THE

CONSTRUCTOR.

REULEAUX.

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To Henry Harrison Suplee, Esqre.
the excellent interpreter of
the authors modest efforts
to serve Science and Practice

F. Reuleaux.

Berlin 19/2 93.

THE
CONSTRUCTOR
A HAND-BOOK
OF
MACHINE DESIGN
BY

F. REULEAUX

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of the Flora Society of Cologne, of the American Philosophical Society
and of the American Society of Mechanical Engineers.

WITH PORTRAIT AND OVER 1200 ILLUSTRATIONS

AUTHORIZED TRANSLATION

COMPLETE AND UNABRIDGED

FROM THE FOURTH ENLARGED GERMAN EDITION

BY

HENRY HARRISON SUPLEE, B. Sc.,

Member of the American Society of Mechanical Engineers,
Member of the Franklin Institute

PHILADELPHIA

H. H. SUPLEE

WEST CHELTEN AVENUE

1894

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TRANSLATOR'S PREFACE.

IN presenting to the engineering profession of England and America this translation of Reuleaux's CONSTRUCTOR, a few prefatory remarks may be permitted. Although the first edition of the German work appeared as long ago as 1861, and translations have been made into French, Swedish and Russian, no English translation has hitherto been made, notwithstanding the fact that repeated editions and enlargements of the original German work have appeared.

The translation here given, therefore, is the first presentation to English speaking engineers of a work which during the past thirty years has acquired the highest reputation over all Europe, and is so well known to German reading engineers and students in this country that no excuse is needed for its present appearance.

The freedom with which the author has drawn from English and American sources as well as from Continental practice gives the work a value not found in other treatises upon machine design, while the vast improvement which has been made by the introduction of the kinematic analysis and the resulting classification of the details of the subject, cannot fail to appeal to the instructor as well as to the practising engineer.

The translation has been made from the Fourth Enlarged German Edition of 1889, the last which has appeared in the original, and is complete and unabridged in every respect. The introduction to this edition is especially worthy of note, as it contains the author's summary of the principles set forth in his larger work on Theoretical Kinematics,* and the more so as it includes a brief glance at the still wider subject included in his work on Applied Kinematics, as yet unpublished in Germany, and embodying a mass of manuscript which it is trusted will at no distant day be given to the public.

The work of translation has been done with the especial sanction and exclusive authorization of Prof. Reuleaux, by whom also the portrait and special introduction to the American edition have been furnished.

The transformation of the notation of the work from the metric system to the English values has involved much labor and while it is too much to expect entire freedom from errors, notwithstanding the care which has been given to this portion of the work, it is trusted that but few errors will be found. It is especially requested that any corrections which may be found necessary will kindly be sent to the translator for future use.

HENRY HARRISON SUPLEE.

PHILADELPHIA, September, 1893.

* It is to be regretted that Prof. Kennedy's translation of this valuable work is now out of print, and it is hoped that a new edition may be issued.

AUTHOR'S INTRODUCTION TO THE AMERICAN EDITION.

THE present translation of the CONSTRUCTOR places my book before a large circle of readers who have been practically active and energetic in the development of machine design, for no one of the technical professions has been followed by the English-speaking race with more activity and success than that of the construction of machinery. I therefore take pleasure in prefacing this book with a few words of special introduction.

During the series of years in which my CONSTRUCTOR has grown from a small beginning to a large volume, the practice of machine construction has also been continuously developing, so that in every new edition changes and additions have been necessary. Much new matter has been added in this edition to the theoretical portion; first, in the section on Graphical Statics, enabling many numerical calculations to be dispensed with, using in their places graphical methods; second, by the introduction of the methods of Kinematics, or the science of controlled movements, a science which reduces the apparently inexhaustible complexity of machine forms to a few simple and fundamental principles, the command of which may be of extraordinary value to the engineer. I am still constantly engaged with the subject of Kinematics, especially with its practical applications, but on account of the pressure of other occupations I have not as yet been able to carry out my intention of treating this portion of the subject in a separate work, corresponding to my work on THEORETICAL KINEMATICS. The work already published on this subject I have therefore characterized as an "outline" of a theory of machines." *

The simplification of the conceptions concerning machines to which these kinematical studies led me, was of such importance that I have introduced the kinematical treatment into the CONSTRUCTOR in various places, especially in the latter portion of the book. Even where no special reference has been made to it, the theory has been followed, although the proof has been omitted in order to avoid burdening the non-theoretical reader with details not absolutely necessary for the practical application. It is in this manner that kinematical axioms have been introduced into Chapter XVIII., where the subject of ratchets is treated. These were formerly considered as devices of only minor importance, but the application of kinematical investigation reveals the fact that they are of the very greatest importance, occupying a position in machine construction superior to that of any other element or combination, and this notwithstanding the apparent simplicity and almost insignificant appearance of the original contrivance. A similar treatment has been given to the subject of Pressure organs, Chapter XXIII. Hitherto fluids, such as water, steam, gas, etc., have been considered as something apart from the machine, not belonging to it, but rather introduced from the outside. The idea that fluids, broadly considered, are but the exact opposites of tension organs, such as ropes, chains, belts, wire cables, etc., is wholly contrary to earlier conceptions, and yet it is just this introduction of the kinematic method which has led to an unexpected insight and very great simplification. An illustration of this is seen in the manner in which valves for pressure organs are treated as ratchets. In Chapter XVIII. ratchets formed of rigid elements only are considered, but the principles there deduced are applied in Chapters XXIII. to XXVI. to fluid elements with most satisfactory results. Since

* F. REULEAUX, The Kinematics of Machinery. Outlines of a Theory of Machines. Translated and edited by Alex. B. W. Kennedy, C. E., London. Macmillan & Co., 1876.

the kinematic analysis has shown that such devices as pneumatic tubes, canal locks, and the like, both ancient and modern, belong to precisely the same class of constrained combinations as steam engines and water wheels, the whole subject has been condensed and simplified in a manner not possible under the earlier conceptions. The value of the kinematic method is evident in in Section 333, where fifty different combinations of pressure organs are gathered together under a few and simple fundamental principles. Another instance is shown near the end of the book in the discussion of what I have called "Fluid valves." From the time of Hero of Alexandria down to the present day, these fluid valves have been used in what is now seen to be a continuous series of applications of a simple kinematical principle. These important simplifications will both excuse and justify the wide departure from previous conceptions which characterizes the latter part of the volume.

