

# ENCYCLOPEDIA OF MATHEMATICAL SCIENCES

INCLUDING THEIR APPLICATIONS

## VOLUME ONE: ARITHMETIC AND ALGEBRA

FELIX KLEIN

Translated from the original German work  
"Encyklopädie der Mathematischen Wissenschaften mit  
Einschluss ihrer Anwendungen"

English Translation by  
S. Vahid Ghayoomie, Claude A. Sonnet

Feb 2025

ENCYCLOPEDIA  
OF  
MATHEMATICAL  
SCIENCES

INCLUDING THEIR APPLICATIONS

---

PUBLISHED

ON BEHALF OF THE ACADEMIES OF SCIENCES  
OF GÖTTINGEN, LEIPZIG, MUNICH AND VIENNA,  
WITH THE COLLABORATION OF NUMEROUS SPECIALISTS

---

VOLUME ONE IN TWO PARTS  
ARITHMETIC AND ALGEBRA

EDITED BY  
WILHELM FRANZ MEYER

IN KÖNIGSBERG I. PR.

PART ONE

LEIPZIG, PRINTED AND PUBLISHED BY B. G. TEUBNER

1898—1904

LIBRARY  
ROYAL PRUSSIAN ACADEMY

ALL RIGHTS RESERVED, INCLUDING THE RIGHT OF TRANSLATION.

*Translator's Note: This work was published over 100 years ago and has entered the public domain. The original copyright restrictions, including translation rights held by the Royal Prussian Academy, are no longer in effect. This translation is legally permitted under public domain laws.*



## Introductory Report on the Enterprise of Publishing the Encyclopedia of Mathematical Sciences

In September of 1894, *Felix Klein* and *Heinrich Weber* met with *Franz Meyer*, then professor at the Mining Academy in Clausthal, on a journey to the Harz Mountains. There, the first plan for the Encyclopedia of Mathematical Sciences was drafted. *Franz Meyer* developed his idea of composing a *dictionary of pure and applied mathematics*.

The ending century has, as in many areas of human knowledge, given rise to the desire for a comprehensive presentation of the scientific work accomplished during its course, which should also include the manifold applications to natural science and technology. Exhaustive, of course, in the sense of a complete presentation delving into all details of the widely branched structure, indicating all paths in both historical and methodological directions, such a work could not be planned, given the lack of comprehensive preliminary work, if one did not want to jeopardize its implementation. Thus, it was initially the intention to compile and characterize only the "most necessary", the fundamental "concepts" of our mathematical knowledge in the form of a *Lexicon*.

"It should" — as *Franz Meyer* explained in a first draft — "provide the explanation of the concept falling under a given keyword in the form in which it first appeared, along with indication of the literary source, as far as possible. While this was mainly intended for newer concepts, the old and even obsolete expressions should nevertheless be mentioned, to preserve them as in a museum. This would be followed by the historical development of the concept

follow up to the most recent times. Almost every concept differentiates and splits over time, takes on different nuances and applications, branches according to the uses made of it, deepens and generalizes. The respective technical term undergoes corresponding changes, additions, and compositions. The most important sections in this concept's career should again be provided with evidence." Thus, the developmental history of each individual concept should, in its part, provide a picture of progressive science.

The plan found full approval from *Klein* and *Weber*.

Fresh courage to execute it might strengthen during the wandering through mountain and forest. A great goal had been brought before their eyes, worth investing the effort and enduring the difficulties that the path would present. The enterprise exceeded the power of the individual; it was to become a collective effort of our German mathematicians, to which each would contribute according to their special field of work, and beyond that, where development brought it with it, researchers from abroad were to be recruited as well.

At that time, the *Cartel of German Academies* had just been formed, determined to implement and promote large scientific enterprises in collaborative work. The task set here appeared genuinely as a task for the Cartel. Through the academies, not only financial support should be offered, but also in scientific terms, the progress of work that would not be completed quickly — at that time, they thought of implementation in six to seven years — should be secured.

The *German Mathematical Association*, however, should primarily make the enterprise their own through the cooperation of their members. For them, the successfully begun plan of large detailed scientific reports on all current areas of mathematics, which were to be recorded in the annual reports, was complemented by this new comprehensive task, for which preliminary work could be drawn from those, at least in part.\*)

---

\*) Already at the first meeting of the German Mathematical Association in Halle, autumn 1891, *Felix Müller* during the discussion of "literary under-

Thus, the importance and need for comprehensive presentation of widely branched knowledge was naturally accompanied by the necessity of uniting their representatives for collaborative work.

\* \* \*

At the *Natural Scientists' Meeting* in *Vienna* in September 1894, the *German Mathematical Association* decided to adopt the plan of composing a dictionary of pure and applied mathematics and commissioned *Franz Meyer* to seek scientific and financial support from the academies and learned societies of *Göttingen*, *Leipzig*, *Munich*, and *Vienna* united in the Cartel.

At the beginning of 1895, the first draft of the book, combined with a preliminary financing plan (which was established with the involvement of *B. G. Teubner* in *Leipzig*) was presented to the academies and received principal approval from *Göttingen*, *Munich*, and *Vienna*, while the *Society of Sciences* in *Leipzig*, due to lack of available funds, found itself compelled to abstain from participation in the enterprise for the time being.

The learned societies commissioned *F. Klein* (*Göttingen*), *W. v. Dyck* (*Munich*), *G. v. Escherich* (*Vienna*) to initiate discussions with the editorial board and with a publisher to be considered, and to draft a detailed plan of the enterprise regarding both its scientific and financial aspects. This academic commission subsequently stood as a permanent institution alongside the editorial board. It strengthened itself right at the beginning through *H. Weber* (*Strasbourg*) as representative of the *German Mathematical Association* and *L. Boltzmann* (*Vienna*) as advisor in scientific matters. Later, *H. v. Seeliger* (*Munich*) and more recently *O. Hölder* (*Leipzig*), who will be mentioned later, joined as well.

In detailed preliminary work, which concerned the organization of the material and its classification into larger comprehensive as well as smaller

---

takings suitable for facilitating the study of mathematics" (1st Annual Report of the *G.M.A.*, p. 59), in connection with the presentation of the draft of his (meanwhile published) mathematical vocabulary, pointed to such an alphabetically arranged mathematical encyclopedia.

individual articles, and then the anticipated scope of the entire work, occupied the summer of 1895. The decision about the feasibility of the enterprise, however, came from a conference of the *academy delegates* with *Franz Meyer* in September 1896 in Leipzig, in which *A. Wangerin*, in place of *H. Weber*, as well as publisher *Alfred Ackermann-Teubner* participated. Alongside a first draft of a keyword-based content arrangement, the manuscript of *Felix Müller's* previously mentioned lexicon of mathematical terminology was present — and it became apparent that for the intended purposes of an encyclopedia, an alphabetical arrangement could not be maintained. If one wanted to link the presentation of our current mathematical knowledge to individual concepts and technical terms and their transformation, as was the original plan mentioned at the beginning, the proper selection of keywords to be included, free from unnecessary ballast, around which the entire presentation would have to be grouped, would already present considerable difficulties. Nevertheless, such an arrangement would result in extensive fragmentation of the content, while on the other hand, particularly in presenting research results and methods, repetitions would hardly be avoidable. The lexicon would moreover acquire a completely inhomogeneous character, because alongside coherent developments about individual areas, very short sections, mere explanations, and countless cross-references would have to be inserted.

Thus in Leipzig, upon *Dyck's* proposal, the decision was made to abandon the idea of a proper *lexicon* and replace the *artificial* system of alphabetical ordering with the *natural* system of a purely subject-based arrangement and presentation of mathematical fields of knowledge. Even in such an arrangement, the manifold connections between individual disciplines are often enough severed, the mutual interweaving in subject matter or methodological terms can only partially be expressed, and the sequential presentation must completely replace the simultaneity of facts. But it is still possible to follow the main thread of guiding thoughts in the simply laid out presentation and incorporate into it the development of individual areas with their further elaboration.



Based on this new principle, the arrangement for the volumes dedicated to pure mathematics was first established. For its development, as well as for the preparation of two articles on "Surfaces of Third Order" and "Potential Theory," they succeeded in gaining *Heinrich Burkhardt*, then lecturer at the University of Göttingen, alongside *Franz Meyer*, and persuaded the former to join the editorial board, for it became apparent from the start that the editorial task could not be managed by a single person. Specifically, *Franz Meyer* later took on the editorship of Volume I (Arithmetic and Algebra) and Volume III (Geometry), while *Heinrich Burkhardt* took that of Volume II (Analysis).

It cannot be denied that with the change in the system of presentation, there was also a shift in content or at least a different emphasis of the same. Not the individual concept, but the structure of content in the results and methods of mathematical research forms the principle of grouping. Thus, the following was established as the task of the "*Encyclopedia of Mathematical Sciences*," as the work was called from then on:

"The task of the *Encyclopedia* shall be to provide, in a concise form suitable for quick orientation, but with the greatest possible completeness, a comprehensive presentation of the mathematical sciences according to their current content of established results, and at the same time to demonstrate through careful literature references the historical development of mathematical methods since the beginning of the 19th century. It shall not limit itself to so-called pure mathematics, but shall also consider applications to mechanics and physics, astronomy and geodesy, the various branches of technology and other fields, and thereby give an overall picture of the position that mathematics holds within today's culture."

A further difficulty now lay in measuring the scope of the entire work and in a proper distribution of space across the individual areas. Comparisons with earlier works of similar nature, with analogous ones from other disciplines, offered only slight

guidance. Here, an initial approach could only be established as a desirable limitation, not as a reliable norm, yet such an estimate had to form the basis for measuring the resources to be contributed by the academies as well as for negotiations with the publishing house.

It was agreed to set six large octavo volumes of forty sheets each as the starting point for space allocation. Three volumes were to serve pure mathematics, two applied mathematics, and another was to be dedicated to historical, philosophical, and didactic questions. Each volume was to be provided with its own index. The final volume should also contain a comprehensive overview and, to make the work usable as a reference work, a detailed alphabetically arranged *index*.

For the entire implementation of the enterprise, the editorial board was to work together with the commission appointed by the academies:

The *editorial board* was tasked with structuring the material in detail based on the work's arrangement established in joint consultations with the commission; to gain contributors, to reach understanding with them about the distribution of areas and to mediate the mutual reference of reviewers concerning neighboring areas; to ensure a unified character of the various articles; to oversee the printing; to compile the indexes; finally, through the commission, to provide regular reports to the participating academies about the work's progress.

The *academic commission* was to be responsible for maintaining the special interest of the academies in the work's prosperity and providing vigorous scientific support to the editorial board. In particular, this commission's approval should be required for any changes proving necessary in the work's plan or in the composition of the editorial board, as well as for the selection of contributors.

\* \* \*

In spring 1896, the presented plans and proposals of the commission and editorial board received the approval of the aca-

demies of *Göttingen, Munich, and Vienna*, and the contract for publication was concluded with *B. G. Teubner* publishing house in Leipzig.

And now the work began — under favorable auspices, for right from the start, the editorial board succeeded in securing a large, significant circle of contributors, ready to put their work in service of the common cause, setting aside their special interests. "*General Principles*" had been issued, which were intended to ensure as much as possible a common basis for the structure of articles and uniform treatment of the material, without overly restricting the scientific freedom and individuality of the individual who bears full responsibility for their presentation.\*)

Regarding the arrangement of individual volumes, as it gradually took shape based on these foundations, this will be reported in the special introductions by the editorial board. Here it should only be emphasized how the establishment and gradual completion of the comprehensive arrangement, the mutual alignment of the content of individual essays, and the clarification of their mutual relationships were particularly promoted in the frequent personal conferences between contributors, editors, and commission members. They represent a sacrifice by all participants that must be acknowledged with the utmost gratitude, but also a lasting

---

\*) We believe we should reproduce them at this point with those modifications and additions which they later received, particularly when undertaking the volumes of applied mathematics.

### **General Principles for the Preparation of Articles.**

1. Within each article, the mathematical *concepts* peculiar to the respective field, their most important *properties*, the most fundamental *theorems*, and the *investigation methods* that have proven fruitful are presented.

2. The execution of *proofs* of the communicated theorems must be omitted; only where principally important proof methods are concerned can a brief indication of them be given.

3. The parts of the work relating to *applications* should fulfill a dual purpose: they should, *on one hand*, orient the mathematician about what questions the applications pose to them, and *on the other hand*, inform the astronomer, physicist, engineer about what answer mathematics gives to these questions. Accordingly, they limit themselves to the mathematical side of applications; instrumentation, observation techniques, collection of constants, regulations fall outside the framework of the work.

benefit for the entire work and for all who have participated in it. The Natural Scientists' Meetings of the last decade, starting from the Vienna meeting of 1894, where the foundation stone of the work was laid, the national Mathematics Congress in Zurich (1897), as well as other conferences of the academic commission and editorial board, which were almost regularly combined with the annual meetings of the Cartel of German Academies, offered important opportunities for joint consultation about the work's progress and exchange of ideas about its detailed development.

The necessity of personal discussion became particularly apparent when, in 1897, after the most essential steps for the arrangement and implementation of the first three volumes of pure mathematics had been taken, it was time to approach the volumes dedicated to applied mathematics. From the outset, it had become clear that only an expansion of the editorial board could ensure the implementation of the enterprise and likewise, that — if one did not want to delay completion

---

If the first of these goals is to be achieved, it will be necessary to: briefly indicate the considerations that led to the mathematical formulation of the problem in question; explicitly establish this formulation; indicate the limits within which the occurring constants lie in practical cases; indicate the degree of accuracy up to which the formulation in question is to be considered correct.

If the second goal is also to be achieved, one must not limit oneself to mere references to those places in the first three volumes where the problem in question is treated; one must briefly state the result of the required mathematical operations (equation solving, geometric construction, integration). However, repetition of literature references is not necessary.

4. Strictly chronological arrangement of the material would necessitate many repetitions for which there is no space; but the *gradual development of concepts and methods* will be explained at appropriate points and documented through *precise literature references*.

5. The existing historical monographs and bibliographic resources will provide good initial orientation services to the contributors; however, the first principle of all historical criticism requires that the presentation ultimately be based on personal *study of the original works*.

