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Hilbert's significance for the philosophy of mathematics (1922)

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If we consider the intellectual relationship of the mathematical sciences to philosophy, as it has developed since the time of the Enlightenment, we notice with satisfaction that mathematical thought is now at the point of regaining the powerful influence on philosophical speculation that it had up to Kant's time, but then suddenly lost. That sudden turn from mathematical thought was influenced by the general turn from the spirit of the Enlightenment that took place at the beginning of the nineteenth century.

This detachment of philosophy from the exact sciences was, however, only a one-sided one: While the dominant philosophy became completely estranged¹ from mathematics, a philosophical orientation continued to evolve among mathematicians.

The most important reason for this was that mathematics had grown far beyond the framework within which it had moved up to the time of Kant. Not only had the domain of investigated facts grown considerably, but the whole form of the investigations became grander and the entire method more encompassing. The concept-formations rose to a higher level of generality; the meaning of the formula became less important than conceptual abstractions

¹Among those philosophers who represented a laudable exception in this respect, Bolzano must be mentioned in particular; he gave the first rigorous foundation of the theory of real numbers.

and leading systematic ideas. Furthermore, the attitude toward the foundations and toward the object of the mathematical sciences also changed.

The task of geometry was understood in broader terms. Formation of geometrical concepts became more general and freed themselves more and more from the connection to spatial representation. In the recently developed geometrical theories, moreover, intuition of space no longer had the significance of an epistemological foundation, but was rather employed merely in the sense of an intuitive analogy.

Research in arithmetic also achieved an essential extension in the formulation of its problems. On the one hand, the concepts of number and of order were generalized, through the invention of set theory, in a completely new way and applied to infinite totalities. On the other hand, the development of algebra led to the objects of investigation no longer being exclusively numbers and quantities; rather, the formalism of calculation itself was made an object of study, and one took as a task the consideration of formalisms quite generally. Numbers as well as quantities now appeared only as something special, and the more one examined their regularity from more general points of view, the more one was weaned away from taking this lawfulness for granted.

In this way, the whole development of mathematics tended toward robbing of its appearance of exclusiveness and finality, that which had previously been considered to be the only object of research and whose basic properties had been taken as given by mathematics, and neither capable nor in need of mathematical investigation. The framework which earlier philosophical views, and even Kantian philosophy, had marked out for mathematics was burst. Mathematics no longer allowed philosophy to prescribe the method and the bounds of its research; rather it took the discussion of its methodological problems into its own hands. In this way the axioms of the mathematical theories were investigated in regard to their logical relationships, and the forms of inference were subjected to more precise critique as well. And the more these problems have been pursued, the more mathematical thought has shown its fruitfulness with respect to them, and has proved itself as an indispensable tool for theoretical philosophy.

To this development, which extends to the present, David Hilbert has contributed isignificantly. What he has accomplished in this field will be described in what follows.

When Hilbert applied himself to the problems in the foundations of mathematical thought that needed to be solved, he not only had at his disposal

his comprehensive command of the mathematical methods, but he was also above all, as it were, predestined for the task by his personal disposition. For mathematics had for him the significance of a world view, and he approached those fundamental problems with the attitude of a conqueror who endeavors to secure for mathematical thought a sphere of influence which is as comprehensive as possible.

While pursuing this goal, it was essential to avoid the mistake of those extreme rationalist thinkers who believed that complete knowledge of everything real could be attained by pure thought. There could be no question of, say, incorporating into mathematics all knowledge of the factual; rather it was necessary, for extending the realm of mathematics in the widest possible way, to sharply delineate the boundaries between the mathematical and the nonmathematical. That would allow one to claim for mathematics all actual mathematical components of knowledge.

In fact, Hilbert understood the problem in just this way. His first and largest work in the field of methodological questions is the *Foundations of Geometry*, which appeared in 1899. In this work, Hilbert laid out a new system of axioms for geometry that he chose according to the criteria of simplicity and logical completeness, following Euclid's concept-formations as closely as possible. He divided the whole system of axioms into five groups of axioms and then investigated more precisely the rôle that the different groups of axioms (as well as single axioms) have in the logical development of geometry.