In regard to the other and principal object of the work, namely, the treatment of the practical construction of machine details, this has not been as consistently and fully revised as I had intended and desired; chiefly owing to the long delay in the completion of the last edition. In my lectures I have been able to follow the the technical advances which have been made in the detailed construction of bearings, levers, cranks, connecting rods, etc., and discuss them accordingly, but in the book itself many of these subjects still appear in the older dress. For these imperfections the kind indulgence of the reader is requested, and in the next edition an earnest endeavor will be made to bring these subjects up to date.

To Mr. HENRY HARRISON SUPLEE, to whom I have given the exclusive right of translation, I take this opportunity to express my particular appreciation of the great care and extraordinary accuracy which he has displayed in the production of this English version, and also my gratification at the care which has been given to the printing and the reproduction of the illustrations. Mr. Suplee has recalculated and transformed all the formulæ and numerous tables into the English system of measurements, and also reworked all the examples, and has shown in this portion of the work a patience that deserves especial recognition. It is a matter of regret that the time has not yet arrived for the general acceptance of the metric system in England and America, and until such time comes tedious transformations of this sort will often be necessary and will merit our gratitude.

I can only add that it is my earnest desire that the friendly acceptance of my book by English speaking engineers may correspond to the magnitude of the labor which has been expended in the preparation of this translation.

F. REULEAUX,

Honorary Member, American Society of Mechanical Engineers.

BERLIN, February, 1893.

INTRODUCTION TO THE FOURTH GERMAN EDITION.

The fourth enlarged edition of the CONSTRUCTOR is presented to its readers much later than I had hoped. As some excuse for the delay I plead the great labor involved in the re-arrangement of more than half the book. As already explained, it has been my intention to re-arrange the matter upon a kinematical basis. It was not, however, entirely due to this re-arrangement that the work was delayed, but also to the fact that nearly one-half of the work had to be re-written. In many places I found almost everything lacking to make what I had previously determined upon, namely, a complete and consistent whole, and much more was needed than I had imagined. In addition to these shortcomings the spirit of invention has been more active than ever during the past few years and advanced at such a rapid rate that I could by no means overtake it. It is hoped that these conditions may be accepted as at least a partial excuse for the delay and for the shortcomings of the work.

The first point to which I desire to call attention in the new matter is the subject of Ratchets, which upon closer examination will be found to be the most important of all forms of driving mechanism. This subject has not until now been treated as an element of construction, it having been apparently overlooked that those forms of driving mechanism in which pawls and ratchet wheels form a part, are in reality a most important and prolific class. Special forms have indeed been treated mainly as checking devices but without any attempt to indicate the general principles, or wide extent of the construction. Locks, in spite of their universal use and of the high order of inventive talent devoted to them, have had no analytical treatment, but have been relegated to the domain of technology rather by accident than otherwise, and from Prechtl to Karmarsch and his followers, have been given an intelligent but by no means fundamental treatment. Gun locks, although having a similar name to door locks, have a very different construction, but have found no resting place in technical literature. It has often been observed that while we place in the hands of our soldiers the modern rifles and cannon, there is no place in the head for them, either in machine shop training, in machine design, in applied mechanics or in technology, or indeed anywhere. In §252 I have placed them in that class which I have termed Locking Ratchets where they fall into their proper place as members of the great division of ratchet gearing. The safety devices for elevators and hoisting machines, —Checking Ratchets, I have termed them—have been entirely overlooked; books have been written about them, catalogues and price lists issued, but the fundamental principle of their construction quite overlooked. As for escapements of clocks and watches, these have been sent hither and thither, now in mechanical text books, now in kinematics, now in applied mechanics, again in encyclopædias, where their fundamental principle has been entirely lost, their intimate relation to ratchet mechanism being hardly noticed. They will here be found classified in their proper place in §258.

Many of the readers of previous editions may shake their heads at this statement, but an examination of the fourth edition will show how the action of the piston engine is similar in principle to a watch escapement, the action of the slide valve being practically identical with the anchor of the escapement, see §§324, 325, pp. 228–232. It has only been by more recent investigations that I have become convinced of the relations of these various forms of escapements. The correctness of this position will be confirmed by comparing the the pneumatic postal tubes, canal locks, sluices, hydraulic cranes and numerous other hydraulic devices, hydraulic riveting machines, and all the many kinds of direct-acting steam pumps; these and many others, when considered from the present point of view, arrange themselves in a complete and orderly manner as true escapements. The similarity is especially well marked in the case of a deep mine pump, of which the successive puffs of the exhaust are not infrequently used by neighboring dwellers to indicate intervals of time; the steam end practically as well as theoretically becoming a time-piece. Nay, more: I am convinced that it is not a pure accident that throughout the centuries in which the delicate clock escapement has been known, the steam engine has so slowly developed; for although both the clock and the engine are in principle escapements, yet in the clock there is an escapement of precision, and in the steam engine an escapement of force,* but both devices are theoretically a solution of the same problem. Closely allied to the steam engine are the various water pressure engines, and water pumps, which as I have shown in § 319, are truly continuous ratchet trains. From the ratchet to the escapement, however, what a long, long gap! The water pump and hydraulic pressure engine differ from each other only in the different motion and action of the valves—and yet the inventive genius of

*In my Theoretical Kinematics, I have considered the steam engine as a reciprocating running ratchet train, but I have since perceived this classification to be incorrect. and therefore desire to emphasize its proper classification here.

mankind required over two thousand years to make that little step, (see § 325). How important, then, to make this fundamental connection clear!

Another important, and hitherto neglected subject, is that of the more recent steering devices, which move in either direction, or remain at rest, as required. This principle has found many applications in power steering gear for vessels, and has even made possible the solution of the difficult problem of guiding the automatic fish-torpedo at a determinate depth. It is not surprising that uncertainty should exist as to the theoretical classification of these devices. I have, however, shown that they are properly considered as escapements, and, in fact, as escapements of a special kind, which I have termed "adjustable" escapements. Such adjustable escapements of rigid construction are shown in § 259, and those constructed with pistons and fluids, in § 329.