6. While results from *older developmental periods* should be included, specific proof of their origin will have to be omitted; otherwise, following principle (5) would delay the completion of the work beyond measure, as the required orienting works are still lacking, especially for the 18th and partly also for the 17th century

of the whole into the distant future — it was necessary to tackle the work from all sides. The academic commission hoped to persuade *F. Klein* to join the editorial board and specifically to take charge of the volume relating to mechanics, and likewise to gain *A. Sommerfeld* (then private lecturer in Göttingen) for the editing of the mathematical-physical part. Initially, *Klein* undertook several major journeys (to England, France, Holland, Italy, and Austria), for which the academies had granted the necessary means in a liberal way, to make the necessary preliminary work for the arrangement, development, and collaboration on these volumes. While the participation of non-German authors had already become of essential importance for the character of the reports in the first volumes, here, with the volumes dedicated to applied mathematics, it is particularly important to be able to count on the collaboration of non-German authors according to the development of individual areas.

As much as we want to claim the entire enterprise as German in its foundation and execution, it is from

---

lacking. Accordingly, the historical presentation will generally begin with the start of the nineteenth century. Insofar as citations to earlier times are given at all, they are to be understood in the sense that no guarantee is provided whether an even earlier source could have been cited.

7. The individual mathematical subjects are not considered as isolated from each other; on the contrary, it is one of the main tasks of the work to bring general awareness to the manifold *interweaving and overlapping of the most diverse areas*.

8. One-sided emphasis of a particular school standpoint runs counter to the work's purpose. The most desirable would be if everywhere it were possible to integrate the results obtained by different paths into an *objective presentation*; where this appears unfeasible, at least each of the opposing views should be given a voice.

9. The Encyclopedia is not called upon to decide pending *disputes*, particularly those about priority.

10. If concepts or theorems belonging to another area are used in one field, reference is simply made to the section treating the *latter area* (using the signature used in the arrangement), even if it appears at a later point in the Encyclopedia. Moreover, things about which one can doubt whether they belong in an earlier or later section will generally be included at the earlier point.

11. As far as it can be done without compromising principles (7) and (10), the requirements for readers' prior knowledge will be kept such that

of utmost importance, if it is not to represent a one-sided viewpoint, that in the conception and presentation of individual areas, all voices that have contributed to the uniqueness of their development are heard. The permanent holdings of any science are an international good, gained from the collective work of scholars of all times and all countries. But in different directions, with varying emphasis and appreciation of individual areas, with characteristic differences in methods and form of presentation, different nations and different epochs have participated in this work. This must be expressed in the Encyclopedia in the presentation of content according to its historical development as well as in the recruitment of contributors. Indeed, the enterprise today counts, alongside its foundation of German authors, scholars from America, Belgium, England, France, Holland, Italy, from Norway, Austria, Russia, Sweden among its contributors.

In the years 1898 and 1899, particularly through the personal efforts and connections of *F. Klein*, the implementation

---

the work can also be useful to someone who seeks orientation about only a specific area.

12. Bibliographic completeness of *literature references* is neither possible nor even desirable, just as exhaustive enumeration of all main proposed theorems or suggested technical terms.

13. However, all important *technical terms* actually in use should appear and find explanation, so they can later be included in the index. Cases should be noted particularly where the same term or symbol is used by different authors with different meanings, especially those where the meaning of a term has imperceptibly expanded over time. Among obsolete terms, a sparing selection should be made.

14. Wherever necessary for understanding, *figures* will be included *in the text*.

15. The enterprise does not have the means for including extensive *collections of formulas*, or similar *tables of numerical values* of the functions treated — which should not be copied from other works without prior verification anyway. However, information about where such can be found is desirable, if necessary with a warning against uncritical use. — Very small tables can find space, which illustrate the behavior of a function through a few appropriately chosen numerical values; often a graphical representation will serve the same purpose even better.

16. *Citations* to frequently used journals will be given in uniform abbreviated

of the volumes dedicated to applied mathematics could be secured and a first arrangement of the same could be drafted. In doing so, it proved necessary to distribute the entire abundant material of applications across three volumes instead of two as planned, of which the fourth would encompass mechanics, the fifth mathematical physics, and the sixth geodesy, geophysics and astronomy, while a seventh volume was reserved for historical, philosophical and didactic questions.

In 1899, *Klein* definitively took over the editorship of the volume dedicated to mechanics, soon after *Sommerfeld* took the editorship of the fifth volume, mathematical physics.

An arrangement of the sixth volume could only be approached after multiple preliminary negotiations in 1900. It was undertaken by *E. Wiechert* in Göttingen for geodesy and geophysics, and by *R. Lehmann-Filhés* in Berlin for astronomy, both thereby joining the encyclopedia's editorial board. Unfortunately, the latter found himself compelled to step down from the editorial board in 1902, where he had conducted the initial negotiations with the selected contributors in a most commendable way. In his

---

form (according to a specially established scheme); books are cited, where they appear in an article for the first time, with family name and abbreviated first name of the author, main part of the title, place and year, in case of multiple occurrences the later times in shorter form. Where the matter doesn't seem important enough for more detailed information, mere enumerations of names usually have little use for the reader.

17. Generally meaningless *ornamental epithets*, such as groundbreaking, ingenious, magnificent, classical etc. should be avoided. Instead, it will be indicated in which direction progress lies in each case: whether in finding *new results* — or in *rigorous foundation* of previously only conjecturally proposed or insufficiently proven theorems — or in shortening cumbersome developments through the use of *new tools* — or finally in *systematic arrangement* of an entire theory.

Specifically for the preparation of volumes for applied mathematics, the following remarks apply:

1. Since the encyclopedia essentially addresses a mathematical audience, it must place emphasis on the *mathematical* side of theories. This will include, on one hand, the mathematical *formulation* of the tasks under consideration, and on the other hand, their mathematical *implementation*. The latter viewpoint, which often recedes in specifically physical and scientific books, will be essentially kept in mind here. On the other hand, however, in contrast to the presentation in the majority of mathematical works, the experimental foundation of individual

place, *K. Schwarzschild*, who had just been appointed to the Göttingen Observatory, joined in 1903.

At Easter 1904, *Conrad H. Müller*, who had been involved in the editorial work for some time, was appointed by the academic commission as co-editor of the fourth volume to support *F. Klein*; finally in July 1904, *Ph. Furtwängler* (in Potsdam) was called to edit the first part of Volume VI (Geodesy and Geophysics) in collaboration with *E. Wiechert*.

Meanwhile, on November 7, 1898, the first issue of the first volume was published, containing *H. Schubert's* report on the foundations of arithmetic, *E. Netto's* report on combinatorics, and *A. Pringsheim's* extensive work on irrational numbers and convergence of infinite processes. In August 1899, the publication of the second volume then began with *Pringsheim's* foundations of general function theory, followed by *A. Voss's* essay on differential and

---

areas should be described, namely to the extent that the reader gains a general judgment about the foundation and accuracy limit of the mathematical theory.

2. The general plan of the encyclopedia corresponds, as emphasized in the writing, to the *historical arrangement of material* and provision of the main moments of *historical development*. However, for the present volumes in this regard, it should be noted that the results of applied mathematics become outdated more quickly than those of pure mathematics, and therefore the historical development here does not have the same importance for understanding the current state of theory as there. Nevertheless, historical presentation will generally be desirable in the following volumes as well, insofar as it is compatible with systematics and clarity.

3. In the fields of applied mathematics, the literature is often very scattered and disconnected. The editorial board has therefore made it their concern to establish connections in advance in as many directions as possible, with mathematicians, physicists, technicians, ... astronomers, as well as in different countries; they will be gladly ready to communicate or at least point out otherwise difficult-to-obtain literature to the contributors based on these connections.

4. Finally, it does not seem necessary that each article be prepared by a single author. Rather, *smaller contributions* that cover only part of the material to be treated in the respective article are sometimes desirable. Such contributions can be printed as an appendix to the comprehensive article or, if the author agrees, be made available to the main reviewer of the area and incorporated by them. The authorship of such contributions will be appropriately expressed in the article's heading.



integral calculus, as well as that of the late *G. Brunel* on definite integrals. In October 1902, the first issue of the third volume appeared with essays by *H. v. Mangoldt* and *R. v. Lilienthal* on differential geometry. The publication of parts dedicated to applied mathematics began in June 1901 with the fourth volume with *M. Abraham's* presentation of geometric concepts for mechanics of deformable bodies and two treatises by *A.E.H. Love* on hydrodynamics. At Easter 1903, Volume V (Mathematical Physics) followed, introduced by *C. Runge's* essays on measurement and measuring and *J. Zenneck's* on gravitation, to which *G. H. Bryant's* general foundation of dynamics is joined. Still in the course of this year, the publication of the first issues of both parts of the sixth volume will begin. They will contain, on one hand, essays by *C. Reinhardt* and *P. Pizzetti* on geodesy, by *S. Finsterwalder* on photogrammetry, and on the other hand (in the astronomical part) treatises by *E. Anding* and *F. Cohn* on the theory of coordinates.

Not everyone has approved of this activity beginning on all sides of the work, fearing that the completion of individual volumes might be delayed too much. Also, the reader currently receives a not easily overlooked patchwork of individual issues, which libraries are also reluctant to release for use. However, it must be said that a delay in publication due to the broad scope of editorial activity does not occur, because it almost always involves different editors and contributors; on the contrary, the uniform progress of the whole is of essential importance for utilizing the mutual relationships between individual volumes and individual essays. On the other hand, the publishing house has recently accounted for the ease of use of individual issues through special equipment and binding of the issues.

Here is the place to emphasize with special thanks the extremely great accommodation of the publishing house *B. G. Teubner*. On one hand, the firm has most willingly fulfilled all extensive wishes and requirements of the editors and authors regarding printing, and on the other hand, through its own commitment to the honoraria to be expended, has made it possible

to meet the increasingly strong need arising in the course of development to carry out the work in a scope considerably expanded compared to the initial plan.

One may regret that the original approach of presenting a very concise overview of our current mathematical knowledge in six manageable volumes has been abandoned, and may not without concern see how from volume to volume the work extends beyond the boundaries drawn at the beginning. However, the striving for greatest possible completeness in individual sections and the desire to be clear and comprehensible, even at the expense of brevity — a desire that has repeatedly been expressed to us from reader circles — form the immediate reason for the growth in scope. But the essential reason lies perhaps deeper: The work is a *first* according to its task, so it cannot be a complete one in fulfilling it. Only when the vast field it encompasses lies before us in this first version as a whole, when the circle of problems it has to present has been measured once, will one be able to see how much remains to be done for deepening its content, for simplifying and making the presentation more concise, for aligning and interconnecting all individual parts.

\* \* \*

Two circumstances significant for the recognition of the scientific work accomplished so far are still to be mentioned in our historical report:

The first is the publication of a French adaptation of the Encyclopedia, for which the publishers *B. G. Teubner* in Leipzig and *Gauthier-Villars et fils* in Paris received authorization from the academies in 1900. *J. Molk*, Professor at the Faculty of Sciences in Nancy, was entrusted with directing this edition initially for the volumes dedicated to pure mathematics, while for publishing the volumes of applied mathematics he collaborated with *P. Appell*, member of the Institut de France (mechanics), as well as with *A. Potier* (physics), *Ch. Lallemant* (geodesy and geophysics) and *H. Andoyer* (astronomy).

It is not merely a translation, but an adaptation envisioned, in which the leading French scholars have promised their participation

have promised. While fully preserving the character of the German original, this edition shall take into account the usage of French circles and, on the other hand, through joint collaboration of authors and editors, the individual articles shall experience manifold additions, especially regarding literature citations.\*)

Thus the German work in its French edition will be made accessible to and appreciated by even wider circles.

We may see a further recognition of the work's implementation so far, which we welcome with particular joy, in the fact that recently the Royal Saxon Society of Sciences in *Leipzig* has also made it possible to participate in the publication of the Encyclopedia. They have delegated *O. Hölder* to the academic commission on their part.

Thus the publication now appears as a joint enterprise of the learned societies united in the Cartel of German Academies in Göttingen, Leipzig, Munich and Vienna, and it also demonstrates the significance of this union for the implementation of tasks that are only possible in united work; at the same time, however, the authority of the academies, which have made the enterprise their own, provides the guarantee that future development, completion of the whole, as well as later revisions are placed in the best hands and secured in their scientific foundation.

\* \* \*

---

\*) The prospectus of the French edition characterizes the nature of the adaptation in the following way:

In the French edition, efforts have been made to reproduce the essential features of the articles from the German edition; however, in the adopted mode of presentation, French customs and habits have been extensively taken into account.

This French edition will offer a very particular character through the collaboration of German and French mathematicians. The author of each article in the German edition has, in fact, indicated the modifications they deemed appropriate to introduce in their article and, on the other hand, the French editing of each article has given rise to an exchange of views in which all interested parties have participated; additions due particularly to French collaborators will be placed between two asterisks. The importance of such collaboration, of which the French edition of the Encyclopedia will offer the first example, will escape no one.

Thus may the Encyclopedia under this friendly aspect, under the protection of the united Academies, serve the sciences in its part:

*Pure mathematical research*, by preparing the old furrowed ground for new sowing and harvest, and opening up conquered land to fertilizing intellectual work;

The *applied branches of knowledge*, by bringing together the often separated paths of mathematical and scientific consideration, and preparing the foundation and method for their further development;

The *totality of all intellectual work*, by designating and circumscribing the position that belongs to the mathematical sciences in the realm of human knowledge.

Munich, July 30, 1904

**Walther von Dyck,**  
as Chairman of the academic commission  
for the publication of the Encyclopedia.

## Preface to the First Volume

The present first volume of the Encyclopedia of Mathematical Sciences encompasses *Arithmetic*, *Algebra*, *Number Theory*, *Probability Calculation* (with applications to adjustment and interpolation, statistics and life insurance), as well as some adjacent disciplines: *Difference Calculation*, *Numerical Computation*, *Mathematical Games*, and *Mathematical Economics*.

These are approximately those parts of pure mathematics that are not specifically of an analytical or geometrical character.

This separation from *Analysis* (Volume II) and *Geometry* (Volume III) could naturally not be entirely rigid; in many cases, an overlap into these two large areas was inevitable, and it was equally impossible to maintain the concept of "pure" mathematics everywhere. This may be elaborated in more detail, following the main features and progression of Volume I.

In Arithmetic (Section A), the irrational and the concept of limits (A 3) simultaneously form the foundation of contemporary analysis; for the convergence and divergence of infinite series, products, fractions, and determinants, analytical and analytic functions therefore had to be drawn upon as evidence. The theory of simple and higher complex quantities (A 4) necessitated an examination of the metric properties of the simplest continuous transformation groups. Set theory (A 5) has become significant as a fundamental classification principle for functions in general, and recently also for the foundations of geometry and analysis situs.

In Algebra (Section B), some of the richest applications of invariant and group theory (B 2, B 3 c, d, B 3 f), especially the theory of finite linear groups, relate to significant geometric configurations; conversely, the doctrine of algebraic formations and transformations is equally

closely linked with the development of algebraic functions, as well as algebraic geometry.