Through its wealth of new, fruitful methods and viewpoints, this investigation has exercised a powerful influence on the development of mathematical research. However, the significance of Hilbert's foundations of geometry by no means lies only in its purely mathematical content. Rather, what made this book popular and Hilbert's name renowned, far beyond the circle of his colleagues, was the new methodological turn that was given to the idea of axiomatics.

The essence of the axiomatic method, i. e., the method of logically developing a science from axioms and definitions, consists according to the familiar conception in the following: one starts with a few basic propositions, of whose truth one is convinced, puts them as axioms at the top, and derives theorems from them by means of logical inference; their truth is then as certain as that of the axioms, precisely because they follow logically from the axioms. In this view, attention is focused above all on the epistemic character of the axioms. Indeed, originally one considered as axioms only propositions whose

truth was evident *a priori*. And Kant still held the view that the success and the fruitfulness of the axiomatic method in geometry and mechanics essentially rested on the fact that in these sciences one could proceed from *a priori* knowledge (the axioms of pure intuition and the principles of pure understanding).

Of course, the demand that each axiom expresses an *a priori* knowable truth was soon abandoned. For, on the manifold occasions that presented themselves for the axiomatic method, especially in the further development of physics, it followed, so to speak, automatically that one chose both empirical statements and also mere hypotheses as axioms of physical theories. The axiomatic procedure turned out to be especially fruitful in cases where one succeeded in encompassing the results of multifarious experiences in a statement of general character through positing an axiom. A famous example of this is that of the two propositions about the impossibility of perpetual motion of the first and second type; Clausius took them as axioms at the outset of the theory of heat.

In addition, the belief in the *a priori* knowledge of the geometrical axioms was increasingly lost among the researchers in the exact sciences, mainly as a consequence of non-Euclidian geometry and under the influence of Helmholtz' arguments. Thus the empirical viewpoint, according to which geometry is nothing but an empirical science, found more and more supporters. However, this abandonment of the *a priori* character did not essentially alter the perspective on the axiomatic method.

A more powerful change, however, was brought about by the systematic development of geometry. Starting out from elementary geometry, mathematical abstraction had raised itself far above the domain of spatial intuition; it had led to the construction of comprehensive systems, in which ordinary Euclidian geometry could be incorporated and within which its regularity appeared only as a special case among others with equal mathematical justification. In this way, a new sort of mathematical speculation opened up, by means of which one could consider the geometrical axioms from a higher standpoint. It immediately became apparent, however, that this type of consideration had nothing to do with the question of the epistemic character of the axioms, which of course had formerly been considered as the only significant feature of the axiomatic method. Accordingly, the necessity of a clear separation between the mathematical and the epistemological problems of axiomatics ensued. The demand for such a separation of the problems had

already been stated with full clarity by Klein in his Erlangen Program.²

What was essential, then, about Hilbert's foundation of geometry was that here, from the beginning and for the first time, in the laying down of the axiom system, the separation of the mathematical and logical realm from the spatial-intuitive realm, and thereby from the epistemological foundation of geometry, was carried out completely and brought to rigorous expression.

To be sure, in the introduction to his book Hilbert does express the thought that laying down the axioms for geometry and the investigation of their relationships is a task that amounts to "the logical analysis of our spatial intuition," and likewise he remarks in the first section that each one of these groups of axioms expresses "certain basic facts of our intuition which belong together."^a But these statements are located completely outside the axiomatic development, which is carried out without any reference to spatial intuition.

A strict axiomatic foundation of geometry has of course always to satisfy the demand that the proofs should exclusively appeal to what is formulated in the axioms, and that they not draw, in any way, on spatial intuition. In recent times, it was especially Pasch who, in his foundation of geometry,³ emphasised the importance of this requirement and has done so in a consistent way.

However, Hilbertian axiomatics goes even one step further in the elimination of spatial intuition. Drawing on spatial representation is completely avoided here, not only in the proofs but also in the axioms and the concept-formations. The words "point," "line," "plane" serve only as names for three different sorts of objects, about which nothing else is directly assumed except that the objects of each sort constitute a fixed determinate system. Any further characterization, then, follows from the axioms. In the same way, expressions like "the point A lies on the line a" or "the point A lies between B and C" are not associated with the usual intuitive meanings; rather these expressions will designate only certain, at first indeterminate, relations, which *are implicitly characterized*⁴ only through the axioms in which these expressions occur.