The chapter upon Ratchet Gearing is not only entirely new, but it has also involved a new and more elaborate treatment of many subjects discussed in earlier chapters of the book. These I here only name: Screw thread systems in Chapter IV.; Thrust-bearings for screw propeller shafts; Columns; Long distance shafting transmission, etc., in § 351; Couplings, Friction gearing; Transmission of motion by toothed gearing (p. 128); Spiral gears (p. 141); Globoid gearing (p. 142), Proportions of gearing, (§ 226–§ 228). Ratchet wheels are treated in a similar manner to spur gear wheels, to which they bear a close relation, (§ 246).

From this point the book takes a fresh start, with the discussion of another species of machine elements, namely, Tension organs, as I have termed them, (Chapters XIX. to XXII). While the elements previously considered approximate so closely to rigidity that they may properly be termed rigid elements, those which follow possess the peculiarity that they are only adapted to resist tension; these elements include cords, ropes, wire, bands, belts, chains, etc. In § 262 it is shown how these are used in connection with other elements in three distinct ways, as for "guiding," for "winding," and for "driving." An examination of pages 182 to 176 will make the importance of this subject evident, and shows its scope to be far greater than might at first have been expected. The important distinction between the functions of "driving" and "guiding" is shown in the discussion of the differential tackle and the ordinary system in connection with Fig 813, (p. 176).

In discussing Cord Friction (§ 264) I have attempted to show by a graphical representation relations not otherwise easy to make clear. In § 268 I have called attention to some points which should be considered in connection with stiffness of ropes. The subject of pocketed sheaves has been treated in connection with chains, and also the chain system of boat propulsion.

In the chapter upon Belt Transmission, is introduced a new subject and one which appears to me of great importance, and which I have called "Specific Capacity." By its use it is possible to facilitate very greatly the calculations of Belting, Rope Transmission, Water Transmission and even Shafting, and bring them to a comparable basis, (see § 349 and § 351).

The discussions of Hemp and Cotton Rope transmission are both new, and that of Wire Rope greatly enlarged over previous editions. By the introduction of the subject of the "mean deflection" (p. 198) and the diagram (Fig. 884) the question of the deflection is greatly simplified, and a graphical solution is also given. Transmission with inclined cables, which in previous editions was only given an approximate solution, unsuited for long spans, is here accurately discussed (assuming the catenary as a parabola) and extended to long stretches of cable. This has been done in view of the use of rope transmissions and telegraph cables over valleys, etc.

Next follows my system of "Ring Transmission" by wire rope. This offers great advantages over the previous system of line transmission, and has met with much success in Germany, Austria, and Switzerland, as well as in America; and further discussion of it will be given hereafter. The use of chain transmission in mines, both in Germany and elsewhere, is discussed. The subject of brakes brings the book to another point where a fresh start must be made.

The third group of machine elements includes those called "Pressure Organs," and those are treated in Chapters XXIII. to XXVI. These are directly opposed to tension organs, since they are only capable of resisting compression, and include not only fluids, both liquid and gaseous, but also granular materials, etc. (§ 308).

Although these elements have been primarily arranged in a manner adapted for a practical hand book, I believe that my theoretical treatment of the subject will also find acceptance, and hence have here included the essentials of the theory also (see § 319). Pressure organs are serviceable not only in machines, but also for the transmission of force and motion; by them we can control the motion of a force in a determinate path and with a determinate velocity quite as well as with rigid elements, and indeed upon closer inspection we perceive that pressure organs are used in nearly all the most important prime movers, (steam engines and hydraulic motors), and hence they are surely entitled to be classed among machine elements. The extent to which this conception facilitates the subject of machine construction will be seen by an examination of the latter part of this volume.

I have thought it advisable to give also at this time a general review of the result of my labors in the field of Kinematics. These have been fully and thoroughly given in my lectures for the past twenty-five years, and are therefore not new to my immediate

pupils, while the publication of my Theoretical Kinematics has placed the the theory before a larger circle of scientific readers. I cannot assume, however, that the readers of this practical hand book are all familiar with the above mentioned work, and I therefore give the following abstract, covering the most important portions of my treatment of the subject.

* * * * * *

Motion and the effects which are dependent upon motion form the subject of the study of Scientific Mechanics; and hence to it belongs properly the problems of motion in machinery. The motions in a machine, however, may be distinguished from others in that they can be treated independently of the material parts of the machine, and of the forces acting upon them. The important bearing which this separation gives to the subject of machine construction was perceived about one hundred years ago, but has made small progress during the century and has only recently been taken up [10–23].*

I took up this subject in 1862, laying down the principles in my lectures; in 1864 first propounded them publicly before the convention of the Swiss "*Naturforscher*" and their German guests; first published them serially in the *Berliner Verhandlungen* in 1865, and finally in 1872–75 published my book entitled "*Theoretische Kinematik.*"

The modern discussion of these principles begins with the publication, by the celebrated physicist Ampère, in 1830, of his *Essai sur la Philosophie des Sciences*, in which he gave the subject the distinctive name Kinematics *(Cinématicque)*, which name is well derived from the Greek *kinéo*, to drive, to constrain, since it treats of constrained or controlled motions.

I have defined the term *Kinematics* [40] as "the study of those arrangements of the machine by which the mutual motions of its parts. considered as changes of position are determined." This I have divided into to parts: "Theoretical" and "Applied" Kinematics, the former treating of the general and fundamental principles, and the latter of their practical applications.

a. Theoretical Kinematics.

It is this branch of the subject which is treated in my well-known book "The Kinematics of Machinery." The following is a condensed analysis of the treatment there expanded at greater length:

1. A material system having motion within itself, I call a machinal system, as may be determined according as the motion is constrained or not [32].

2. Motions can only be constrained by forces. These forces differ in the two systems, since in the pure machinal system sensible and latent forces enter into equilibrium with each other, while in the pure cosmical system sensible forces enter into equilibrium with sensible forces, [33]. It therefore follows that the two systems can not always be accurately determined [34].* The terms "latent" and "sensible" are here used in a similar sense as in thermal physics. Latent forces are those which exert internal resistance to deformation of a body under the action of external forces; sensible forces are those which act upon the body from without [33].

3. The motions of the machine can be logically controlled according to a predetermined conception, since the action of all external forces which do not tend to produce the desired end can be opposed and neutralized by latent forces [35].