In the section (C) on Number Theory, it is primarily the approximation methods of analytic number theory (C 3) that substantially originated from analysis and, conversely, have promoted it; a main application to geometry appears to be the impossibility of squaring the circle. The article (C 6) on complex multiplication could with equal justification be viewed as an integral component of the theory of elliptical functions.

Finally, reference should be made to the manifold relationships between probability and difference calculus, along with their applications (D, E), to the approximation of certain integrals, the intervention of the theory of general systems and methods of descriptive geometry in numerical computation (F).

Precisely these final sections (D, E, F, G) simultaneously teach the extent to which principles originally drawn from pure mathematics prove their power in solving the most diverse technical problems.

We now turn to the systematic division of sections into individual articles and can be briefer in doing so, as the detailed overall table of contents in any case permits an external orientation about the distribution of material.

The section (A) on *Arithmetic* begins with the elements (A 1, *H. Schubert*), the arithmetic basic operations and their applications to positive and negative, whole and fractional numbers; connected to this naturally is combinatorics (A 2, *E. Netto*), whose most essential offshoot is the theory of determinants.

From the elements, one can proceed within arithmetic in four different directions.

Either one expands (A 3, *A. Pringsheim*) the domain of rational numbers by incorporating the irrational, and simultaneously transfers the arithmetic basic operations to an unlimited number of objects. From this emerges the concept of the limit of a number sequence, and from this again through specification the theory of convergence and divergence of infinite series, products, continued fractions, and determinants. In this context, the theory of finite continued fractions could also be included.

Secondly, one can drop the restriction to the real and expand the domain of arithmetic quantities through the creation of

expand the domain of general and higher complex quantities (A 4, *E. Study*); suitable classification principles enable the organic integration of particularly significant complex quantities, especially quaternions.

Thirdly, the natural number sequence can be continued beyond itself (A 5, *A. Schoenflies*) and one arrives at the various modifications of sets and transfinite numbers.

Or finally, one builds (A 6, *H. Burkhardt*), in connection with combinatorics, on the basis of the permutation process, the doctrine of substitutions of a number of elements. As the most far-reaching type of summarizing substitutions proves to be the "group", initially for a finite, subsequently for an unlimited series of elements or operations.

By borrowing from analysis the concept of a continuously variable quantity, one enters the domain of *Algebra*, as treated in Section B. With the help of the first three or four arithmetic species, the entire or fractional rational functions of one and several variables arise (B 1 a, b, *E. Netto*). The investigations belonging here group themselves around two main problems, first the formal elimination of unknowns from equation systems, which reaches a certain conclusion in the theory of modular systems, then the proof of existence for solutions of algebraic equations and equation systems.

The theory of entire functions experiences a sharper formulation on the basis of the concept of the "rationality domain", whereby the coefficients of the functions are themselves conceived as entire functions of a number of original variables, but with only integer coefficients (B 1 c, *G. Landsberg*). Thereby it succeeds in subordinating the properties of algebraic formations, especially with respect to rational transformations, to the various operations of a fundamental process, the reduction of infinite function or form systems to a finite number. These developments therefore simultaneously serve as the algebraic foundation of higher number theory (Section C).

From this point, a branching into subspecialties of specific character occurs again in Section B. Apart from the article B 3 a (*C. Runge*), which discusses more practical questions of how to enclose equation roots within suitable limits and approximate them using numerically usable algorithms, the group concept emerges as the predominant one. Among the rational transformations

of variables of entire functions (forms) are primarily the linear to be considered (B 2, *W. Fr. Meyer*). If one subjects those variables to any linear group, the coefficients of the given forms are likewise subject to a certain linear group, and the task of linear invariant theory is to establish the invariants of this latter group, or more generally, of any linear group, to classify them appropriately, and to represent the limited series of these as entire or rational functions of a finite number among them. A special interest is claimed by the groups composed of a finite number of substitutions, due to their relationships to theory, analysis, and geometry, to which therefore a special article (B3f, *A. Wiman*) is dedicated.

As the actual carrier of the entire section may be considered the *Galois* theory of equation groups (B 3 c, d, *O. Holder*), already touched upon in B 1 c, which, originally proceeding from the special question of the solvability of certain equations by root signs, has in its further development subordinated the theories of rational as well as arithmetic and geometric rationality domains (as well as the formal integration theories of differential equations). An introduction to this theory is formed by the doctrine (B 3 b, *K. Th. Vahlen*) of one- and multi-valued algebraic functions of one or more quantity series, especially the roots of equations and equation systems.

*Number theory*, or the explicit execution of the characteristics of individual arithmetic rationality domains, could be directly connected to the article B 1 c from today's standpoint. For historical reasons, however, the formation of a separate section (C) was recommended.

Following the presentation of the elementary divisibility laws of natural numbers (C 1, *F. Bachmann*), the treatment of linear, bilinear, quadratic, and certain higher forms, equations, and congruences follows (C 2, *K. Th. Vahlen*); the concepts of elementary divisors and the rank of a matrix, already emerging in algebra, serve here as fundamental principles.

The following article (C 3, *P. Bachmann*) on analytic theory will once do justice to the scattered methods of additive composition of numbers, whose systematic treatment is still pending. On the other hand, it goes into the approximate determination of mean values of number-theoretic functions.



Finally, in connection with the periodic properties of algebraic numbers, discusses the recently emerged questions of the transcendence of specific irrationalities, such as  $e$  and  $\pi$ .

The main goal of contemporary systematic number theory, the extension of the divisibility laws of natural numbers, as well as subsequently the reciprocity laws of power residues to algebraic number fields, that is, to the rational functions of algebraic numbers, especially quadratic ones, is pursued in C 4 a, b (*D. Hilbert*). While the task in the case of a circular field was solved by introducing ideal numbers, in the general case the creations of field ideals or field forms take their place.

The special case of quadratic class fields occurring in the complex multiplication of elliptic functions finds its resolution in C 6 (*H. Weber*).

Of the lower and higher arithmetic and algebra treated up to this point, it can be said that they constitute a closed unity.

This is not the same for the following sections, already mentioned above; they satisfy more of a *negative definition, belonging neither to the preceding nor to the next two volumes*.

Section D is essentially dominated by probability calculation; although, for example, the adjustment calculation (D 2) can be theoretically constructed without the help of specific probability concepts, the relevant concepts and methods have gradually developed through probability calculation.

*Probability calculation* (D 1, *E. Czuber*), initially only an application of combinatorics to some hazard games, has, namely after the adoption of infinitesimal and geometric concepts, extended its scope so extensively that it lies at the basis of a considerable number of mathematical approximation methods, explicitly or implicitly. From an epistemological perspective, it has the service of resolving the concept of chance, or rather the circumstances accompanying it, to a certain degree into mathematical approaches and laws.

The most productive source of *adjustment calculation* (D 2, *J. Sehinger*) is the principle of the minimum sum of squares, which in a modified form, as the principle of least constraint, can also serve as the source of entire dynamics.

In *interpolation calculation* (D 3, *J. Bauschinger*)

any arbitrary function determined by certain data through an entire rational function or also through a finite trigonometric series; both in the practical elaboration of the required algorithms and in the more theoretical establishment of remainder terms, difference calculus renders full service, which is independently treated in Article E (*D. Selivanoff*).

The tasks of *statistics* (D 4 a, *L. v. Bortkiewicz*) and *life insurance* (D4b, *G. Bohlmann*) speak for themselves.

The article F (*R. Mehmke*), on *numerical computation*, contains more than its title indicates. Starting from techniques and tables that serve to facilitate practical calculation with rational and other numbers, the material expands through the use of the most diverse types of computing apparatus and machines into a wide mathematical-technical discipline; also, it becomes a kind of geometric arithmetic through the inclusion of fruitful graphical methods.

The articles G 1 (*W. Ahrens*), G 2 (*L. Pareto*) on *games* and *economic theor* may be viewed as an appendix.

The article G 3 (*A. Pringsheim*) on *infinite processes with complex terms*, which represents a direct supplement to both A 3 and A 4, was originally intended for the second volume. With regard to its close relationship to these essays and in accordance with the arrangement in the French edition of the Encyclopedia, it has subsequently been assigned to the first volume as the concluding article.

To enable the reader a more convenient handling of the volume, it has been divided into two parts. For internal and external reasons, it was recommended to conclude the first part with the last article (B 3 f) of Section B (Algebra).

May the Encyclopedia, which presents the mathematical inventions of a century in historical development, also enliven the epistemological study of the fundamental question of what should actually be considered "new" in mathematics! Does the new lie in an expansion and deepening of a stock of a priori knowledge gained through inner intuition, or does it merely come down to a different grouping of existing empirical facts?

Then it shall still be permitted to set forth the guiding perspectives according to which the *register* has been prepared. It was to be a word and subject register. In the *word register*, only expressions are included

in the present volume; if this inclusion has also extended to a considerable number of terms that are either outdated, or less in circulation, and may often have sprung from a momentary idea of the author, this was done to satisfy to a certain degree those who are interested in the philological side of word formations. The selection was less straightforward with the considerable treasure of technical expressions, as found primarily in the articles on statistics and life insurance, numerical computation, games, and economic theory. The editor has endeavored to extract expressions for such subjects that still retain a certain measure of mathematical thinking.

Regarding the subject *register*, two difficulties should be pointed out at the outset, which could only be approximately resolved.

First is the question of which authors to cite. With some exceptions, only those authors who no longer belong to the present are considered here under the keywords, and even these mostly only when their name — often merely by chance or even improperly — has become a kind of common currency associated with a specific concept, sentence, or specific method. On the other hand, there was a temptation, when an author was mentioned, to strive for a certain completeness with respect to their outstanding achievements. The justified wish that some might have harbored, that this principle should have been extended to as many or even all authors, could not be satisfied already with regard to the available space. Where, conversely, the name of a researcher was mentioned within the register text, often only for greater clarity, it was not highlighted by print, as such emphasis was reserved for other purposes (see below).

The other difficulty lay in the *word formations* themselves. The large number of contributors makes it understandable that the same word does not always denote the same concept, and conversely, that the same concept — not to mention sentences — is labeled with the most diverse names.

The editor has spared no effort to unite factually related citations at a single location, but is very well aware that many gaps may still remain in this regard, and conversely, that something superfluous may have been

found. That for keywords indicating more extensive categories, details had to be suppressed as much as possible, hardly requires justification. That, conversely, the clarity of the register text has suffered from frequent interlocking, shall be readily admitted.

It may perhaps raise concerns that a series of *adjectives* have been incorporated into the keywords. This was done, however, for such adjectives that are more than mere epithets, that express a particularly characteristic property of the noun. Since, on the other hand, the noun as a word must not be missing, the register in various respects resembles a mathematical table with double, sometimes even multiple, entries.

Regarding emphasis through print, it is to be noted that the keywords, as well as references to such, are rendered by spaced letters. The *italic* print is related to the marking of subsections within larger word articles, whether these sections relate to characteristic areas of the volume, or also to derivations and compositions of the word. It appeared expedient to name those characteristic areas briefly in part. For example, the articles B 1 c and C 4 a, b were summarized under the generic name "Body Theory", furthermore the graphical methods occupying a large space under "Graphics", among others. A specific note at the head of the first register page provides information about the specific use of semicolons, as well as round and square brackets.

From the original intention of giving each citation with mention of the article and its author, abstention was made with consideration of the scope. Precisely regarding the scope, the editor has received the most diverse wishes, ranging approximately from two to ten sheets. The actual scope of not quite  $3\frac{1}{2}$  sheets results in a percentage of somewhat over 6% in relation to the  $70\frac{1}{2}$  sheets of text in the volume.

For the assessment of the register, reference should be made to its origin; only after a separate register had been prepared for each article were these, as best as possible, drawn together into a whole.

Originally there was an intention to add corrections and supplements to the volume. Meanwhile, what has previously been

in this respect so inhomogeneous that abstention was taken from it, in the hope that it will later be possible, which is also entirely desirable for other reasons, to allow supplementary volumes to follow the respective completed volumes of the Encyclopedia from time to time.

In conclusion, the editor gladly fulfills the duty to express his special thanks in various directions: first and foremost to the Academies of Göttingen, Leipzig, Munich, and Vienna, as well as the commission appointed by them; then to all the gentlemen contributors of the first volume, who have expended their notable time and effort; furthermore to colleague *H. Burkhardt*, who subjected every article to multiple corrections and contributed an extensive series of critical and historical remarks; and not least to the *Teubner* publishing house for its far-reaching accommodation during the arduous and lengthy printing process.

Königsberg i/Pr., April 1904.

**W. Franz Meyer**  
as Editor.

# Contents of Volume I, Part I

---

## A. Arithmetic

### 1. Foundations of Arithmetic. By H. Schubert in Hamburg

1. Counting and Number .....	1
2. Addition .....	6
3. Subtraction .....	8
4. Combination of Addition and Subtraction .....	10
5. Zero .....	11
6. Negative Numbers .....	12
7. Multiplication .....	13
8. Division .....	16
9. Combination of Division with Addition, Subtraction and Multiplication .....	17
10. Fractional Numbers .....	19
11. The Three Operations of Third Level .....	22

(Completed in July 1898.)

### 2. Combinatorics. By E. Netto in Giessen

1. Combinatorics; Historical Appreciation .....	29
2. Combinatorial Operations. Definitions .....	29
3. Inversion; Transposition .....	30
4. Permutations with Limited Positioning .....	30
5. Related Permutations .....	31
6. Sequences .....	31
7. Application to Arithmetic Questions .....	32
8. Combinations with Specific Sum or Product .....	32
9. Combinations with Limited Positioning .....	33
10. Triple Systems .....	33
11. Extension of the Concept of Variation .....	34
12. Formulas .....	34
13. Binomial Coefficients .....	84
14. Applications .....	35
15. Determinants. Explanation of the Concept .....	36
16. Definitions .....	37
17. Number Problems Regarding Elements .....	38
18. Elementary Properties .....	38
19. Laplace's and Other Decomposition Theorems .....	39
20. Developments .....	39
21. Composition and Product .....	40
22. Other Types of Composition .....	40
23. Composite Determinants .....	40
24. Rank of Determinant .....	41
25. Relations between Coaxial Subdeterminants .....	42
26. Symmetric Determinants .....	42
27. Recurring Determinants. Circulants .....	43
28. Half-Symmetric Determinants .....	43
29. Skew Determinants .....	44
30. Centrosymmetric and Other Determinants .....	44

31. Further Determinant Formations .....	44
32. Determinants of Higher Rank .....	45
33. Infinite Determinants .....	45
34. Matrices .....	45
35. Monographs .....	46

(Completed in October 1898.)