² *Vide* [?].

³ *Vide* [?].

⁴ One speaks in this sense of "implicit definition."

^a *Vide* [?], pp. ■ , ■ .

Following this conception, the axioms are in no way judgments that can be said to be true or false; after all, they have a sense only in the context of the whole axiom system. And even the axiom system as a whole does not state a truth; rather, the logical structure of axiomatic geometry in Hilbert's sense—completely analogous to that of abstract group theory—is a purely hypothetical one. If there are anywhere in reality three systems of objects, as well as determinate relations between these objects, such that the axioms of geometry hold of them (this means that by an appropriate assignment of names to the objects and relations, the axioms turn into true assertions), then all theorems of geometry hold of these objects and relations as well. Thus the axiom system itself does not express something factual; rather, it presents only a possible form of a system of connections that must be investigated mathematically according to its *internal* properties.

Accordingly, the axiomatic treatment of geometry amounts to separating the purely mathematical part of knowledge from geometry, considered as a science of spatial figures, and investigating it on its own. The spatial relationships are, as it were, mapped into the sphere of the abstract mathematical in which the structure of their interconnections appears as an object of pure mathematical thought. This structure is subjected to a mode of investigation that concentrates only on the logical relations and is indifferent to the question of the *factual* truth, that is, the question whether the geometrical connections determined by the axioms are found in reality (or even in our spatial intuition).

This sort of interpretation, which the axiomatic method in Hilbert's *Foundations of Geometry* presented, offered the particular advantage of not being restricted to geometry but indeed of being directly transferable to other disciplines. From the beginning, Hilbert perceived the uniformity of the axiomatic method in its application to the most diverse domains, and guided by this viewpoint, he tried to bring this method to bear as widely as possible. In particular, he succeeded in providing a rigorous axiomatic basis for the kinetic theory of gases as well as the elementary theory of radiation.

Moreover, many mathematicians subscribed to Hilbert's axiomatic mode of investigation and worked in the spirit of his endeavors. In particular, it was a success of axiomatics when in the field of set theory, Zermelo overcame the previous uncertainty regarding modes of inference by a suitable axiomatic specification of the inferences and, at the same time, created with his system

a common foundation for number theory, analysis, and set theory.⁵

In his Zurich lecture on “■ Axiomatic Thought” (1917),⁶ Hilbert gave a summary of the leading methodological principles and an overview of the results of research in axiomatics. Here he characterizes the axiomatic method as a general procedure of scientific thought. This procedure applies to any field of knowledge where one has already arrived at the point of setting up a theory, or, as Hilbert says, at an arrangement of the facts by means of a framework of concepts. It then becomes obvious that a few propositions suffice for the logical construction of the theory, and through this the axiomatic foundation of the theory is made possible. This will at first take place in the old sense of axiomatics. However, one can always—as in geometry—move on to Hilbert’s axiomatic standpoint by disregarding the epistemic character of the axioms and by considering the whole framework of concepts only in regard to its internal structure (as a *possible* form of a system of interconnected relationships).

Thus the theory becomes the object of a purely mathematical investigation, which is exactly what is called an *axiomatic* investigation. And, of course, the same principle questions can always be considered for any theory: first of all, in order to represent a possible system of interconnected relations, the axiom system must satisfy the condition of *consistency*; i. e., the relations expressed in the axioms must be logically compatible with one another. Consequently, the task of proving the consistency of the axiom system arises—a problem with which the old conception of axiomatics was not acquainted, since here indeed every axiom counts as stating a truth. Then comes the question of gaining an overview of the logical *dependencies* among the different theorems of the theory. A particular focus of investigation must be on whether the axioms are logically independent of each other or whether, say, one or more axioms can be proved from the remaining ones and are thus superfluous in their role as axioms. In addition, there remains the task of investigating the possibilities of a “deepening of the foundations” of the theory, i. e., examining whether the given axioms of the theory might not be reduced to propositions of a more fundamental character that would then constitute “a deeper layer of axioms” for the framework of concepts under

⁵ *Vide* [?].