4. From the preceding follows the definition of a machine:—

A machine is a combination of resistent bodies so arranged that by their means the mechanical forces of nature can be compelled to do work accompanied by certain determinate motions [35, 50, 203].

5. If we consider the machine to be made of rigid materials and neglect its mass, we need only take into account geometrical considerations [42]. If a body A, by means of latent forces, is to be prevented from being put in motion by any external forces (case 3), it must be held in a stationary position by at least one body B. The body B, then acts as the envelope of A, and conversely A is the envelope of B, the relation being a reciprocal one. There are also reciprocal envelope forms possible between the bodies A and B for a relative motion, which shall exclude all other relative motions [43]. Such a pair of bodies, I have called a kinematic pair of elements and a machine consists solely of bodies which thus correspond, pairwise, reciprocally [43].

6. In order to obtain a determinate motion in a given space by means of a kinematic pair of elements, one of the elements of the pair must be held at rest with regard to the given portion of space under consideration. The relative motion of the moving element to the fixed one will then be that of absolute motion, so far as the given portion of space is concerned [43].

7. The choice between the two elements as to which shall be stationary and which movable is not limited; the substitution of the fixed for the moving element I have called the *inversion* of the pair [93].

8. The control which can be exercised over a determinate motion in this manner is not mathematically exact but only approximate (case 5) because the latent forces of bodies can only be brought into action by their deformation. If, however, the elements are made of materials which possess a high degree of resistance and are given proper dimensions (machine construction) the deformation can be kept within such small limits as to be practically insignificant, and the result considered as determinate [33]. (Compare cases 46 to 49, below).

* The numbers in brackets refer to the pages of Reuleaux's "Kinematics of Machinery. Translated by Prof. A. B. W. Kennedy. London, Macmillan & Co., 1876.

* The internal forces of a moving system form the subject of d'Alembert's principle.

9. Each element of a kinematic pair may be rigidly combined with an element of another similar pair without interfering with the relative motion of the separate pairs. In this manner a large number of pairs of elements may be arranged in a series, so that each element of a pair is firmly connected with an element of another pair. Such a series of pairs of elements returns upon itself, resembling a chain [46], consisting of links connected together. I have called such a series a kinematic chain, and the body which is formed by the junction of the elements of two different pairs is a link of the kinematic chain [46]. There are therefore as many links as there are pairs of kinematic elements.

10. A kinematic chain may close or return upon itself in various ways; among these is one in which every alteration in the position of a link relatively to the one next to it is accompanied by an alteration in the position of every other link relatively to the first [46]. In such a chain each link has only a single relative motion with regard to every other link. Such a kinematic chain I call a constrained closed—or simply a closed chain [46].

11. A constrained closed kinematic chain compels a definite determinate motion in a given portion of space when one link of the chain is fixed, with regard to this given portion of space. A closed kinematic chain of which one link is thus made stationary, is called a mechanism [47].

12. A constrained closed kinematic chain, therefore, can be formed into a mechanism in as many ways as it has links [47]. The substitution of the stationary link of a kinematic chain for another link I have called its inversion.

13. A kinematic chain may have so few members and be closed in such a manner that the links can have no motion relative to each other, and that the pairs themselves do not have their own motion. This I have termed fixed closure [485].

14. The manner of closure of the chain can be chosen so that adjoining links can have more than one relative motion. This I have called unconstrained closure [485].

15. A kinematic chain in which a series of pairs of elements are arranged in the stated manner, but of which the first and last elements are not connected, I have called an open chain.

16. Kinematic chains of the kinds above mentioned can be combined with each other, forming constructions which may be called compound chains. These may have constrained, unconstrained, or fixed closure or may be open chains. The same conditions exist for these as for the previously described chains, which may for sake of distinction, be called simple chains.

17. From the preceding we may give the following general definition of a mechanism, as follows:

A mechanism is a closed kinematic chain of which one link is fixed: this chain is compound or simple and consists of kinematic pairs of elements; these carry the envelopes required for the motion which the bodies in contact must have, and by these all motions other than those desired in the mechanism are prevented [50].

18. From all that has preceded, it is apparent that the investigation of the motions in machinery is a subject which is based in great part upon geometry. This has been treated as a separate subject of Phoronomy, or the study of geometrical motion. The most important principles of this subject I have treated in Chapter II. of my "Theoretical Kinematics," with applications to constrained as well as cosmical motions [56 to 85]. It is there shown that all relative motion can be considered as that of a pair of ruled surfaces, so that the motion is reduced to a rolling of the two ruled surfaces upon each other, and under certain circumstances with a simultaneous endlong sliding upon each other of the generators which are in contact. These rolling surfaces, for which previously no special name had been used, I have called *axoids*, the combined sliding and rolling motion being termed *twisting*. When rolling motion is absent only sliding remains, when on the contrary, the sliding is omitted only the motion of rolling remains. In the latter case certain sections through the axoids give curves which twist upon each other, or roll with a cross sliding action. The combined points of these curves form centres of rotation or poles about which, as instantaneous centres, both bodies turn. These centres or poles travel in the paths of the aforesaid curves whence the latter may be called *pole-paths* (Polbahnen) or centroids.* The study of axoids and centroids will greatly extend the range of phoronomic researches.

19. In order to pass from the general principles to the special applications of kinematics, further consideration must be given to the elementary pairs, The simplest form must necessarily be that in which the corresponding envelopes actually surround, one the other, and such I have called a closed pair. Of this there are but three forms: 1, the twisting pair (screw and nut); 2, the turning pair (pin and collar); 3, the sliding pair (full and open prism, or prism pair [91]. The two latter may be considered as particular cases of the first. In all three no change in the character of the motion is caused by inversion (case 7).

20. In a pair of elements it is not always necessary to use all of both envelope forms. The question of the minimum number of points necessary to insure resistence to disturning forces, I have discussed in § 17 of my Kinematics, under the title: "The Necessary and Sufficient Restraint of Elements."

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* The term "centroid," due to Prof. Clifford, and used by Prof. Kennedy in his translation of the "Kinematics," will be hereafter used as the translation of Polbahn.—TRANS.

21. We have thus far omitted from consideration such elementary pairs as are not closed. These possess the general property of giving a change in the character of the motion when they are inverted. I have called them "higher" pairs of elements [115], and conversely the closed pairs may be termed "lower" pairs. It is only in special cases that no change occurs in the character of the motion by inversion of higher pairs. A series of higher pairs, for the most part entirely new, has been discussed in § 21 of my Kinematics.