### 3. Irrational Numbers and Convergence of Infinite Processes.

By A. Pringsheim in Munich

1. Irrational Numbers. Euclid's Ratios and Incommensurable Quantities .....	49
2. Michael Stifel's Arithmetica Integra .....	50
3. The Concept of Irrational Numbers in Analytic Geometry .....	51
4. Cantor-Dedekind Axiom and Arithmetic Theories of Irrational Numbers .....	53
5. Theories of Weierstrass and Cantor .....	54
6. Dedekind's Theory .....	55
7. Du Bois-Reymond's Struggle Against Arithmetic Theories .....	56
8. Complete Arithmetization in Kronecker's Sense .....	58
9. 10. Various Representations of Irrational Numbers and Irrationalities of Certain Forms .....	59. 61
11. Geometric Origin of the Limit Concept .....	63
12. Arithmetization of the Limit Concept .....	64
13. Criterion for Limit Value Existence .....	65
14. The Infinitely Large and Infinitely Small .....	67
15. Upper and Lower Limits .....	70
16. Upper and Lower Bounds .....	72
17. Calculating with Limit Values. The Number $e = \lim(1 + \frac{1}{\nu})^\nu$ .....	73
18. So-called Indeterminate Expressions .....	74
19. Graduation of Infinite and Null Values .....	75
20. Limit Values of Doubly Infinite Number Sequences .....	76
21. Infinite Series. Convergence and Divergence .....	77
22. 23. Convergence Criteria of Gauss and Cauchy .....	79. 80
24. Kummer's General Criteria .....	82
25. Theories of Dini, du Bois-Reymond and Pringsheim .....	83
26. 27. Criteria of First and Second Kind .....	84. 86
28. Other Criteria Forms .....	88
29. Scope of Criteria of First and Second Kind .....	89
30. Limit Areas of Divergence and Convergence .....	90
31. Conditional and Unconditional Convergence .....	91
32. Value Changes of Conditionally Convergent Series .....	93
33. Criteria for Possibly Only Conditional Convergence .....	94
34. Addition and Multiplication of Infinite Series .....	96
35. Double Series .....	97
36. Multiple Series .....	100
37. Transformation of Series .....	101
38. Euler-MacLaurin Summation Formula. Half-Convergent Series .....	102
39. Divergent Series .....	105
40. Divergent Power Series .....	108
41. Infinite Products. Historical .....	111
42. Convergence and Divergence .....	113
43. Transformation of Infinite Products into Series .....	114
44. Factorials .....	117
45. Continued Fractions. General Formal Properties .....	118
46. Recursive and Independent Calculation of Approximation Fractions .....	121
47. Approximation Fraction Properties of Special Continued Fractions .....	123
48. Convergence and Divergence of Infinite Continued Fractions. General Divergence Criterion .....	126
49. Continued Fractions with Positive Terms .....	128
50. Convergent Continued Fractions with Terms of Arbitrary Signs .....	129

51. Periodic Continued Fractions .....	130
52. Transformation of Infinite Continued Fractions .....	133
53. Transformation of an Infinite Series into an Equivalent Continued Fraction .....	133
54. Other Continued Fraction Developments of Infinite Series .....	135
55. Continued Fractions for Power Series and Power Series Quotients .....	136
56. Relationships between Infinite Continued Fractions and Products .....	139
57. Ascending Continued Fractions .....	140
58. Infinite Determinants. Historical .....	141
59. Main Properties of Infinite Determinants .....	143

(Completed in September 1898.)

#### 4. Theory of Common and Higher Complex Quantities.

By E. Study in Greifswald (now Bonn)

1. Imaginary Quantities in the 17th and 18th Centuries .....	148
2. Calculating with Quantity Pairs .....	149
3. Common Complex Quantities .....	152
4. Absolute Value, Amplitude, Logarithm .....	135
5. Representation of Complex Quantities by Points in a Plane .....	155
6. Representation of Certain Transformation Groups Using Ordinary Complex Quantities .....	156
7. General Concept of a System of Complex Quantities .....	159
8. Types, Shapes, Reducibility .....	162
9. Systems with Two, Three, and Four Units .....	166
10. Special Systems with $n^2$ Units. Bilinear Forms .....	168
11. Special Systems with Commutative Multiplication .....	172
12. Complex Quantities and Transformation Groups .....	175
13. Classification of Systems of Complex Quantities .....	180
14. Approaches to a Function Theory and Number Theory of Systems of Higher Complex Quantities .....	182

(Completed in November 1898.)

#### 5. Set Theory. By A. Schönflies in Göttingen (now Königsberg)

1. Accumulation Points of Point Sets and Their Derivatives .....	185
2. The Concept of Countability and the Continuum .....	186
3. Cantor's First Introduction of Transfinite Numbers .....	187
4. Transfinite Sets. Cardinality or Cardinal Number .....	188
5. Order Types .....	190
6. Well-Ordered Sets and Their Sections .....	191
7. Order Numbers and the Number Class $Z(N_0)$ .....	192
8. Sets of Higher Cardinality .....	192
9. General Calculation Laws of Order Numbers .....	193
10. Normal Form of Order Numbers and 8-Numbers .....	194
11. General Definitions and Formulas for Point Sets .....	195
12. General Theorems about Point Sets .....	196
13. Closed and Perfect Sets .....	197
14. Decomposition of a Set into Separated and Homogeneous Components .....	198
15. Content of Point Sets .....	199
16. The Continuum .....	201
17. Infinitesimal Calculus. The Infinite ( $U$ ) of Functions .....	202
18. Archimedes' Axiom and Continuity .....	205
19. The Most General Size Classes .....	206

(Completed in November 1898.)

#### 6. Finite Discrete Groups. By H. Bürkhardt in Zürich

1. Permutations and Substitutions .....	209
2. Order of a Substitution .....	210
3. Cycles .....	210
4. Analytical Representation of Substitutions .....	211
5. Substitution Groups .....	211



6. Transitivity, Primitivity .....	212
7. Symmetric and Alternating Group .....	213
8. Possible Order Numbers of Groups .....	213
9. Multiply Transitive Groups .....	214
10. Linear Homogeneous Group .....	214
11. Group of the Modular Equation .....	216
12. Other Subgroups of the Linear Homogeneous Group .....	216
13. Enumeration of Groups of Lowest Degrees .....	216
14. Isomorphism .....	217
15. General Group Concept .....	217
16. Normal Subgroups .....	218
17. Composition Series .....	220
18. Isomorphisms of a Group with Itself .....	220
19. Generating Operations. Geometric Images of Groups .....	221
20. Abelian Groups .....	222
21. Sylow's Theorems .....	223
22. Simple Groups .....	224
23. Solvable Groups .....	225
24. Group Determinant .....	226

(Completed in November 1898.)

## B. Algebra

### 1a. Rational Functions of One Variable; their Zeros. By E. Netto in Giessen

1. Definitions .....	228
2. Constant Counting. Interpolation Problem. Partial Fractions .....	228
3. Interpolation and Adjustment Calculation .....	230
4. Difference Calculus .....	231
5. Roots and their Multiplicity. Zeros .....	232
6. Derivative and Continuity .....	233
7. Fundamental Theorem of Algebra .....	233
8. Factorization .....	238
9. Field of Rationality .....	239
10. Reducibility. Irreducibility .....	239
11. Divisibility Properties .....	241
12. Greatest Common Divisor .....	241
13. Irreducible Functions .....	242
14. Separation of Multiple Roots .....	243
15. Algebraic Congruences .....	244
16. Resultant Representation .....	245
17. Conditions for Common Divisors .....	247
18. Properties of Resultants .....	248
19. Calculation of Resultants .....	249
20. Discriminant .....	251
21. Properties of the Discriminant .....	251
22. Discriminant Surface .....	252
23. Functions with Real Zeros. Reality Relations .....	253
24. References to Adjacent Areas .....	253

(Completed in May 1899.)

### 1b. Rational Functions of Several Variables. By E. Netto in Giessen

1. Definitions .....	256
2. Roots. — Identical Vanishing .....	256
3. Power Series Development of Certain Rational Functions .....	257
4. Multiple Roots. — Infinitely Large Roots .....	257
5. Reducibility and Irreducibility .....	258
6. Elimination. — Bézout's Method .....	260

7. Poisson's Method — Eliminant .....	262
8. Cayley's and Sylvester's Method .....	262
9. Kronecker's Method — Degree Number .....	263
10. Minding's Rule — Labatie's Theorem .....	264
11. Multiple and Infinite Roots of a System of Equations .....	266
12. Solution of Linear Equations — Special Elimination Problems .....	268
13. Properties of the Eliminant .....	270
14. Resultant and its Properties .....	271
15. Reduced Resultant .....	273
16. Reducibility and Divisibility of Systems of Equations .....	273
17. Discriminant of a System of Equations .....	274
18. Discriminant of an Equation .....	274
19. Independence of Functions .....	275
20. Independence of Equations .....	276
21. Functional Determinant .....	276
22. Hessian Determinant .....	277
23. Jacobi's Extension of an Euler Formula .....	278
24. Root Relations of a System of Equations — Interpolation .....	279
25. Characteristic of a System of Functions .....	279
26. Module or Divisor Systems .....	280
27. Further References .....	280

(Completed in July 1899.)

**1c. Algebraic Structures. Arithmetic Theory of Algebraic Quantities.**

By G. Landsberg in Heidelberg

1. Task of the Arithmetic Theory of Algebraic Quantities .....	284
2. Fields or Domains of Rationality .....	284
3. Integral Quantities of a Rationality Domain, Irreducibility .....	286
4. Conjugate Fields, Discriminants .....	288
5. Relations to Galois Theory of Equations .....	290
6. Fundamental Systems .....	292
7. Types or Species .....	294
8. Decomposition of Integral Quantities into Prime Divisors or Prime Ideals .....	294
9. Representation of Prime Divisors through Association of Containing Types or through Association of Transcendental Functions .....	296
10. The Fundamental Equation .....	298
11. Implementation of Arithmetic Theory in Detail .....	299
12. Connection with Theory of Module Systems and Algebraic Structures .....	301
13. Elementary Properties of Module Systems .....	301
14. The Degree Concept. Prime Module Systems .....	302
15. Decomposition into Prime Module Systems. Discriminant of a Module System .....	305
16. Applications of Module Systems. Complex Numbers with Multiple Units .....	306
17. Dedekind's Theory of Modules .....	307
18. Hilbert's Theorems .....	309
19. Generalization of Divisibility and Equivalence Concepts .....	312
20. Noether's Fundamental Theorem .....	313
21. Module Systems of Second Degree, their Normal Forms .....	314
22. Representation of Algebraic Structures through Rational Parameters, Lüroth's Theorem .....	316
23. Transformation of Algebraic Structures .....	318

(Completed in August 1899.)

**2. Invariant Theory. By W. Fr. Meyer in Königsberg**

1. Origins of the Theory .....	322
2. Development of the Invariant Concept .....	323
3. Equivalence of Quadratic and Bilinear Forms and Form Systems .....	327
4. Equivalence of Forms Higher than Second Order .....	334

5. Automorphic Forms. Invariants of Finite Groups .....	336
6. Form Relationship. Finiteness .....	341
7. Associated Forms and Typical Representation .....	347
8. Syzygies .....	350
9. Enumerative Direction .....	353
10. Canonization .....	356
11. Inverse Problems. Irrational Forms .....	358
12. Invariant Processes. Symbolism and Graphical Representation .....	360
13. Aronhold's Process. Polars .....	366
14. Transvection and $\Omega$ -Process. Normalization of a Linear Equation .....	367
15. Substitution of One-sided Derivatives .....	370
16. Substitution of Homogeneous Derivatives .....	371
17. Series Developments .....	373
18. Differential Equations of Comitants .....	375
19. Extensions, Higher Transformations .....	378
20. The Extended Projective Group. Reciprocants and Invariants .....	380
21. Projective Invariants of Curvature Theory .....	383
22. Differential Forms and Differential Parameters of Surface Theory .....	384
23. Special Groups and Forms. Semi-invariants .....	386
24. Combinants and Apolarity .....	390
25. Resultants and Discriminants .....	395
26. Reality Questions .....	399
27. Further Special Forms and Groups .....	400

(Completed in September 1899.)

**3a. Separation and Approximation of Roots. By C. Runge in Hannover**

1. Introduction .....	405
2. Separation of Roots. Bounds for the Roots .....	407
3. The Difference Equation .....	408
4. Descartes' Rule of Signs and Budan-Fourier's Theorem .....	409
5. Sturm's Theorem .....	416
6. Cauchy's Integral .....	418
7. Theory of Characteristics .....	422
8. Quadratic Forms in Connection with Sturm's Theorem .....	427
9. Numerical Example for Separation .....	431
10. Approximation of Roots. Newton's Method .....	433
11. More General Methods .....	433
12. Horner's Scheme .....	436
13. Bernoulli's Method .....	439
14. Graeffe's Method .....	440
15. Approximation for the Case of Several Variables .....	446

(Completed in September 1899.)

**3b. Rational Functions of Roots; Symmetric and Affect Functions.**

By K. Th. Vahlen in Königsberg

1. Symmetric Functions of a Series of Quantities; Definition, Main Theorem, Notation; Numbers ...	450
2. Formulas and Methods of Cramer, Newton, Girard, Waring, Faà di Bruno .....	450
3. Reduction of a Function according to Waring and Gauss, according to Cauchy and Kronecker ...	452
4. Cauchy's Method and its Generalization by Transon .....	452
5. Generating Functions of Borchardt and Kronecker .....	453
6. Fundamental Systems .....	455
7. Theorems on Degree and Weight; Classifications .....	455
8. Partial Differential Equations and Differential Operators .....	456
9. Tables; Tabular Laws. The Cayley-Betti Symmetry Law and its Generalization by Mac Mahon ...	460

10. Mac Mahon's New Theory of Symmetric Functions .....	462
11. Relations to Number Theory .....	464
12. Special Symmetric Functions .....	464
13. Symmetric Functions of Root Differences; Semi-invariants .....	466
14. Two-valued and Alternating Functions .....	467
15. Multi-valued Affect Functions. Group .....	468
16. General Theorems of Lagrange, Galois, Jordan .....	468
17. Possible Number of Values .....	468
18. Construction of Affect Functions, Kirkman's Problem .....	469
19. Enumerations .....	469
20. Rationalization of Affect Functions; Affect of an Equation .....	469
21. Cyclic, Cycloidic, Metacyclic Functions .....	469
22. Equations Solvable by Radicals. Equations Solvable by Square Roots .....	470
23. Equations of 7th Degree whose 30-valued Affect Functions are Rational .....	470
24. Functions of Several Variable Series, Roots of Systems. Calculation of Symmetric Functions according to Poisson, v. Escherich .....	471
25. Symmetric Functions of Series of Variables that are Independent of Each Other. Theorems, Formulas, Methods of Mertens, Waring, Schläfli, Mac Mahon, Junker .....	473
26. Relations between Elementary-symmetric Functions: Brill and Junker .....	475
27. More General Functions .....	479

(Completed in September 1899.)