⁶ *Vide* [?].

consideration.^b

This sort of investigation, which is of a thoroughly mathematical character, can now be applied to any domain of knowledge that is at all suitable for theoretical treatment, and its execution is of the highest value for the clarity of knowledge and for a systematic overview. Thus, through the idea of axiomatics, mathematical thought gains a universal significance for scientific knowledge. Hilbert can indeed claim: “Everything whatsoever, that can be the object of scientific thought is subject, as soon as it is ripe for the formation of a theory, to the axiomatic method and thereby to mathematics.”^c

Now, by means of this comprehensive development of the axiomatic idea, a sufficiently wide framework for the mathematical formulation of problems was indeed obtained, and the epistemological fruitfulness of mathematics was made clear. But with regard to the *certainty* of the mathematical procedure, a fundamental question still remained open.

Namely, the task of proving the consistency of the axiom system was indeed recognized as first and foremost in the axiomatic investigation of a theory. In fact, the consistency of the axioms is the vital question for any axiomatic theory; for whether the framework of concepts represents a system of interconnected relations at all or only the appearance of such a system depends on this question.

If we now examine how things stand with the proof of consistency for the several geometrical and physical theories that have been axiomatized, then we find that this proof is produced in every case only in a relative sense: the consistency of the axiom system to be investigated is proved by exhibiting a system of objects and of relations *within mathematical analysis* that satisfies the axioms. This “method of reduction” to analysis (i. e., to arithmetic in the wider sense) presupposes that analysis itself—independently of whether it is considered as a body of knowledge or only as an axiomatic structure (i. e., as a merely possible system of relations)—constitutes a consistent system.

However, the consistency of analysis is not as immediately evident as one would at first hope. The modes of inference applied in the theory of real numbers and real functions do not have the character of tangible evidence that is characteristic, for instance, of the inferences of elementary number theory. And if one wants to free the methods of proof from everything that is somehow problematic, then one is compelled to set up analysis axiomatically.

^b *Vide* [?], p. ■ .

^c *Vide* [?], p. ■ .

Thus it turns out to be necessary to provide also a consistency proof for analysis.

From the beginning, Hilbert recognized and emphasized the need for such a proof to guarantee the certainty of the axiomatic method and of mathematics in general. And although his efforts concerning this problem have not yet reached the ultimate goal, he has nonetheless succeeded in finding the methodological approach by which the task can be mathematically undertaken.

Hilbert presented the main ideas of this approach already in 1904 in his Heidelberg lecture “On the Foundations of Logic and Arithmetic.”⁷ However, this exposition was difficult to understand and was subject to some objections. Since then, Hilbert has pursued his plan further and has given his ideas a comprehensible form, which he recently presented in a series of lectures in Hamburg.

The line of thought on which Hilbert’s approach to the foundations of arithmetic and analysis is based is the following: The methodological difficulties of analysis, on the basis of which one is compelled to go beyond the framework of what is concretely representable in this science, result from the fact that continuity and infinity play an essential role. This circumstance would also constitute an insuperable obstacle to the consistency proof for analysis, if that proof had to be carried out by showing that a system of things as assumed by analysis, say the system of all finite or infinite sets of whole numbers, is logically possible.

However, the claim of consistency by no means needs to be proved in this way. Rather, one can give the following entirely different twist to the claim: The modes of inference of analysis can never lead to a contradiction or, what amounts to the same thing: It is impossible to derive the relation $1 \neq 1$ (“1 is not equal to 1”) from the axioms of analysis by means of its methods of inference. Here it is not a question concerning the possibility of a continuous, infinite manifold of certain properties, but concerning the impossibility of a mathematical proof with determinate properties. A mathematical proof is, however, unlike a continuous infinite manifold, a concrete object surveyable in all its parts. A mathematical proof must, at least in principle, be completely communicable from beginning to end. Moreover, the required property of the proof (i. e., that it proceeds according to the principles of analysis and leads to

⁷Appendix VII to [?].

the final result $1 \neq 1$) is also a concretely determinable property. This is why there is also, in principle, the possibility of furnishing a proof of consistency for analysis by means of elementary, and evidently certain, considerations. We only have to take the standpoint that the object of investigation is not constituted by the objects to which the proofs of analysis refer, but rather these proofs themselves.