22. I have given (§ 30 to § 39) seven geometric methods of determining the restraining bodies for higher pairs, many of which were already known, but which were then for the first time grouped into one general system.

23. Incomplete pairs [169] are those which are not entirely closed by the latent forces, but are partly closed in some other manner. Examples of these are half-journal bearings, in which the weight of the parts is used to keep the journal down in its bearing; knife-bearings for scale beams, the V bearings for the beds of planing machines, etc. Pairs may also be closed by the action of springs or other external forces. The closure of a pair of elements in this manner I have termed "force closure." This form of closure can only be used when the disturbing forces are not sufficiently great to overcome the closing force.

24. Force closure also finds application in higher pairs of elements. An important example is found in the driving wheels of locomotive engines, and another still more important, in the axoid rolling action of friction wheels. (See Chapter XVI. of this volume.)

25. The application of force closure can be carried still further. By its application we are enabled to utilize two classes of elements which are only capable of opposing resistance in one direction (case 8). These are what I have called "tension organs" and "pressure organs," (see § 261 and § 308 of this volume). These I have grouped together as "flectional" kinematic elements [173]. They include a long series of most useful machines, such as belt and rope transmission systems, pumps, water-wheels, etc., all involving the principles of force closure.

26. Force closure may be used in a dynamical as well as in a statical manner, as in the case of an engine crank which is carried over the dead centre by the action of the fly wheel [186].

27. In such cases the closure may also be effected by means of another kinematic chain used in combination with the first [178]. This I have called chain closure. An example is found in a double engine with cranks at right angles.

28. The preferable form of chain-closure is that in which similar elements are employed. This occurs (case 25) when one force-closing chain is used in connection with another of the same kind, the two being so combined that each supplies the necessary closing force for the other; whence it follows that the sensible and latent forces in the two chains counteract each other in the same manner as if they were composed of rigid elements. [§ 44, "Complete Kinematic Closure of the Flectional Elements."] Examples of this are found in the ordinary belt transmission, and in the so-called "water rod." By means of this method of closure, which is destined to be much more widely used than heretofore, the applications of flectional elements have been greatly extended for purposes to which rigid elements are not adapted, such as the transmission of force in a path of constantly changing direction, as in the use of high pressure water transmission systems through pipe conductors.

29. Finally a kinematic chain may be closed by the application of springs [176]. These may be so constructed as to oppose resistance in a number of chosen directions, but not in all directions; e. g., both tension and compression, also bending in one plane, but not in a second plane at right angles to the first. This latter condition is seen in the case of flat or plate springs, also in the plate link shown in Fig. 507 of this book, where the spring acts as a substitute for a pin connection. In the plate link the force closure and complete kinematic closure are replaced by chain closure. Another example is found in the Emery Scale, Fig. 789c.

30. The pairing of flectional with rigid elements may be assumed, *a priori*, to be practicable in the same manner as that of rigid elements [544].

31. If the principles of investigation, however they may be set forth, are correctly based, they should when applied to the historical development of machines, shed a light upon the whole subject from the rude attempt at invention to the highest attainments of mechanical ingenuity. This subject I have discussed as a "Sketch of the History of Machine Development, [201 to 246], in which the substitution of pair closure for force closure is made most apparent.

32. In order to facilitate the elucidation of the action of machinery, and to abridge the labor of the application of the preceding methods, it became necessary to devise a system of kinematic notation. This is given in Chapter VII., pages 247–273, of my Kinematics of Machinery. The elements are designated by capital letters, of which twelve are required, and the relations of these are indicated by auxiliary symbols derived for the most part from those already used in mathematical notation. For the symbolical representation of the kinematic chain I have also introduced the conception of an order in which each pair in the chain is numbered from 1 upwards, and the links represented by the small letters from *a* onwards [270–273]. The pair and the link at which the numbering and lettering is to begin may be agreed upon previously, as well as the direction in which they are to proceed. The link between the pairs 1 and 2 will then be indicated by *a*; that between

2 and 3, by *b*, etc. For instance, the connecting rod and crank device, shown in Fig. 1022 of this book, is indicated by the formula $(C_3'' P\perp) \frac{a}{c}$. Translated, this means that the kinematic chain of the mechanism consists of three parallel, closed cylinder pairs, and one closed prism pair at right angles to them; that it contains four links, which I have called the crank, the coupler, the slide and the link, and designated by a, b, c, and d; that this chain is converted into a mechanism by the link d being held fast; that the right line from the centre of the bearing 2 to the end of the coupler b (the connecting rod) moves around the axis 1 of the crank shaft, and that the crank a is driven, by means of the coupler b, by the slide (cross-head) c. This is certainly expressing very much by means of very few symbols, dispensing with long and comprehensive definition. According to case 12, this chain can be converted into three other kinds of machines, symbolically indicated by: $(C_3'' P\perp)^a$, $(C_3'' P\perp)^b$, etc. These symbols have as yet been used but little by practical designers, but those who have made use of them have found them brief and accurate both for writing and for description otherwise requiring much longer explanation.

33. The application of the system of symbols leads to what I have termed "Kinematic Analysis," [Chapter VIII.] The application of this analysis to the so-called "mechanical powers," [275–283] leads to interesting conclusions, this is also the case with the cylindric crank chain [283–341], which taken in connection with Chapter V., yields a wealth of valuable results.

34. This is followed by an analysis of "chamber-crank" trains, Chapter IX. In this, it is shown that upwards of a hundred pressure organ machines, hitherto considered as separate inventions, have a systematic relationship dependent largely upon kinematic inversion; and a number of difficulties are cleared up.

35. In Chapter X. the subject of the so-called "chamber-wheel" trains is analyzed; the principles of which I had previously investigated in 1868.

36. Finally, in Chapter XI., is given the Analysis of the Constructive Elements of Machinery, including a brief investigation of ratchet mechanisms. At the time this portion was written my investigation of that subject, however, had not been carried to any great extent, and in the present volume for the first time have I set forth the extraordinary and varied importance of ratchet mechanism.