### 3c, d. Galois Theory with Applications. By O. Hölder in Leipzig

1. Introduction .....	481
2. Definition of the Group of an Equation .....	483
3. Further Properties of the Group .....	485
4. Actual Construction of the Group .....	486
5. Monodromy Group .....	487
6. Transitivity and Primitivity .....	487
7. Adjunction of a Natural Irrationality .....	488
8. Cyclic Equations .....	490
9. Pure Equations .....	490
10. Decomposition of the Equation Problem through Resolvent Formation .....	491
11. Adjunction of an Accessory Irrationality .....	493
12. Adjunction of a Radical .....	496
13. Concept of Solution .....	495
14. Criterion of Solvability .....	496
15. Treatment of Non-solvable Equations .....	497
16. General Equations .....	498
17. Equations of the First Four Degrees .....	499
18. Non-solvability of General Equations of Higher Degree .....	504
19. Equations with Regular Group .....	505
20. Equations with Commutative (Permutable) Group .....	505
21. Abelian Equations .....	506
22. Cyclotomic Equations .....	507
23. Division and Transformation Equations of Elliptic Functions .....	509
24. Reduction of Equations to Normal Forms .....	513
25. Irreducible Equations of Prime Degree .....	515
26. Sylow Equations .....	516
27. Casus Irreducibilis of the Cubic Equation .....	517
28. Construction with Compass and Ruler .....	518
29. Geometric Equations .....	518

(Completed in October 1899.)

**3e. Systems of Equations.** By E. Netto in Giessen and  
K. Th. Vahlen in Königsberg (See: B 1b and B 3b.)

**3f. Finite Groups of Linear Substitutions.** By A. Wiman in Lund

1. Periodic Substitutions.....	523
2. Finite Binary Groups .....	523
3. Extensions .....	526
4. Algebraically Integrable Linear Differential Equations of 2nd Order.....	527
5. Finite Ternary Groups .....	528
6. Algebraically Integrable Linear Differential Equations of Higher Order .....	530
7. Groups from Regular Bodies in Higher Spaces.....	530
8. Invariant Definite Hermitian Forms .....	532
9. First Solution of Equations of 5th Degree .....	533
10. Solution through Mediation of Jacobi's Equations of 6th Degree.....	534
11. Theorem Concerning the Possibility of Resolvents with Only One Parameter .....	536
12. Solution through the Icosahedral Irrationality .....	537
13. Reduction of Equations of 5th Degree to a Ternary Form Problem.....	540
14. Solution through Elliptic Transformation Quantities and Metric Functions.....	541
15. The General Algebraic Form Problems .....	543
16. Equations of 7th Degree with a Group of 168 Substitutions.....	544
17. Collineation Groups of Elliptic Normal Curves .....	545
18. Groups from Elliptic Transformation Theory .....	546
19. Quaternary Form Problems Isomorphic with Equations of 6th and 7th Degree.....	547
20. Reduction of General Equations of 6th Degree to a Ternary Form Problem .....	548
21. Theorem on General Equations of Higher Degree.....	549
22. Quaternary Group of 11520 Collineations.....	549
23. Quaternary and Quinary Groups from the Trisection of Hyperelliptic Functions .....	551
24. Groups of One-to-One Transformations of an Algebraic Curve into Itself.....	552
25. Finite Groups of Birational Transformations.....	553
26. Extension to Infinite Discontinuous Groups.....	554

(Completed in December 1899.)

---

# Contents of Individual Issues of Volume I Part I with their Publication Dates

## Part 1

### A. Arithmetic

Issue 1. 7. XI. 1898.	{	1. Schubert: Foundations of Arithmetic 2. Netto: Combinatorics 3. Pringsheim: Irrational Numbers and Convergence of Infinite Processes
Issue 2. 26. I. 1899.	{	4. Study: Theory of Common and Higher Complex Quantities 5. Schoenflies: Set Theory 6. Bürkhardt: Finite Discrete Groups

### B. Algebra

Issue 3. 15. IX. 1899.	{	1. Foundations: 1 a. Netto: Rational Functions of One Variable; their Zeros 1 b. Netto: Rational Functions of Several Variables 1 c. Landsberg: Algebraic Structures. Arithmetic Theory of Algebraic Quantities 2. Meyer: Invariant Theory
Issue 4. 17. X. 1899.	{	3. Equations: 3 a. Runge: Separation and Approximation of Roots 3 b. Vahlen: Rational Functions of Roots; Symmetric and Affect Functions 3 c. d. Hölder: Galois Theory with Applications
Issue 5. 29. V. 1900.	{	3 e. Netto & Vahlen: Systems of Equations (See: B 1b and B 3b) 3 f. Wiman: Finite Groups of Linear Substitutions

---

# I A 1. FOUNDATIONS OF ARITHMETIC

(THE FOUR BASIC OPERATIONS; INTRODUCTION OF NEGATIVE  
AND FRACTIONAL NUMBERS; THIRD-LEVEL OPERATIONS  
FROM A FORMAL PERSPECTIVE)

BY

**H. SCHUBERT**

IN HAMBURG

---

## Table of Contents

1. Counting and Numbers
2. Addition
3. Subtraction
4. Combination of Addition and Subtraction
5. Zero
6. Negative Numbers
7. Multiplication
8. Division
9. Combination of Division with Addition, Subtraction and Multiplication
10. Fractional Numbers
11. The Three Third-Level Operations

---

**1. Counting and Numbers.** *Counting* things<sup>1)</sup> means viewing them as similar<sup>2)</sup>, comprehending them together, and to them individually other things

---

1) That *non-physical* things can also be counted was emphasized by *G. F. Leibniz* against the Scholastics in "De arte combinatoria" (1666), as well as by *J. Locke* in his work "An Essay concerning human understanding" (1690, Book II). In contrast, *J. St. Mill* (Logic, Book III, 26) sees the fact stated in the definition of a number as *physical*, similar to *G. Frege* in "Foundations of Arithmetic" (Breslau 1884).

2) *E. Schröder* in his "Textbook of Arithmetic" (Leipzig 1878) p. 4 emphasizes that the counting process must be preceded by both a combining of the things to be counted and the recognition of the similarity of the things to be counted, as does *E. Mach* in his book "The Principles of Heat Theory" (Leipzig 1896) (No. 7).

to assign<sup>3)</sup>, which are also viewed as similar<sup>4)</sup>. Each of the things to which other things are assigned during counting is called

3) That counting is not possible without a more or less conscious *assignment* or mapping was emphasized by *K. Weierstrass* in the introduction to his lectures on the theory of analytical functions. (See *E. Kossak* "The Elements of Arithmetic", Berlin, Progr. Friedr. Werder-Gymn., 1872). This is similarly emphasized by *E. Schröder* in his textbook, *L. Kronecker* in his essay "On the Concept of Number" (Philosophical Essays dedicated to Zeller, Leipzig 1887, Journ. f. Math. 101), *R. Dedekind* in his work "What are Numbers and What Should They Be?" (Braunschweig 1887 and 1893), in which "assignment" is thoroughly analyzed through a series of definitions (chain) and theorems.

4) In this definition of number, all philosophers and mathematicians essentially agree. However, opinions differ on which psychological moments enable the formation of the number concept. Following *I. Kant's* example, *W. R. Hamilton* emphasizes *time* perception as the foundation of the concept. For him, algebra is "Science of Order in Progression" or "Science of Pure Time". He first expresses this in his paper published in *Dubl. Trans.* 17, II (1835) "Theory of Conjugate Functions or Algebraic Couples with a Preliminary and Elementary Essay on Algebra as the Science of Pure Time". Later he repeats this view in the preface to his work "Lectures on Quaternions" (Dublin 1853). *H. Helmholtz* takes the same position in his paper "Counting and Measuring" in the philosophical essays dedicated to *Eduard Zeller* (Leipzig 1887); as does *W. Brix* in his paper "The Mathematical Concept and its Development Forms" (Volumes V and VI of *Wundt's* Philosophical Studies; also published as dissertation, Leipzig 1889). In contrast, *J. F. Herbart* in his "Psychology as Science" (Königsberg 1824, Volume II) says that number has no more to do with time than many other types of ideas. *J. J. Baumann* and *F. A. Lange* believe that number aligns far better with *spatial representation* than with time representation, specifically *J. J. Baumann* in his work "The Theory of Space, Time and Mathematics in Modern Philosophy" (Berlin 1869) and *F. A. Lange* in his "Logical Studies" of 1877. Similarly, *F. G. Husserl* opposes efforts to base the concept of number on the idea of time, specifically in Volume I of his work "Philosophy of Arithmetic", Halle 1891.

*Aristotle* is often presented as the first to define number through the concept of time. This is incorrect. *Aristotle* conversely defines time through the concept of number in his "Physics" (Book IV, Chapter 11, p. 219 B or German translation by Prantl, Leipzig 1854, p. 207 ff.), where it states: "Time is the number of movement according to before and after" and further: "Time is the number of circular motion". *Euclid's* often repeated statement (Elements, Book VII) "Number is a multitude of units" can hardly be considered a definition.

Analyses of the number concept can be found, besides in the already cited writings, particularly in the following recent papers and books:

- W. Wundt*, Logic, Volume I;
- G. Frege*, Foundations of Arithmetic, Breslau 1884;
- R. Lipschitz*, Foundations of Analysis, Bonn 1877 (§ 1);
- U. Dini*, Foundations for a Theory of Functions of a Variable Quantity, translated by J. Lüroth (Leipzig 1892);



a unit<sup>5)</sup>; each of the things that are assigned to other things during counting is called a one<sup>5)</sup>. The result of counting is called a *number*. Due to the similarity of the units among themselves and the ones among themselves, the number is independent of the order in which the ones are assigned to the units<sup>6)</sup>.

When one reminds of a number through an added concept of how the units were viewed as similar, one expresses a *denominate number*. By completely disregarding the nature of the counted things, one arrives from the concept of denominate number to the concept of *undenominate number*. By number alone, an undenominate number is always to be understood.

To *communicate* numbers, one can choose any similar things as ones (fingers, counting beads, chalk marks). Primitive peoples who have no writing use stones or shells as ones when they want to communicate numbers. If one assigns similar written characters to the things to be counted, one obtains the usual *numerical symbols*<sup>7)</sup>. Thus, in ancient times, the Romans represented the numbers from one to nine through a sequence of strokes, the Aztecs

*G. Peano*, Arithmetices principia nova methodo exposita, Torino 1889;

*K. Th. Michaelis*, On Kant's Concept of Number, Progr. Charlottenburg, Berlin, at Gärtner, 1884;

*E. Knoch*, On the Concept of Number and Elementary Instruction in Arithmetic, Program of the Realprogymnasium in Jenkau, 1892;

*G. F. Lipps*, Investigations on the Foundations of Mathematics in Wundt's Philosophical Studies (from Volume X onwards); the fourth chapter (in Volume XI) contains the logical development of the number concept.

Of these authors, *G. Peano* and *E. Knoch* build upon Dedekind's foundations in his already cited work.

The laws of arithmetic can be built upon the concept of number without any axiom, as *K. Weierstrass* emphasized in his lectures, among others.

5) The distinction between units and ones in this sense comes from *E. Schröder* (Textbook of Arithmetic and Algebra, Leipzig 1873, p. 5 or Outline of Arithmetic and Algebra, first issue, p. 1).

6) *H. Helmholtz* and *L. Kronecker*, in the already cited essays for Zeller's jubilee, conceive the assignment as if the numbers One, Two, Three, etc. are assigned to the units to be counted. This view is opposed by *E. G. Husserl* in the appendix to the first part of his "Philosophy of Arithmetic" (Halle 1891).

7) On *number communication* and *number representation* through word or writing, one finds detailed information in the following writings:

represented the numbers from one to nineteen through combinations of individual circles. Modern civilized peoples still have natural symbols only on dice, dominoes, and playing cards. If one assigns similar sounds to the things to be counted, one obtains the natural number sounds, as heard, for example, from the chimes of clocks. Instead of such natural number symbols and number sounds, one usually uses symbols and words that are methodically composed of a few elementary symbols and word stems<sup>7)</sup>. The modern numeral writing, which is based on the principle of place value and the introduction of a symbol for nothing, was invented by Indian Brahma priests, became known to the Arabs around 800 and reached Christian Europe around 1200, where over the course of the following centuries the new numeral writing and new calculation gradually displaced calculation with Roman numerals<sup>7)</sup>.

The study of relationships between numbers is called *arithmetic* ( $\alpha\rho\iota\theta\mu\acute{o}\varsigma$  = number). *Calculation* means methodically deriving sought numbers from given numbers. In arithmetic, it is customary to express any number through a *letter*, whereby it must only be noted that within one and the same consideration

---

*M. Cantor*, Mathematical Contributions to Cultural Life of Peoples, Halle 1863;

*G. Friedlein*, The Numerals and Elementary Calculation of Greeks and Romans and of Christian Occident from 7th to 13th Century, Erlangen 1869; Gerbert, The Geometry of Boethius and the Indian Numerals, Erlangen 1861.

*H. Hankel*, On the History of Mathematics in Antiquity and Middle Ages, Leipzig 1874;

*M. Cantor*, Lectures on History of Mathematics, Leipzig 1880, Volume I;

*A. F. Pott*, The Quinary and Vigesimal Counting Methods Among Peoples of All Parts, Halle 1847;

*A. F. Pott*, The Language Diversity in Europe, Demonstrated by Numerals, Halle 1868;

*K. Fink*, Brief Outline of a History of Elementary Mathematics, Tübingen 1890;

*A. von Humboldt*, On the Systems of Numerals Common Among Different Peoples and on the Origin of Place Value in Indian Numbers (J. f. Math., Volume 4);

*P. Treutlein*, Progr. Gymn. Karlsruhe 1875.

*M. Charles*, On the Passage of the First Book of Boethius' Geometry, Brux. 1836; Historical Overview..., Brux. 1837; Par. C. R. 4, 1836; 6, 1838; 8, 1839.

