Ferdinand Jakob Redtenbacher (1809–1863)

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Abstract The rapid development of technology in the twentieth century, especially in the automotive and aircraft industries as well as machine tool and manufacturing engineering, is causally connected to the developments of the scientific principles of mechanical engineering in the nineteenth century. The transformation of mechanical technology from a mainly workshop-based profession into an engineering science, particularly in the area of design of machines and mechanisms, is closely related with the name of Ferdinand Redtenbacher. He was of eminent historical importance for this evolution of mechanical engineering to a technical science in the nineteenth century. Redtenbacher's role as the originator of mechanical engineering as a science in Germany is fundamental and of general interest since the introduction of science into engineering is a "sine qua none" for the development of a powerful high tech industry. As a professor and the director of the Polytechnic School in Karlsruhe, Germany – today the University of Karlsruhe (TH) –, Redtenbacher's influence therefore helped establish the German manufacturing systems engineering even today.

Biographical Notes

At the beginning of the nineteenth century, Germany and Austria were increasingly anxious to establish industries to counter the English manufacturing dominance. This beginning development of capitalist industrialization was accompanied by the

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Fig. 1 Lithograph of Ferdinand Redtenbacher (1809–1863)

institution of technical educational establishments modeled after the founding of the Ecole Polytechnique (1794) in Paris. Among the first polytechnic schools in middle Europe were the Vienna Polytechnic Institute (1815) in Austria and the Polytechnic School of Karlsruhe (1825) in Germany.

Early Years

Redtenbacher's childhood and early teens in Austria fell in the time of transition into the industrial age. The hustle of the iron and steel industry of his hometown, later known as the "Austrian Birmingham", were parts of the surrounding scenery for Redtenbacher, in which he was born into. But it was not the primary factor that became decisive for his later lifework. The ideals of education put forward by Vienna Polytechnic Institute and its director Johann Joseph Chevalier von Prechtl, influenced the young generation in Austria including Redtenbacher.

Ferdinand Jakob Redtenbacher (1809–1863) (Fig. 1) was born on July 25, 1809 in Steyr, Upper Austria. His parents' home was closely connected with the systems of acquisition and economy that had barely changed during the centuries. His father, Alois Vincent Redtenbacher, a scion of an old-established reputed dynasty of business magnates from Upper Austria, had inherited Voith's hardware shop in Steyr. Due to his economic wealth, Alois Redtenbacher belonged to the dignitaries of the small city. The father was described as a bright and likeable person, witty in his views and with affinities to literature and languages to pass them on to his children Alois and Ferdinand. Growing up in this contemplative atmosphere of the Biedermeier period, Ferdinand Redtenbacher had only sparse contact with engineering and technology in his young childhood.

The father wanted Ferdinand to become a merchant. At the age of 10 years he was put into a retail apprenticeship at his uncle's general store in Steyr. For 5 long years, Redtenbacher had to hold out and at the end of 1824 he had finished this first education step. It is difficult to say what these unloved years mattered for the adult intellect. However, it can be assumed that the young Redtenbacher could draw such advantages from this severe time as work discipline and practical understanding.

Besides his job, he took time to learn the basics of technical drawing and mathematics through private study, and this may certainly be interpreted as the first independent act to escape the retail career after the apprenticeship. The skills were definitely helpful and necessary when, after the end of the apprenticeship from January 1825 through September of the same year, Redtenbacher was employed by the building authority of Linz, Austria to draw construction plans and to help take geometrical measurements. Also during this time in Linz, Redtenbacher tried through private learning to come closer to becoming a capable engineer. In the fall of 1825, the free-thinking father let the single-minded son go to take up his studies at the Vienna Polytechnic Institute.