37. To this subject is added an analysis of the complete machine [486–526], in which the strict limits of theoretical kinematics are frequently overstepped and encroachments made upon the domain of applied kinematics. The older ideas of the "receptor" the "communicator," and the "tool" are examined and rejected and machines classified as "place-changing" and "form-changing" machines. This classification will be found to possess a decided value and will be referred to again. (Cases 42 to 49.)

38. Kinematic Analysis has as a necessary counterpart Kinematic Synthesis. This has been already seen (cases 19, 21, 30) in the application of pairs, chains and mechanisms to given machinal purposes. Kinematic synthesis may also be called a theory of the invention of mechanisms. This it can only be, however, in a limited sense. It can in no case enable the genius of the inventor to be dispensed with, but by the aid of this theory his scope can be greatly extended. The application of synthesis to problems which have already been solved may also point the way to the solution of others as yet undetermined.

In discussing this synthesis, I have grouped the pairs of kinematic elements into 21 orders [538–544] by means of which the determination of the greater number of kinematic chains and dependent mechanisms may be made; also eight classes of simple chains. The application of synthesis may be made in two forms, the direct and the indirect, and these again into general and special synthesis. Of these the indirect synthesis is the most useful [529]. It is my expectation that this theoretical exposition of the subject, which I cannot expect to extend further, but by means of which I have been able to devise a number of new mechanisms, may find many successful applications by others.

b. Applied Kinematics.

39. Applied Kinematics is not so much to be considered as standing in opposition to theoretical kinematics as it is included in it. In fact, applied kinematics has existed as a study for a long time, as in the treatise of Monge, without the existence of any theoretic foundation. That such a treatment of kinematics may be very useful for a time is readily admissible, but an *ex post facto* theoretical discussion may seem of little value to the practical man. Indeed my highly esteemed former preceptor, Redtenbacher, considered an actual theoretical treatment of the movements of machinery to be an impossibility.

Under these circumstances I did not feel inclined to follow the "Theoretical Kinematics" hastily with a treatise on the applied science. For this purpose it was not possible to arrange all the various forms of machines under the new classification hurriedly and properly in permanent form. Notwithstanding the simplicity of the preceding system, its application developed many difficulties and required a succession of researches with which even my immediate pupils are not fully acquainted. A not inexcusable impatience on their part has led me to have my investigations in applied kinematics multiplied for a limited circulation although the matter was incomplete. I gave this permission reluctantly and with the condition that only a limited number of impressions, to be considered as "manuscript," should be circulated. In this manner

four parts of the work have appeared, the last consisting entirely of the application of the symbols to lecture room models. The result of such premature publication cannot always be foreseen by those who have urged it, but for the misunderstandings which have arisen from this source I can only express my regret.

In the meantime I have since 1882 been engaged in the partial application of the principles of kinematics to this book in such a manner as to avoid burdening the reader with theoretical matter, which would be contrary to the purpose of the work. The most important subjects to which the kinematic method has been applied are here briefly noted.

40. With the great extension of modern mechanical engineering we find that the various mechanisms, (the number of which as we have seen is not great), are given a great variety of applications. It is the object of applied kinematics to furnish a clear distinction between the various methods of practical application. It is apparent that the preceding analysis does not extend to this point, since it does not include the subject of the method of constraint, but only treats of the combination of the elementary parts which are involved. We may therefore properly term it the Elementary Kinematic Analysis. As a counterpart for this in applied kinematics we may place the subject of another analysis which relates to the conditions of motion in a given train, and which may be called Train Analysis, or the Analysis of Trains. This analysis is not intended to solve anew the construction of the various trains, but rather to elucidate clearly their method of action; a train consisting of a closed group of elements and bearing the same relation to a machine as an atom does to a molecule.

41. Train analysis does not admit of an arrangement logically similar to the elementary analysis, but possesses a new and different order. This is due to the fact that the elements of which trains are composed occur only in pairs, while the trains of which machines are composed are considered singly. In Vose's pump, for example, Fig. 979[a], there are two ratchet trains combined in one machine, while in Downton's pump, Fig. 979[c], there are three trains.

42. The various methods of tain action may be divided into four principal kinematic divisions, viz.: Guiding, Storing, Driving, and Forming, §333.* The first three divisions are "Place-changing" and the last is "Form-changing."

43. Various forms of guiding devices may be mentioned; linkages by means of which curved paths are obtained, parallel and straight line motions, also "position motions," as I have termed those by means of which a system of points may be transferred to another position parallel to the first. Guiding devices can be constructed from kinematic chains of every kind. It was by means of examples with chains for this purpose that the general conditions of motion in theoretical kinematics were illustrated, and the same conditions belong also to applied kinematics.

34. Storing includes those especial machine organs by means of which work can be accumulated and the supply drawn upon for later use. This, until now has not been considered as a special mechanical conception, although it has had numerous applications. Storage of power may be accomplished in three quite different ways.

a. By means of rigid elements, this being statical or dynamical. Examples of statical storage are found in elevated weights, compressed springs, etc., and of dynamical storage in fly wheels, or pendulums. One of the oldest forms of dynamical storage is the old-fashioned spindle [216].

b. By means of tension organs, acting by winding the tension organ upon a drum or pulley. Examples are seen in tower clocks, etc.

c. By means of pressure organs. These are the most frequently used, and examples include tanks for water, oil, gas, air, steam, also hydraulic accumulators.

45. Driving. In this term I include the transmission of motion within a single train and also from one system to another. As "guiding" includes the control of the path of a point, "driving" considers the control of the velocities of various points in their paths. Examples in this branch of applied kinematics are those which take into consideration the velocity of the various parts of a mechanism. (See the close of Case 38).

46. Forming, includes the working of materials by means of machine tools. This fourth division is the richest of all, and offers the widest range to the genius of invention. This operation takes place by the action of the tool upon the material, or as I have called it, the "work piece" [495]. In form changing machines, the work-piece is a part or the whole of a kinematic link, and is paired or chained with the tool by so arranging the latter that it itself changes the original form of the work-piece into that of the envelope corresponding to the motion in the pair or linkage employed [495]. We can distinguish between three forms in which this action can occur.

a. The tool is hard and operates by cutting the material from the work-piece which lies without the envelope of the desired form. Examples are found in lathes, planers, grinding machines, etc.

b. The tool is of high resistance so as to be able to maintain its form, but does not act by cutting, but by pressure upon the yielding work-piece. It follows that the material which lies outside of the desired form is forced into another part of the work-piece without being removed from it. Examples are found in coining presses, rolling mills, wire drawing benches, etc.

c. The tool and the work-piece are both alike yielding, and act each upon the other, each being the

* In § 333, the second of these has been translated "Supporting," and the English language lacks a suitable equivalent for "*Haltung*," but in a correspondence with the author, the above has been adopted.—TRANS.

tool for the other piece. Examples are the various kinds of spinning, weaving, and other textile machinery. All three forms are described in this volume, many examples being given among the pressure organs.