*F. Unger*, The Methodology of Practical Arithmetic in Historical Development, Leipzig 1888;

*H. G. Zeuthen*, History of Mathematics in Antiquity and Middle Ages, Copenhagen 1896;

*H. Schubert*, Counting and Number, a Cultural-Historical Study, in Virchow-Holtzendorff's Collection of Popular Scientific Lectures, Hamburg 1887.

the same letter must always represent one and the same number<sup>8)</sup>.

Two numbers  $a$  and  $b$  are called *equal*<sup>9)</sup> when the units of  $a$  and those of  $b$  can be assigned to each other in such a way that all units of  $a$  and  $b$  participate in this assignment. Two numbers  $a$  and  $b$  are called *unequal*<sup>9)</sup> when such an assignment is not possible. Since during counting the units are considered as similar, it is irrelevant for determining whether  $a$  and  $b$  are equal or unequal which units of  $a$  and  $b$  are assigned to each other. When two numbers are unequal, one is called the *greater*, the other the *lesser*<sup>9)</sup>.  $a$  is called greater than  $b$  when the units of  $a$  and  $b$  can be assigned to each other in such a way that while all units of  $b$  participate in this assignment, not all units of  $a$  do. The judgment that two numbers are equal or unequal is called an *equation* or *inequality*, respectively. For equal, greater, lesser, arithmetic uses the three symbols  $=, >, <$ ,<sup>9)</sup> which are placed between the compared numbers. When drawing a conclusion from multiple comparisons, this is indicated by a horizontal line. The most fundamental conclusions of arithmetic are:

$$\frac{a = b}{b = a}; \quad \frac{a > b}{b < a}; \quad \frac{a < b}{b > a}.$$

These conclusions refer to only two compared numbers. The following conclusions refer to three numbers:

---

8) The first seeds of arithmetic letter calculation can already be found among the Greeks (*Nikomachos* around 100 AD, *Diophantos* around 300 AD), even more among the Indians and Arabs (*Alchwarizmî* around 800 AD, *Alkalsâdî* around 1450). However, proper letter calculation using the symbols  $=, >, <$ ; and operation symbols was only developed in the 16th century (*Vieta* † 1603), primarily in Germany and Italy. The currently common equality sign first appears in *M. Recorde* (1556). More details on this in:

*L. Matthiessen*, Principles of Ancient and Modern Algebra of Literal Equations, 1878;

*P. Treutlein*, The German Coss, Zeitschr. f. Math., Volume 24;

*S. Günther*, History of Mathematical Education in Medieval Germany until 1525, Berlin 1887; Contributions to the Invention of Continued Fractions, Progr., Weissenburg 1872; Mixed Investigations on the History of Mathematical Sciences, Leipzig 1876.

Only through *L. Euler* (from 1707-1783) did the arithmetic symbolic language acquire its current more fixed form.

9) A more precise analysis of the concepts equal, more, less, greater and smaller can be found in *E. G. Husserl's* Philosophy of Arithmetic, Volume I, Chapters 5 and 6 (Halle 1891), where additional philosophical literature can also be found.

$$\frac{a = m}{b = m}; \quad \frac{a > m}{b = m}; \quad \frac{a < m}{b = m}; \quad \frac{a > m}{m > b}.$$

$$\frac{a = m}{a = b}; \quad \frac{a > m}{a > b}; \quad \frac{a < m}{a < b}; \quad \frac{a > m}{a > b}.$$

**2. Addition**<sup>10)</sup>. When one has two groups of units, and indeed in such a way that not only are all units of each group similar, but also each unit of one group is similar to each unit of the other group, one can do two things: either one can count each group individually and interpret each of the two counting results as a number, or one can extend the counting over both groups and interpret the counting result as a number. In the former case, one obtains two numbers, in the latter case only one number. One then says of this

---

10) The logically precise *construction* of the four fundamental operations of arithmetic carried out here in the text was most thoroughly implemented by *E. Schröder* in his textbook (Leipzig 1873, Volume I: The Seven Algebraic Operations). Besides him, the following have contributed to such a construction:

1) *M. Ohm*, Attempt at a Completely Consistent System of Arithmetic (2 volumes, 2nd edition, Berlin 1829);

2) *W. R. Hamilton*, Preface to the Lectures on Quaternions, Dublin 1853;

3) *M. Cantor*, Foundation of Elementary Arithmetic, Heidelberg 1855;

4) *H. Grassmann*, Textbook of Arithmetic, Berlin 1861;

5) *H. Hankel*, Theory of Complex Number Systems, Leipzig 1867 (Section I, I, II);

6) *J. Bertrand*, Treatise on Arithmetic, 4th edition, Paris 1867;

7) *R. Baltzer*, The Elements of Mathematics, Volume I, last (7th) edition, Leipzig 1885;

8) *O. Stolz*, Lectures on General Arithmetic, Leipzig 1885.

A combination of consistent construction with didactic considerations for beginners was first attempted by *E. Schröder* in his Outline of Arithmetic and Algebra, Part I, Leipzig 1874, then more extensively by *H. Schubert* in his textbooks (Collection of Arithmetic and Algebraic Questions and Problems, four editions, Potsdam 1883 to 1896, System of Arithmetic, Potsdam 1885, Arithmetic and Algebra in Götschen Collection (Leipzig 1896, 1898).

In earlier centuries, there was even uncertainty about which operations should be considered as basic arithmetic operations, as in the middle of the 15th century with *J. Regiomontanus*, *G. v. Peurbach*, *Lucius Pacioli* and in the *Bamberg arithmetic book*. *Peurbach's* Algorithm, for example, knows eight basic operations, namely Numeratio, Additio, Subtractio, Mediatio, Duplatio, Multiplicatio, Divisio, Progressio.

The operations and laws of arithmetic appear in connection with more general viewpoints in *formal arithmetic*, in *logic calculus*, and in *conceptual notation*. Formal arithmetic studies the relationships of quantities without regard to these quantities being numbers. In particular, one should read on this subject on one hand *H. Grassmann's* Theory of Extension, 1844 and 1878, on the other hand *H. Hankel's* Theory of Complex Number Systems, Leipzig 1867. Regarding logic calculus and conceptual notation, cf. Vol. VI.

latter case obtained number that it is the sum of the two numbers obtained in the former case, and these two numbers are called the *summands* of the sum. The transition from two numbers to a single one just described is called *addition*. Counting and adding thus differ only in that counting deals with a single group, while adding deals with two groups of units. To indicate that from two numbers  $a$  and  $b$  a third number  $s$  has emerged through addition, one places the symbol  $+$  (plus) between the two summands. From the definitions of being greater and of addition follows: A sum is greater than one of its summands, namely by the other summand. When  $a > b$ , then  $a$  can be the sum of two summands, one of which is  $b$ .

From the concept of counting follows that there can always be only one number which is the sum of any two numbers, and conversely that there can also be only one number which, when combined with a given number through addition, leads to a *greater* given number as sum.

Since the result of counting is independent of the order in which one counts, it must be:

$$a + b = b + a$$

One calls the law expressed herein the *commutation law*<sup>11)</sup> of addition. Despite this law, one can conceptually distinguish the two

---

11) If  $+$  is the symbol for a very generally conceived connection of two quantities, then for this connection the *commutative* law applies when  $a + b = b + a$ , the *associative* law applies when  $(a + b) + c = a + (b + c)$ . Furthermore, if  $\times$  is the symbol for a second generally conceived connection, then the *distributive* law applies to both when  $(a + b) \times c = (a \times c) + (b \times c)$ , or when  $(a \times b) + c = (a + c) \times (b + c)$ . The distinction of these three basic laws and their names are first found in Germany in *H. Hankel* (Theory of Complex Number Systems, Leipzig 1867), in England already since about 1840, and (according to Hankel) the terms commutative and distributive were first used by *Servois* (Gergonne's Ann., Vol. V, 1814, p. 93), associative probably first by *Hamilton*. These three basic laws also play a fundamental role in more general relationships than arithmetic operations, such as in formal mathematics, logic calculus and conceptual notation. (Cf. here Vol. VI.) In logic calculus,  $a + b$  means everything that is either  $a$  or  $b$ ,  $a \cdot b$  everything that is both  $a$  and  $b$ . For each of these operations, the commutative and associative laws apply. Additionally, the distributive law applies in both forms, as  $(a + b) \cdot c = (a \cdot c) + (b \cdot c)$  and furthermore  $(a \cdot b) + c = (a + c) \cdot (b + c)$ . *E. Schröder* drew attention to this in his work "Operation Circle of Logic Calculus" (Leipzig 1877).

summands, by conceiving in the operation of addition one as passive<sup>12)</sup>, the other as active<sup>12)</sup>. The passive summand could be called *augend*<sup>12)</sup>, the active *auctor*<sup>12)</sup> (increment<sup>12)</sup>). This conceptually possible distinction is arithmetically unnecessary due to the commutation law.

From the concept of counting further follows:

$$(a + b) + c = a + (b + c)$$

The expressed law is called the *association law*<sup>11)</sup> of addition.

From the uniqueness of addition alone follows the law about combining two equations through addition, whereby from  $a = b$  and  $c = d$  follows:  $a + c = b + d$ . However, how an equation and an inequality or two inequalities are to be combined can only be recognized through application of the association law. The combined effect of both basic laws of addition yields:

When any number of numbers are combined through addition in any order such that the sum of two numbers always appears again as a summand of a new addition, the number that represents the final result is always the same, regardless of the order in which the given numbers are combined by addition.

This truth justifies calling the final result the *sum of all* given numbers, and thereby extending the concept of sum such that it may have not only two, but any number of summands.

**3. Subtraction**<sup>13)</sup>. In addition, two numbers, the two summands  $a$  and  $b$ , are given, and from them emerges a third number, the sum  $s$ . If one now conversely considers the sum  $s$  and one summand as given, then the other summand emerges from this as a number which (according to No. 2) is completely determined. Finding this number from the sum  $s$  and the given summand is called *subtraction*<sup>13)</sup>. The number  $s$ , which was previously sum

12) The distinction of the two numbers connected by an arithmetic operation through the terms *passive* and *active* was first given by *E. Schröder* in his "Outline of Arithmetic and Algebra" (Leipzig 1874). In addition, he calls the passive number *augend*, the active increment. *H. Schubert* distinguishes between *augend* and *auctor*, for example in his "Arithmetic and Algebra" in "Göschen Collection" (Leipzig).

13) Addition, multiplication and exponentiation are usually called direct operations and their inversions indirect operations. In *H. Hankel* (Theory of complex number systems,

is called *minuend* in this just defined *inverse*<sup>13)</sup> calculation method. The given summand could be called "minutor" as the active number. However, the name *subtrahend* is customary for this. The result of subtraction is called difference. The sign of subtraction is a horizontal line (minus), before which one places the minuend and after which one places the subtrahend. Thus it is:

$$(s - a) + a = s$$

the *definition formula* of subtraction. From the uniqueness of subtraction follows secondly:

$$(s + a) - a = s$$

The *transposition rule of first degree* is also based on the definition of subtraction, whereby a subtrahend (summand) on one side of an equation may be omitted there to appear on the other side as summand (subtrahend). Through transposition, an unknown summand or an unknown minuend can be *isolated*, i.e., it can be arranged that it stands alone on one side of an equation.

An equation is called *identical* if it remains correct regardless of what numbers one may substitute for the letters appearing in it. An identical equation is called a *formula* if it serves to express a truth in arithmetic symbolic language. An equation is called a *determining equation* if it becomes correct only when the letters appearing in it are replaced by specific (not by all) numbers. If in a determining equation all occurring numbers except one are known, one usually denotes the still unknown number with  $x$ <sup>14)</sup>, and then arises the task of *solving the equation*, i.e., finding the number that must be substituted for  $x$  for the equation to become correct. An equation in which  $x$  is summand or minuend is solved by the transposition rule of first degree

---

Leipzig 1867) the direct operations of arithmetic belong to the *thetic*, the indirect to the lytic types of connections. From the thetic connection type  $a \times b = c$  follow the two lytic  $c \div a = b$  and  $c \div b = a$ .

14) In *Diophantos*, the unknown is denoted by a final sigma as the last letter of  $\alpha\rho\iota\theta\mu\acute{o}\varsigma$ . On the origin of the designation  $x$  for an unknown number, one should read: *Treutlein*, The German Coss, Zeitschr. f. Math. Vol. 24 and the multiply doubted view of *P. A. de Lagarde*, Where does the mathematicians' x come from? (Gött. Nachr., 1882).

**4. Combination of Addition and Subtraction.** From the definition of subtraction follow, when applying the commutation law and the association law of addition, the four formulas:

$$a + (b - c) = (a + b) - c$$

$$a - (b + c) = (a - b) - c$$

$$a - (b - c) = (a - b) + c$$

$$a - b = (a - n) - (b - n)$$

Since in each of these formulas there stands a difference on at least one of the two sides, the *proof* of the same only concerns checking whether the other side fulfills the property prescribed by the definition of subtraction, in which checking only the two basic laws of addition or a formula may be applied that precedes the one to be proved here and so can already be considered as proved.

Since from  $p = q$  according to No.1 follows  $q = p$ , every arithmetic formula contains two truths, which one obtains depending on whether one interprets the formula from left to right or from right to left. When one reads the association law of addition and the first three of the four above formulas from left to right, they yield rules about adding and subtracting sums and differences. When one reads them from right to left, they yield rules about increasing and decreasing sums and differences. These formulas provide the proof that summands and subtrahends can be brought into any order, and the rules according to which from an equation and an inequality or from two inequalities through subtraction of the right and left sides a new inequality can be concluded.

The arithmetic symbolic language<sup>8)</sup> has developed such that in the operations of addition and subtraction the parentheses<sup>15)</sup> around the *preceding* calculation type may be omitted, but must be placed around the following one, so that the association law of addition and the first three of the above formulas may also be written as:

---

15) *E. Schröder* first states in his textbook the following general rule about placing parentheses in arithmetic: An expression that is part of a new expression is enclosed in parentheses. Gradually it has become customary to omit these parentheses in two cases, first when of two *same-level* operations the *precedin* one should be executed first, second when of two *different-level* operations the one of higher level should be executed first.



$$\begin{aligned} a + (b + c) &= a + b + c; & a + (b - c) &= a + b - c; \\ a - (b + c) &= a - b - c; & a - (b - c) &= a - b + c; \end{aligned}$$

**5. Zero**<sup>16)</sup>. Since according to the definition of subtraction the minuend is a sum whose one summand is the subtrahend, the connection of two equal numbers by the minus sign has no meaning. Such a connection has indeed the form of a difference but represents no number in the sense of No. 1. Now arithmetic follows a principle that one calls the *principle of permanence*<sup>17)</sup> or of exceptionlessness and that consists in four things:

*first, in giving every sign connection that represents none of the numbers defined up to then such a meaning that the connection may be treated according to the same rules as if it represented one of the numbers defined up to then;*

*second, in defining such a connection as a number in the extended sense of the word and thereby extending the concept of number;*

*third, in proving that for numbers in the extended sense the same theorems hold as for numbers in the not yet extended sense;*

*fourth, in defining what equal, greater and lesser means in the extended number domain*<sup>19)</sup>.