On the basis of this consideration, the task then arises for Hilbert to examine more precisely the forms of mathematical proofs. We must, so he says in his lecture on axiomatic thought, “make the concept of specific mathematical proof itself the object of an investigation, just as the astronomer takes into account the motion of his location, the physicist concerns himself with the theory of his apparatus, and the philosopher criticizes reason itself.”^d The general forms of logical inference are decisive for the structure of mathematical proofs. That is why the required investigation of mathematical proofs must, in any case, also concern the logical forms of inference. Accordingly, already in the Heidelberg lecture, Hilbert explained that “a partially simultaneous development of the laws of logic and arithmetic is necessary.”

With this thought Hilbert took up *mathematical logic*. This science, whose idea goes back to Leibniz, and which, in the second half of the nineteenth century developed from primitive beginnings into a fruitful field of mathematical thought, has developed the methods for achieving a mathematical mastery of the forms of logical inference through a symbolic notation for the simplest logical relations (such as “and,” “or,” “not,” and “all”). It turned out that only by means of this “logical calculus” does one gain a complete overview of the system of logical forms of inference, of which he inferential figures treated in traditional logic constitute only a relatively small subfield. In particular, Peano, Frege, and Russell succeeded in developing the logical calculus in such a way that the mental inferences of mathematical proofs can be perfectly represented by means of symbolic operations.

This procedure of the logical calculus forms a natural supplement to the the axiomatic method of grounding a science, to the following extent: along with the exact determination of the *presuppositions*, as is brought about by the axiomatic method, it permits also an exact pursuit of the *modes of inference* by which one proceeds from the principles of a science to its conclusions.

^d *Vide* [?], p. ■ .

In adopting the procedure of mathematical logic, Hilbert reinterpreted it just as he had done with the axiomatic method. Whereas as he had formerly stripped the basic relations and axioms of geometry of their intuitive content, he now eliminated the intellectual content of the inferences from the proofs of arithmetic and analysis which he took as the object of his investigation. He achieved this by taking the systems of formulas, by which those proofs are represented in the logical calculus—detached from their contentual-logical interpretations—, as the immediate object of consideration, and thereby replacing the proofs of analysis with a purely formal manipulation of definite signs according to fixed rules.

Through this mode of consideration, in which the separation of the specifically mathematical from everything contentual reaches its high point, Hilbert's view of the nature of mathematics and on the axiomatic method finally finds its real completion. For we recognize at this point that that sphere of the abstract mathematical, into which the mathematical method of thought translates all that is theoretically comprehensible, is not the sphere of contentual logic but rather the domain of pure formalism. Mathematics turns out to be the general doctrine of formalisms, and by understanding it as such, its universal significance also becomes immediately clear.

This understanding of mathematics as a general doctrine of forms has come to light in recent physics in a most brilliant way, especially in Einstein's theory of gravitation, in which the mathematical formalism gave Einstein the leading idea for setting up his law of gravitation, whose more exact form could never have been found without enlisting mathematical tools. And here it was once again Hilbert who first brought this law of gravitation to its simplest mathematical form. And by showing the possibility of a harmonious combination of the theory of gravitation with electrodynamics, he initiated the further mathematical speculations connected to Einstein's theory, which were brought to systematic completion by Weyl with the help of his geometrical ideas. If these speculations should stand the test in physics, then the triumph of mathematics in modern science would thereby be a perfect one.

If we now look at the intellectual results of Hilbert's philosophical investigations as a whole, as well as the effect brought about by these investigations, and if we, on the other hand, bear in mind the unfolding of mathematics in recent times as outlined above, then the essence of Hilbert's philosophical accomplishment reveals itself. By developing a sweeping philosophical conception of mathematics, which does justice to the significance and scope of its method, Hilbert has succeeded in forcefully establishing the claim that

mathematics, through its depth and profundity, has a universal intellectual influence throughout the sciences. For this, the friends of mathematics will always be indebted to him.