47. It may appear from the preceding as if the theory of the action of the tool breaks through the logical arrangement given in the theoretical kinematics, since in Case *a*, one of the elements, the tool, cuts away and destroys its partner because it is enough harder to cut it. We must here distinguish between yielding and unyielding elements. This looks like a return to empiricism. The defect in the logic, how- is only apparent. All elementary pairs without exception involve the idea that both of the partners evoke the latent forces by the action of deformation; and at the same time the friction between the moving parts induces wear. Applied mechanics takes friction into account in considering elementary pairs and investigates and provides for the consequent wear. The machine constructor endeavors by all means within his power to reduce the alteration of form at points where it is not desired, but where it is the end to be accomplished he takes every opportunity to increase it. The form-changing action which occurs between the tool and the work-piece differs in degree only and not in kind, from the action taking place between the elements of every other pair in the machine [503].

48. A similar idea may arise in connection with the method of form-changing given above under *(b)*, in which an alteration of form takes place without an actual removal of any of the particles. In this case the the correspondence of the kinematic to the mechanical action is evident. In case 8, as already noted, the deformation which takes place in non-rigid bodies makes it only practicable to obtain approximate solutions. This only involves a quantitative, and not a qualitative distinction [502].

Examples of this occur in the construction of instruments of precision. It is not possible to construct even a simple cylindrical pair (case 19) such as a centre for a theodolite, or for an astronomical telescope, entirely free from error. By the use of a variety of methods the errors are kept as small as possible, and then by other methods, nearly always kinematic, the residual errors are determined and the proper corrections made.

49. In other instances the designer may utilize the elastic yielding of the members of a kinematic chain, as for instance in the method of Adolph Hirn, by which the springing of the beam of a steam engine is used to produce the indicator diagram of the steam pressure; or the torsional deflection of a large shaft to measure the power transmitted.*

This method is also found in Gidding's device for measuring valve friction (p. 285), and also in the Emery scale, in which a very small deflection of a diaphragm measures accurately weights of many tons.

Although in many instances the deformations of material may be neglected, yet we should never permit ourselves to forget that they have been neglected. Otherwise important errors may creep into theoretical deductions, as well as in practical construction. This subject of the yielding of materials is receiving more attention at present than formerly.

50. The "order" of a system of transmission is a subject of importance since there are several methods by which the various parts may be kinematically arranged. I have applied the term "order" to the method of arrangement, and distinguish between three different methods.

a. "Series Order." This "order" exists when a number of transmissions are arranged in series, so that each acts upon the following one. If in a single machine, two, three, four or "n" transmissions are thus arranged in series, I call the whole a system of the second, third, fourth or n^{th} order. Examples are found in Figs. 766, 767.

A transmission can return upon itself. This I have called a "ring" system of transmission. (See p. 208). This return to the original must always occur in the kinematic chain of any mechanism since the elements exist only in the relation of pairing (Case 5). In the system under consideration (Case 41), the groups of elements follow each other in a series, or line as it may be termed, whence I have termed such a series a "line" transmission (p. 257). Ring transmission may also be combined with line transmission, the line being divided into two or more parts. An example of the first kind is seen on page 229, in which the pump mechanism is combined with the steam mechanism, as a line with a ring system. An intermediate form between ring and line transmission is referred to on page 208.

b. Combined Order. By this title is meant a combination of transmissions in which each transmission is connected to the next, but in which any one can be stopped without stopping the others. An example of this is shown in the ring transmission in Fig. 917.

Under certain circumstances a number of the driven pulleys T_1, T_2, T_3 -- T_n, may be allowed to run empty, in which case they become merely supporting sheaves (Case 43); as soon, however, as any load is thrown on any of them, the entire system is influenced by the increased stress upon the rope.

Another example of "compound" order, is the multiple expansion steam engine. Here each engine of the compound, triple, or multiple expansion engine may be considered singly as a separate chain, and the entire machine as a series of transmissions. Each engine, T_1, T_2, T_3, etc., exerts an influence upon the action of the others, but is not indispensable to their action, as would be the case if arranged in "series" order. Compound, Triple, Quadruple expansion en-

* See *Berliner Verhandlungen.*

gines are therefore, respectively of the second, third, and fourth order, but should also be considered to belong to the class of "Compound order."

c. "Parallel Order." This arrangement is the oldest and the one which occurs most frequently. It occurs when a number of different machines are all driven from one and the same transmission, this being the usual arrangement in manufacturing establishments. Any of the machines can be stopped or started independently of the others without affecting the motion, a suitable regulator being assumed. This principle may also be applied to the motors by which the transmission is driven, automatic couplings, such as shown on page 101, being used. A "parallel" order occurs in rope transmission when a number of ropes are used on the same pulley; another instance is that of a train which is pulled by two locomotive engines.

The three different "orders" are not always sharply defined, but the distinction will be found of material assistance in the study of transmissions. An example in which all three "orders" are used is found in the engine shown in diagram in Fig. 1023. Here the cylinder, piston, valve and steam form an escapement: the connection c l r being driven, and in turn operating a second r_1 l_1 b, and thence the valve. These three transmissions therefore form a "series" order, this also returning to itself and being thus a ring system, and of the third order. The fly-wheel and its bearings form a dynamical power storage system, absorbing and giving out power in response to the irregularities of the action of the piston, this being of the "compound" order. Frequently such an engine is made with an additional cut-off valve gear, with governor, also of "compound" order, also possibly a feed pump, ("parallel" order) and the engine usually drives an extensive transmission system by which a number of machines are operated ("parallel" order).

In § 260 is shown the manner in which physical and chemical trains are arranged in series, the action of heat, of gases and electricity being considered; the steam engine being the most notable example.