Accordingly, the sign connection  $a - a$  is subjected to the two basic laws of addition and the definition formula of subtraction, whereby it is achieved that the formulas of No. 4 must also hold for the sign connection  $a - a$ . Through

16) *Zero* appears as the common symbol for all difference forms in which minuend and subtrahend are equal only since the 17th century. Originally, zero was only a vacant sign for a missing level number in the *place-value* numeral writing invented by the Indians. (Cf. the literature indicated in note 7.) It is called "tziphra" in the arithmetic book of the monk *Maximus Planudes* living in the 14th century (German by *H. Waeschke*, Halle 1878), from which the English cypher and the French zero for zero originated. The German word Ziffer, also coming from tziphra, has gained a more general meaning in German. Other numeral writings, like the additive of the Romans or the multiplicative of the Chinese, have no sign for zero.

17) The principle of *permanence*, which is given here in the text the form suitable for the extension of the number concept, was first expressed in most general form by *H. Hankel* (§ 3 of the *Theory of Complex Number Systems*, Leipzig 1867), after *G. Peacock* had already emphasized the necessity of a purely formal mathematics and in connection with it a principle from which through extension that of permanence emerges (*G. Peacock* in *Brit. Ass. III*, London 1834, *Symbolical Algebra*, Cambridge 1845).

application of the formula  $a - b = (a - n) - (b - n)$  to  $a - a$ , one then recognizes that all difference forms in which the minuend equals the subtrahend are to be set equal to each other. This justifies introducing a common fixed symbol for all these equal sign connections. This is the symbol 0 (zero)<sup>16)</sup>. Furthermore, one calls what this symbol expresses a "number", which one also calls zero. But since zero is not a result of counting (No. 1), the concept of number has experienced an extension through the inclusion of zero in the language of arithmetic. From the definition  $a - a = 0$  follows how to proceed with zero in addition and subtraction, namely:  $p + 0 = p$ ,  $0 + p = p$ ,  $p - 0 = p$ ,  $0 + 0 = 0$ ,  $0 - 0 = 0$ .

**6. Negative Numbers**<sup>18)</sup>. When in  $a - b$  the minuend  $a$  is smaller than the subtrahend  $b$ , then  $a - b$  represents no number in the sense of No. 1. According to the principle of permanence<sup>17)</sup> introduced in No. 5, the difference form  $a - b$  must then be subjected to the definition formula of subtraction  $a - b + b = a$ , from which follows that the formulas treated in No. 4 become applicable to  $a - b$  also in the case where  $a < b$ . Hereby one recognizes that all difference forms can be set equal<sup>19)</sup> to each other in which the subtrahend is greater than the minuend by the same amount. It is therefore natural to express all difference forms  $a - b$ , in which  $b$  is greater than  $a$  by  $p$ , through  $p$ . Finally, by calling such difference forms also "numbers", one extends

---

18) Although in a logical construction of arithmetic the introduction of *negative numbers* must precede the introduction of fractional numbers, historically negative numbers came into use much later than fractional numbers. The Greek arithmeticians calculated only with differences in which the minuend was greater than the subtrahend. The first traces of calculating with negative numbers are found with the Indian mathematician *Bhāskara* (born 1114), who distinguishes between the negative and positive value of a square root. The Arabs also recognized negative roots of equations. *L. Pacioli* at the end of the 15th century and *Cardano*, whose *Ars magna* appeared in 1550, know something of negative numbers but attach no independent meaning to them. *G. Cardano* calls them *aestimationes falsae* or *factae*, *Michael Stifel* (in his *Arithmetica integra* appearing in 1544) calls them *numeri absurdi*. Only *T. Harriot* (around 1600) considers negative numbers for themselves and lets them form one side of an equation. The actual calculation with negative numbers, however, begins only with *R. Descartes* († 1650), who assigned to one and the same letter sometimes a positive, sometimes a negative numerical value.

19) That the extension of the concepts equal, greater and lesser brought about by an extension of the number concept requires closer discussion is emphasized in newer textbooks.

the number concept and arrives at the introduction of negative numbers. Accordingly, the definition formula of the *negative number*  $-p$  (minus  $p$ ) reads:

$$-p = b - (b + p)$$

In contrast to negative numbers, the results of counting defined in No. 1 are called *positive* numbers. From the definition formula of the negative number  $-p$  follows for  $p = 0$  that  $-p = 0 - p$ , and since also  $p = 0 + p$ , it is natural to set  $+p$  for  $p$ . The plus and minus signs placed before a number (in the sense of No. 1) are called *signs*. Negative numbers thus have the sign minus, positive ones the sign plus. Of the two signs, each is called the *inverse* of the other. Numbers provided with signs are called *relative*. If one omits the sign from a relative number, there results a number in the sense of No. 1, which one calls the *absolute value*<sup>20)</sup> of the relative number. From these definitions follows how relative numbers are to be connected through addition and through subtraction. As result always appears a relative number or zero.

The introduction of relative numbers makes it possible to conceive any parentheses-free sequence of additions and subtractions as a "*sum*" of purely relative numbers. One calls a sum conceived in this way *algebraic* and the relative numbers that compose it its *terms*. If an algebraic sum stands in parentheses before which a plus sign or minus sign stands, the same may be omitted if one retains or reverses all the signs of the terms contained in it.

Through the introduction of the number zero (No. 5) and negative numbers, the comparison conclusions indicated in No. 2 and No. 4 receive a more extended meaning when one applies greater and lesser also to the newly introduced numbers. One calls, regardless of whether  $a$  and  $b$  are zero, positive or negative,  $a > b$  when  $a - b$  is positive,  $a < b$  when  $a - b$  is negative<sup>19)</sup>.

Finally, the newly introduced numbers also make such equations solvable that according to the original number concept had to be considered unsolvable. Thus the equation  $x + 5 = 5$  is unsolvable according to No. 1, but solvable according to No. 5. Thus further the equation  $x + 5 = 3$  is unsolvable according to No. 1, but solvable according to this number<sup>17)</sup>.

**7. Multiplication**<sup>21)</sup>. Since due to the basic laws of addition the order in which additions are performed, the result leaves unchanged, so that at the

---

20) The expression "absolute value" for the modulus of any complex number has become customary through *K. Weierstrass'* lectures.

end of No. 2 the result of any number of successive additions could be conceived as a *sum of many* summands. If the latter now all represent one and the same number  $a$ , it is natural to set this number only once and add a sign which indicates *how many* summands  $a$  the sum should contain. One thereby arrives at a *new* connection of two numbers, namely the number  $a$ , which is thought of as summand and the number  $p$ , which counts *how often* this summand is thought. One calls this new connection *multiplication* and designates it as an operation of *second degree*, while one calls addition and its inverse, subtraction, operations of *first degree*. To multiply a number  $a$  (passive) with a number  $p$  (active) thus means to calculate a sum of  $p$  summands, each of which is  $a$ . The number  $a$ , which appears as summand thereby, is called *multiplicand*, the number  $p$ , which counts *how often* the summand is thought, is called *multiplier*. The result is called product. Due to No. 5 and No. 6 the multiplicand can be positive, zero or negative. The multiplier however, which indicates *how many* summands are meant, can only be a result of counting, thus only a number in the sense of No. 1. By conceiving a number  $a$  also as a sum of a single summand, the multiplier may also be the number 1. The sign of multiplication is a point set between the multiplicand  $a$  and the multiplier  $p$ . The definition formula of multiplication accordingly reads:

$$\begin{array}{ccccccc} & 1) & 2) & 3) & & p) & \\ a \cdot p = & a & + & a & + & a & + \dots + a \end{array}$$

where the number set above each summand indicates which summand it is. Earlier one set instead of the point the sign  $\times$ .

From the uniqueness of addition follows the uniqueness of multiplication, and from that follows that equal multiplied with equal yields equal. From the definition formula of multiplication follow through the formulas of No. 3 and No. 4 the four *distribution laws*<sup>11)</sup>:

- I.  $a \cdot p + a \cdot q = a \cdot (p + q)$ ;
- IIa.  $a \cdot p - a \cdot q = a \cdot (p - q)$ , when  $p > q$ ;
- IIb.  $a \cdot p - a \cdot q = 0$ , when  $p = q$ ;
- IIc.  $a \cdot p - a \cdot q = -[a \cdot (q - p)]$ , when  $q > p$ ;
- III.  $a \cdot p + b \cdot p = (a + b)p$ ;
- IV.  $a \cdot p - b \cdot p = (a - b)p$ .

[About omitting the parentheses on the left sides of these formulas read note 15.]

Formulas I and II show, read forward, how a common multiplicand is *separated*, read backward, how to multiply *with* a sum or difference. Formulas III and IV show, read forward, how a common multiplier is *separated*, read backward, how a sum or difference is multiplied. From the distribution laws follows how an equation and an inequality or two inequalities are to be combined through multiplication, if the four compared numbers are positive.

How a product is to be treated whose multiplicand is zero or negative follows from No. 5 and No. 6. But when in a product the *multiplier is zero or negative*, this initially represents a meaningless sign connection. According to the principle of permanence<sup>17)</sup>, it is now to be given a meaning that permits calculating with it according to the same rules as if the multiplier were a difference that represents a number in the sense of No. 1. Therefore in formula II the restriction  $p > q$  is to be lifted, to derive from it how to multiply *with* zero and negative numbers. Thus it follows that  $a \cdot 0 = 0$  and  $a \cdot (-w) = -(a \cdot w)$ . From this then also follows how relative numbers are to be connected through multiplication.

From the distribution laws also follows that for multiplication the *commutation law*<sup>11)</sup> and the *association law*<sup>11)</sup> are correct.

The commutation law of multiplication eliminates the necessity of distinguishing between multiplicand and multiplier for pure arithmetic. One therefore designates both with the common name *factor* and writes them in any order. One calls the product a *multiple* of each of its factors and each factor a *divisor* of the product. Furthermore, one calls in a product each factor the *coefficient* of the other.

With denominate numbers the distinction between multiplicand and multiplier emerges through the fact that the former can be denominate but the latter must be undenominate. Therefore with denominate multiplicand the commutation law is meaningless.

For the arithmetic of undenominate numbers follows from the combined effect of the commutation law and the association law that the order in which multiplications follow each other is irrelevant regarding the final result. This justifies extending the concept of product such that it may have not just two, but any *number of factors*.

Through the fact that these factors can all represent the same number, the possibility of defining a direct operation of third degree - exponentiation<sup>21)</sup> - is given.

An algebraic sum whose terms can also be products is called a *polynomial*. One multiplies two polynomials by multiplying each term of one with each term of the other and combining the obtained products again into an algebraic sum. Each term becomes positive or negative depending on whether it arises through multiplication from terms with equal or unequal signs. The proof of this rule follows from formulas I to IV.

From the definitions and results developed so far, one can conclude that when any number of numbers that are zero or relative are connected in any way through addition, subtraction and multiplication, the final result must always be zero or relative, thus one of the numbers defined so far.

**8. Division**<sup>10)</sup>. Division emerges from multiplication through inversion<sup>13)</sup>, namely through considering the product and one factor as given, the other factor as sought. Thereby the number that was previously product receives the name *dividend*, the given factor the name *divisor*, the sought factor the name *quotient*. The sign of division is a colon (read: divided by), before which one places the dividend and after which one places the divisor. Accordingly, the *definition formula of division* reads:

$$(p : a) \cdot a = p$$

Instead of  $p:a$  one also writes  $\frac{p}{a}$ , more rarely  $p/a$ . Like subtraction, division also has conceptually two inversions, since both the passive factor, the multiplicand, and the active factor, the multiplier, can be sought. If the dividend is a denominate number, then finding the multiplicand is called *partition*, finding the multiplier *measurement*. Due to the commutation law, however, with undenate numbers it is unnecessary to distinguish between the two inversions of multiplication. For  $p:a$  to have meaning,  $p$  must be able to be a product whose one factor is  $a$ , i.e.,  $p$  must be a multiple of  $a$ , or, what is the same,  $a$  must be a divisor of  $p$ .

From the fact that  $0 \cdot m = 0$  follows two things:

---

21) Cf. here No. 11.

1) Zero divided by zero is to be set equal to any arbitrary number. Therefore one calls the sign connection  $0:0$  *ambiguous*.

2) Zero divided by any arbitrary number always yields the number zero.

But when the divisor is zero and the dividend is not zero but any relative number  $p$ , then arises the question which number, multiplied by zero, leads to the relative number  $p$ . Since none of the numbers defined so far has the required property, the principle of permanence<sup>17)</sup> is to be applied. But the investigation of *what* meaning is then to be assigned to  $p:0$  when  $p$  is not zero belongs in another chapter of mathematics (cf. I A 3).

Since division leads uniquely to one of the already defined numbers only when the divisor is not zero, one may conclude a third equation from two equations through division only *when the divisors are different from zero*. Many fallacies of elementary arithmetic as well as higher analysis are based on disregarding this restriction.

How relative numbers are divided follows from the corresponding rules for the multiplication of relative numbers.

From the definition formula of division also follows:

$$(p \cdot a) : a = p, \text{ if } a \text{ is not zero}$$

This formula yields in conjunction with the definition of division the rule that multiplication and division with the same number cancel each other out, *if this number is not zero*.

From the fact that the two equations  $x \cdot b = p$  and  $x = p:b$  mutually condition each other, if  $b$  is not zero, follows the *transposition rule of second degree*. Through second-degree transposition one can either isolate an unknown factor or an unknown divisor and accomplish the solution of determining equations.

**9. Combination of Division with Addition, Subtraction and Multiplication.** With help of the definition formula of division (No. 8) one can recognize the correctness of the following formulas:

$$\text{I. } (a + b) : m = a : m + b : m,$$

$$\text{II. } (a - b) : m = a : m - b : m,$$

$$\text{III. } a \cdot (b : c) = a \cdot b : c,$$

$$\text{IV. } (a : b) \cdot c = a : b : c,$$

$$\text{V. } a : (b : c) = a : b \cdot c,$$

$$\text{VI. } a : b = (a \cdot m) : (b \cdot m),$$

$$\text{VII. } a : b = (a : n) : (b : n)$$

[About omitting the parentheses on the right sides of F. I to V read note 15.]

