Verwendung kommen sollten; da aber $\mathcal{F}$ alle möglichen Belegungen enthält, so haben wir hier den Widerspruch. Wir wenden wieder das Princip des Cantorschen Diagonalverfahrens an. In der Belegung f_1 entspreche dem Element u_1 dasjenige $u_{f_1^{(1)}}$:

$$f_1(u_1) = u_{f_1^{(1)}};$$

ist $u_{g^{(1)}}$ ein von $u_{f_1^{(1)}}$ verschiedenes Element, so ordnen wir in der neu zu konstruierenden Belegung g dies dem u_1 zu:

$$g(u_1) = u_{g^{(1)}} \neq u_{f_1^{(1)}}.$$

Nach diesem Princip verfahren wir weiter; die Bezeichnung der Elemente von $\mathcal{U}$ und $\mathcal{F}$ durch Zahlenindices ist übrigens unwesentlich und soll nicht etwa andeuten, daß diese Mengen abzählbar sind, was keineswegs der Fall ist. Ist u_2 irgend ein Element von $\mathcal{U}$, so gehört ihm in der Abbildung von f auf u eine Belegung f_2 |[209] zu; wir suchen das Element $f_2(u_2) = u_{f_2^{(2)}}$, das sie dem u_2 zuordnet, wählen $u_{g^{(2)}} \neq u_{f_2^{(2)}}$ und definieren eine Belegung g, die dies dem u_2 zuordnet:

$$g(u_2) = u_{g^{(2)}} \neq u_{f_2^{(2)}}$$

Die Belegung g, die wir so erhalten, hat das Schema

$$g(u_1) = u_{g^{(1)}} \neq u_{f_1^{(1)}}, g(u_2) = u_{g^{(2)}} \neq u_{f_2^{(2)}}, g(u_3) = u_{g^{(3)}} \neq u_{f_3^{(3)}} \dots$$

Sie unterscheidet sich von jeder Belegung f_k aus $\mathcal{F}$ in mindestens einer Zuordnung; ist nämlich u_k das in der Abbildung von $\mathcal{F}$ auf $\mathcal{U}$ dem f_k entsprechende Element (oder eines derselben), so ist nach der Definition von g:

$$f_k(u_k) = u_{f_k^{(k)}} \qquad g(u_k) = u_{g^{(k)}} \neq u_{f_k^{(k)}}.$$

Wir haben damit in der Tat den Widerspruch, daß die wohldefinierte Belegung g nicht in der Menge aller Belegungen enthalten sein könnte. Wir könnten ihn auch dahin formulieren, daß gemäß der letzten Betrachtung die Menge $\mathcal{U}^{\mathcal{U}}$ stets größer [von Hilberts Hand: von grösserer Mächtigkeit] als $\mathcal{U}$ ist, nach der ersten aber in $\mathcal{U}$ enthalten. Dieser Widerspruch ist noch keineswegs geklärt; es ist wohl zu sehen, daß er jedenfalls darauf beruhen muß, daß die Operationen des Zusammenfassens irgend welcher Mengen, Dinge zu |[210] neuen Mengen, Allheiten doch unerlaubt ist, obwohl es die traditionelle Logik doch stets gebraucht, und wir es in vorsichtiger Weise stets nur auf ganze Zahlen und daraus entstehende Mengen, also auf rein mathematisches anwandten.

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