51. The magnitude of the exponent of the order of any train has an important influence upon the hurtful resistance of a machine, especially in a series order of a high degree. In such cases the injurious resistance increases at least directly as the exponent, and frequently more rapidly. It is therefore important in machine design to keep the degree of the order as low as practicable. In the system of pneumatic clocks of Mayrhofer (p. 171) the mechanism for several years was as high as the 17th order, but the degree subsequently reduced to the 8th order. It may safely be affirmed that the simplicity of a machine may be measured by the closeness which the exponent of its order approaches unity. Examples are found in the Giffard injector, in which the guiding and driving mechanisms are united in one, and exponent becomes =1; the same is true of Siemens Geyser pump, Fig. 971a. The apparatus of Morrison & Ingram, Fig. 1181, is a device of the 2nd order, which acts by a combination of guiding and driving.

52. The preceding pages have shown that applied kinematics, by means of the separation of the controlled motion into the forms of Guiding, Storing, Driving and Forming, and by means of the division of the various "orders," has enabled the machine problem to be solved as a whole. Theoretical kinematics has assisted in this solution by enabling the various problems to be investigated in a purely scientific manner. Without such a theoretical investigation, a system of applied kinematics would be an impossibility. At the same time practical instruction must be given by actual daily work as well. A clear understanding of the principles of the applied science cannot but be useful to the practical man, and as I believe, welcome also.

The fundamental principles of machine construction as I have sought to lay them down in the preceding pages, coincide in many points with the practical methods already in use. The practical mechanic is well acquainted with crank trains, gear trains, and the like, or if he is not familiar with them he is readily taught, but in combining these and arranging them so as to act upon each other the theory comes into play and shows clearly the best arrangement for the end in view. This is well shown in the case of the various valve gears, which have been in fact developed independently, instead of being the result of a theoretical analysis of various combinations of kinematic chains. The application of the kinematic analysis will facilitate work of this sort, making it clearer and simpler the more fully the fundamental principles are understood. For this reason I have introduced the kinematic principles into this work, not to reduce invention to an art to be taught, but rather to bring the principles of science to its assistance.

I am ready to admit that the general view of theoretical kinematics which I have placed before the practical man, may not be accepted without further proof being demanded. It may be considered only as an ingenious form of theorizing, of but little practical value. For the present I must ask my readers to prove by the test of practical application how far the principles of kinematics may be made of genuine practical value.

The principles included in cases 40 to 51 are practically applied in the latter half of this volume. The application of the analysis to the subject of ratchet gearing has produced an extensive series of results. Storage is clearly shown to be a form of ratchet gear; the discussion of the degree of "order" of ratchet trains will also, I believe, be found very useful. In the discussion of pressure organs (Chapter XXIII. and following) the subject of storage is highly developed. The notion of the two divisions of guiding, and driv-

ing will also be found most useful. In like manner the methods of analysis as applied to ratchet trains, are found capable of equally prolific results when applied to pressure organ trains, not, to my knowledge, otherwise attainable. The great number of applications in this direction will be seen in § 333, these being the result of the application of the theory sketched under Case 46, above.

Since the subject of friction was considered in connection with rigid elements, it was also necessary to to take into account this resistance to the motion of fluids (§ 340), as also the loss of heat in steam pipes (briefly discussed in § 338). In § 362 the very important subject of boiler design is only generally considered.

The closing chapter relates to valves. These are treated as ratchets, not only from the theoretical standpoint, but also practically, and much more fully than in previous editions. The section on "fluid valves" will, I trust, be found of use to the practical man, as a subject worthy of further investigation.

In closing, I may refer to the increasing size of this volume. In spite of my earnest efforts, it has not been possible to reduce its bulk. In many places evidence will be found of attempts at condensation, but nevertheless the work can hardly be called properly a "hand book" any longer. When discussing purely technical matters I can be brief, but in a practical work, it is above all things necessary to be clear and intelligible. In this I have endeavored to be guided by the dictum of Boileau: "*Un ouvrage ne doit point paraître trop travaillé, mais il ne saurait être trop travaillé.*"

FUNCHAL, *February, 1889.*

F. REULEAUX.

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ERRATA.

Page 14, Case IV., first panel of table should read $P=4\,\pi^2\,\frac{J\,E}{l^2}$

Page 15, line 13 from bottom, second column, omit words "$\frac{3}{8}$" thick."

Page 53, line 31 from bottom, second column, read "interpolated diameter," instead of "interpolated meter."

Page 61, formula (89) substitute P, instead of p.

Page 61, line 11 from top, second column, after "Proportions of Journals," insert the formula number (93).

Page 63, line 39 from top, first column, after "Formula for Fork Journals" insert the formula number (98).

Page 64, the formulæ on lines 12 and 14, of § 96, should be numbered respectively (99) and (100).

Page 64, line 33 from top, second column, for "Prowny" read "Prony."

Page 89, line 17 from bottom, first column, for 85 mm.$=8\frac{3}{8}''$ read 85 mm.$=3\frac{3}{8}''$.

Page 89, illustration at the bottom of second column, the diagram to the left should be Fig. 409, and that to the right, Fig. 410.

Page 97, line 16 from bottom, second column, for "drawn" read "driven."

Page 103, the last formula on first column should be numbered (154) instead of (155).

Page 144, formula at bottom of first column, the cube root sign applies to the whole of the second member and not to the numerator only, as printed.

Page 175, line 17 from bottom. second column, for Harturcn, read Hartwich.

Page 195, line 29 from top, second column, for "can only be given by indeterminate results," read "can only give approximate results."

Page 206, title of § 301 read Reuleaux's instead of Reuleux's.

Page 255, example in second column, for 4 in. stroke, read 40 in. stroke.

Page 263. The following revisions of formulæ (385) and (386) have been communicated by Prof. Reuleaux and should be inserted:

$$s_5=\gamma\frac{R}{2}\left\{\left[1-\left(\frac{D}{D_0}\right)^2\right]H-\frac{f}{3}\left[1-\frac{D}{D_0}-2\left(\frac{D}{D_0}\right)^2\right]\right\}\qquad(385)$$

$$s_6=\gamma\frac{R}{2}\left\{\left[\left(\frac{D}{D_0}\right)^2-1\right]H-\frac{f}{3}\left[1+\frac{D}{D_0}-2\left(\frac{D}{D_0}\right)^2\right]\right\}\qquad(386)$$