Here the occurring divisors are naturally to be understood as divisors of the associated dividend. In particular, none of the divisors may be zero. Formulas III, IV, V, VII correspond in the second degree exactly to the four formulas established in No. 4 for the first degree.

The two distribution formulas III and IV in No. 7, as well as the formulas designated here with I and II teach, read in one direction, how a sum or difference is multiplied or divided, read in the other direction, how products with equal factor or quotients with equal divisor are added or subtracted. In the first case parentheses are dissolved, in the second set.

From formulas I and II also follows how an algebraic sum is divided by a number, and how conversely any algebraic sum of quotients with common divisor can be transformed into a quotient whose divisor is the common divisor of all terms. When in an algebraic sum of quotients the *divisors are different*, one can transform these quotients through formula VI into other quotients that all have the same divisor (general divisor), and then apply the rule just mentioned.

The association law of multiplication and the above formulas III, IV, V teach, depending on whether one reads them in one direction or the other, both how to multiply or divide with products or quotients, and how products or quotients are multiplied or divided. In the first case parentheses are dissolved, in the second set. Furthermore, these forms show that factors and divisors can be brought into any order without the final result thereby changing.

When two quotients have equal positive divisor, that one represents the larger number which has the larger dividend. But when two quotients, whose dividend and divisor are positive, have equal dividend, that one which has the larger divisor represents the *smaller* number. These rules follow from the established formulas and yield how an inequality and an equation or two inequalities are to be combined through division when the divisors are positive and divisors of the associated dividends.



**10. Fractional Numbers**<sup>21)</sup>. In §5 and §6 the principle of permanence<sup>17)</sup> created from  $a - b$ , where  $a$  is not greater than  $b$ , zero and negative numbers. In the same way arise from  $a:b$ , where  $a$  is not a multiple of  $b$ , the *fractional numbers*, namely through transferring the definition formula of division

$$(a : b) \cdot b = a$$

to  $a:b$ , if  $a$  is not a multiple of  $b$ . Thus one also achieves the transfer of all definitions and formulas established so far to the quotient form  $a:b$  and the lifting of the restriction expressed in No. 8 and No. 9, "if the divisor is a divisor of the dividend". In particular, the equation  $b \cdot x = a$  now appears solvable even when  $b$  is not a divisor of  $a$ .

By calling the quotient form  $a:b$ , where  $b$  is not a divisor of  $a$ , a "*number*", one extends anew the concept of number, enlarges the field of investigation of arithmetic and perfects the means<sup>22)</sup> with which it works. In contrast to the fractional numbers thus arising, all numbers defined so far (Nos. 1, 5, 6) are called *whole numbers*. The dividend  $a$  of a fraction  $a:b$  is called its *numerator*, the divisor  $b$  its *denominator*. One designates a fraction by a horizontal line<sup>21)</sup>, a whole number set above it, which is its numerator, and a whole number set below it, which is its denominator.

---

21) Calculation with *fractions* was already done in antiquity. Indeed, the oldest mathematical manual, the *Rhind Papyrus* in the British Museum, already contains a peculiar fraction calculation (details in *M. Cantor's History of Mathematics*, Volume I), in which each fraction is written as a sum of different *unit fractions*. The *Greeks* distinguished numerator and denominator in their letter-numeral writing through different stroking of the letters, but preferred unit fractions. The *Romans* sought to represent fractions as multiples of  $\frac{1}{12}$ ,  $\frac{1}{24}$ , etc. up to  $\frac{1}{288}$ , in connection with their coin division. The *Indians* and *Arabs* knew unit fractions and derived fractions, but preferred, just like the ancient *Babylonians* and, following them, the *Greek astronomers*, *sexagesimal fractions* (cf. note 24). The *fraction line* and today's writing of fractions comes from *Leonardo of Pisa* (called *Fibonacci*), whose *liber abaci* (around 1220) became the source for the arithmetic books of the next centuries.

22) That the introduction of negative and fractional numbers can be dispensed with by algebra, and that those numbers are only symbols that facilitate calculation, *L. Kronecker* expounded in his treatise "On the Concept of Number" (*J. f. Math.* 101, 1887). According to *Kronecker*, therefore, the extensions of the number concept serve only for what *E. Mach* calls "economy of science". (Cf. *E. Mach*, *Mechanics*, Leipzig 1883; *Popular Scientific Lectures*, Leipzig 1896; *The Principles of Heat Theory*, Leipzig 1896, p. 391 ff.)

To compare fractions, one brings them to a common denominator through application of formula VI in No. 9 and calls a fraction equal to another, greater or smaller<sup>19)</sup>, than the other, when its numerator is *equal* to the numerator of the other fraction, *greater* or *smaller* than its numerator. One calls a fraction  $\frac{a}{b}$  greater or smaller than the whole number  $c$ , depending on whether  $a > b \cdot c$  or  $a < b \cdot c$ . A fraction that is smaller than 1 is called *proper*, a fraction that is greater than 1 *improper*. Through application of the considerations in No. 5 and No. 6 to fractions, one arrives at the concepts of negative fraction, positive fraction, relative fraction and absolute value<sup>20)</sup> of a relative fraction. Each of the numbers defined so far is thus zero or positive-whole or negative-whole or positive-fractional or negative-fractional. One combines all numbers that have one of these characteristics, thus all numbers defined so far, through the word "*rational*"<sup>23)</sup>, in contrast to the later defined irrational numbers (cf. IA 3). The rules for how rational numbers are to be connected through addition, subtraction, multiplication and division follow from the formulas established in the earlier paragraphs.

According to formula VII in No. 9, a fraction whose numerator and denominator have a common whole-number divisor can be set equal to that fraction which arises when one divides numerator and denominator by this divisor. This procedure is called *reducing* the fraction. The first-degree analogue to reducing fractions is the reduction of the minuend and subtrahend of a difference by one and the same whole number. While however in this procedure any arbitrary whole number can be achieved as minuend and as subtrahend from any arbitrary difference of whole numbers, through reducing any arbitrary fraction not any arbitrary whole number can be achieved as numerator

---

23) The distinction between rational and irrational quantities appears among the Greeks in geometric form already before *Euclid* (around 300 BC), first probably with *Pythagoras* (around 500), who recognized that the hypotenuse of an isosceles right triangle is unspeakable (*αρρητος*) when the catheti are speakable. *Plato* (429-348) recognized the irrationality in the diagonal of the square over five (*Plato's Republic*, VII 546). Even more extensively *Euclid* treated the irrational (*αλογον*) in the 10th book of his "*Elements*", and indeed in geometric form, distinguishing whether two lines are commensurable or incommensurable (*ασυμμετρος*). *Archimedes* (287-212) in his calculation of the number  $\pi$  enclosed the square root of three and of other numbers in very close rational bounds. About the irrational in modern times cf. here IA 3.

or denominator. One must be content to reduce until numerator and denominator no longer have a common divisor. If the numerator of a fraction is a divisor of the denominator, then through reduction a fraction can be achieved whose numerator is 1. Such fractions with numerator 1 are called *unit fractions*<sup>21)</sup>. Any arbitrary fraction can be conceived as the product of its numerator with its unit fraction, i.e., with that fraction which has the same denominator. When  $a > b$  and  $a$  and  $b$  are whole numbers, then  $a = m \cdot b + v$  can be set where  $m$  is a quite definite whole number and  $v < b$ , from which follows that every fraction is greater than a whole number by a proper fraction, or that every rational number can be enclosed<sup>19)</sup> between two bounds that are whole numbers, differ by 1, and of which one is greater, the other smaller<sup>19)</sup>, than the rational number.

Through continuation of the place-value principle, on which our numeral writing is based, to the right one arrives at *decimal fractions*<sup>24)</sup>, i.e. fractions of which only the numerator needs to be written because the denominator is ten or hundred or thousand etc. Which of these numbers is meant as denominator is indicated by the position of a comma<sup>24)</sup>. (Cf. Numerical Calculation in IF.)

The introduction of relative numbers transforms every subtraction into an addition, namely through reversal of a sign. Similarly, the introduction of fractional numbers transforms every division into a multiplication. If one understands by *reciprocal value* of a fraction the fraction whose numerator and denominator are denominator and numerator of the original fraction, then one recognizes that the result of division by a fraction agrees with the result of multiplication with its reciprocal value.

The arithmetic which comprises only the operations of first and second degree concludes, as follows from the above, with the following two final results:

---

24) *Decimal fractions* arose during the 16th century. *Johann Kepler* (1571-1630) introduced the decimal comma. The principle underlying decimal fraction notation was already used in antiquity with *sexagesimal fractions*. In these one lets multiples of  $\frac{1}{60}$  and then of  $\frac{1}{3600}$  follow the wholes. That these are of *Babylonian* origin has become undoubted through the discovery of a sexagesimal place-value numeral writing (with 59 different numerals, but without a sign for nothing) used by Babylonian astronomers. The Greek astronomers too (*Ptolemy*, around 150 AD) calculated with sexagesimal fractions. For example, *Ptolemy* set  $\pi = 3 \dots 8 \dots 30 = 3 + \frac{8}{60} + \frac{30}{3600}$ . Our sixty-division of the hour and degree, as well as the expressions *minute* (pars *minuta prima*) and *second* (pars *minuta secunda*) are remnants of the old sexagesimal fractions.

1) When general number symbols (letters) are connected in any way through operations of first and second degree, the result can always be represented as a quotient whose dividend and divisor is an algebraic sum of products;

2) When any number of rational numbers are connected in any way through operations of first and second degree, the result is always a rational number, provided division by zero does not occur.

New extensions of the number domain become necessary only when one connects the numbers defined so far through operations of third degree. (Cf. No. 11 as well as IA 3 and IA 4.)

**11. The Three Operations of Third Degree.** In No. 7 the definition of product is extended such that it may contain any number of factors. The case where these are all equal leads to the direct operation of third degree, *exponentiation*<sup>25)</sup>. To raise a number  $a$  (passive) to the power of a number  $p$  (active) thus means to form a product of  $p$  factors, each of which is  $a$ . The number  $a$ , *which* is set as factor of a product, is called *base*, the number  $p$ , which indicates *how often* the other number  $a$  is to be set as factor of a product, is called *exponent*<sup>25)</sup>. The result of exponentiation, which one writes  $a^p$  and reads "a to the power p", is called power. Insofar as one conceives  $a$  as product of one factor, one sets  $a^1 = a$ . Through the definition of exponentiation,

---

25) Powers with exponents 1 to 6 were already designated in abbreviated form by *Diophantus*. He calls the second power  $\delta\upsilon\nu\alpha\mu\upsilon\varsigma$ , a word to which through the Latin translation *potentia* the word "power" is to be traced back. In the 14th to 16th centuries there are already traces of calculation with powers and roots, as with *Oresme* (†1382), *Adam Riese* (†1559), *Christoff Rudolf* (around 1530) and notably with *Michael Stifel* in his *Arithmetica integra* (Nuremberg 1544). More details about this in *M. Cantor's* History of Mathematics. But only the invention of logarithms at the beginning of the 17th century procured full citizenship in arithmetic for operations of third degree. The deeper understanding of their connection however belongs to an even later time. The inventors of logarithms are *Jost Bürgi* (†1632) and *John Napier* (†1617). *Kepler* (†1630) also has great merits regarding the spread of knowledge of logarithms, *Henry Briggs* (†1630) introduced base ten and published a collection of logarithms of this base. (Cf. Numerical Calculation, IF.) The word logarithm ( $\lambda\omicron\gamma\omicron\nu\alpha\rho\iota\theta\mu\omicron\varsigma$  - number of a ratio) is explained by the fact that one sought to relate two ratios by raising one to a power to obtain the other. Thus one called 8 to 27 the third ratio of 2 to 3. Also the expression "numerus rationem exponens" occurs for logarithm, from which perhaps the word "exponent" derives.

the following laws of exponentiation arise from the laws of multiplication:

$$\begin{array}{ll}
 \text{I. } a^p \cdot a^q = a^{p+q}; & \\
 \text{IIa. } a^p : a^q = a^{p-q}, \text{ if } p > q \text{ is;} & \\
 \text{IIb. } a^p : a^q = 1, \text{ if } p = q \text{ is;} & \\
 \text{IIc. } a^p : a^q = 1 : a^{q-p}, \text{ if } p < q \text{ is;} & \left. \vphantom{\begin{array}{l} \text{IIa.} \\ \text{IIb.} \\ \text{IIc.} \end{array}} \right\} \begin{array}{l} \text{(Distribution} \\ \text{formulas with} \\ \text{same base.)} \end{array} \\
 \\
 \text{III. } a^q \cdot b^q = (a \cdot b)^q; & \\
 \text{IV. } a^q : b^q = (a : b)^q; & \left. \vphantom{\begin{array}{l} \text{III.} \\ \text{IV.} \end{array}} \right\} \begin{array}{l} \text{(Distribution formulas with} \\ \text{same exponent.)} \end{array} \\
 \\
 \text{V. } (a^p)^q = a^{p \cdot q} = (a^q)^p; & \text{(Association formula.)}
 \end{array}$$

According to the definition of exponentiation, the base can be any number; the exponent however must be a result of counting, thus a positive whole number. For "positive-whole" one also says "*natural*"; accordingly a power with such an exponent is called a "*natural*" one.

Due to a geometric application, powers with exponent 2 are also called squares, with exponent 3 also cubes.

If the base is a sum, a difference, a product, a quotient or a power, it is to be enclosed in parentheses. On the other hand, the higher position of the exponent makes parentheses around it superfluous.

According to the definition of exponentiation,  $a^0$  and  $a^{-n}$ , where  $-n$  is a negative whole number, are initially meaningless signs. Also products whose multiplier is zero or negative were, according to the original definition of multiplication, meaningless signs. Yet such signs received meaning, according to the principle of permanence, through the desire to be able to multiply with such differences just as with differences that represent a positive number. In the same way one proceeds with the power forms

$$a^0 \text{ and } a^{-n}.$$

One thus sets  $a^0 = a^{p-p}$ , lifts the restriction  $p > q$  in formula IIa, and applies the same, read backwards. Then comes:

$$a^0 = a^{p-p} = a^p : a^p = 1$$

Similarly one sets  $a^{-n} = a^{p-(p+n)}$ , lifts the restriction  $p > q$  in formula IIa, finds thereby  $a^p : a^{p+n}$ , now applies formula IIc and obtains  $1 : a^n$ .

The extension of the concept of exponentiation to the case where the exponent is a fractional number can only be accomplished after the laws of radicalization, one of the two inversions of exponentiation, are established.