Education in Vienna

During Redtenbacher's time of studying in Vienna, reform of technical education began, but it was far from the result realized by Redtenbacher later at the Polytechnic School of Karlsruhe. However, the schools at that time cannot be compared with the technical universities of today. The Vienna school had an entrance age of 13 years for pupils. The preparatory junior school with its two annual classes, taught the subjects of religion, exercises in good reading, German grammar and style, element and (basics of) advanced mathematics, geography, history, drawing, good writing, Italian, French and the possibility to learn English, Czech and Latin. Only after taking these subjects would the technical section start with further instruction, depending on the career aspirations, in subjects today taught in the departments of mathematics, physics, chemistry, architecture, civil engineering or mechanical engineering. All this was certainly less thoroughly practiced than today but in its great variety and large extent, it was no less exhausting than the study of contemporary engineering.

Redtenbacher was studied not exactly a prodigy at the age of 16 years but, with his deficient elementary education, he faced up to the demands of the school. After successfully passing the junior school he studied technical drawing and design (with Arzberger), surveying and mapping, planimetry, drawing theory of maps, leveling and altimetry, drawing of geometrical layouts and maps, practical measuring (with Simon Stampfer), as well as road construction, hydrology, civil engineering economy, drawing of architecture layouts (with Josef Purkinje). He passed all exams with first-class grades and preference when he finished his engineering study. It is important to state that in the early nineteenth century, a mechanical engineering curriculum did not exist and engineering training was associated with what is called today civil engineering.

A special feature of Redtenbacher's studies in Vienna was that from the first school year, he participated, at his own option, in additional so-called "Tentamina", ceremonial public exams where the professors recognized a small selection of their outstanding students and the results of their work. Parallel to his study in the technical section of the Polytechnic Institute he enrolled at the University of Vienna for courses in advanced mathematics (with Andreas von Ettingshausen) and astronomy (with Karl-Ludwig von Littrow), passing the corresponding exams with excellent results.

The appreciation of bright students by his professors offered Redtenbacher, in 1829, an assistantship in mechanics and machine design. After studying with Arzberger for 2 years, his engagement was renewed in 1831 for a further 2 years. His natural teaching ability exhibited in his tutorials on the basics of machine design, became clearer simultaneously with his methodical intellectual power. Furthermore, he had to teach technical drawing and to sketch machines that were manufactured in the workshop of the Polytechnic Institute for the growing model cabinet. No doubt, the easy-going years of his assistantship represented the real student time in which Redtenbacher broadened his mind, through inquisitiveness and diligence.

In Vienna, Redtenbacher also stated for the first time that there is no real knowledge and no certainty excepting such that could be mathematically founded. In this period, Redtenbacher was also for the first time the co-author of a scientific contribution on a fire engine in a Technical Encyclopedia by Prechtl. From this article, it cannot be seen what portion of it was written by his professor and what part by him. Anyway, it is clearly and coherently written and deals with the technical matter in a thorough manner. These 4 years were accompanied by vacations of hiking trips in the vicinity of his homeland where he also inspected machine technology on route (e.g. the grand pumping station of Berchtesgaden, which delivered the brine over the mountain into the brewery of Reichenhall). He also trained himself in freehand drawing, composed outdoor sketches and started to paint, a hobby which he enjoyed for the rest of his life.

Zurich Appointment

The assistantship at the Polytechnic Institute was limited by imperial statute to 4 years and ran out irrevocably in September 1833. In the spring of 1834, his cousin, Dr. Joseph Redtenbacher, accidentally read of a job posting at the Higher Industrial School of Zurich. Dated April 26, 1834, the 25 year old Redtenbacher was appointed as a lecturer of mathematics and descriptive geometry at the Senior Industrial School, initially for 1 year, then finally as a professor.

The technical equipment and experience vital for Redtenbacher's new position was arranged by the Zurich company Escher, Wyss Cie. which started its business in 1805 as a spinnery, later going on to make manufacturing machines for spinning works in its workshop and, since 1836, changed over to the construction of steamboats and locomotives. The head of the company, Hans Caspar Escher, gave Redtenbacher the room to do multi-purposed and comprehensive tests to collect and to separate such data important for the practical daily work that became the starting point of all his subsequent publication activities. His results relating to mechanical engineering were so successful in the Zurich period that Redtenbacher purposed his first publication. However, the emergence of turbines instead of classical water wheels halted his work. Redtenbacher therefore first turned intensively to this new type of power engine, which then became the topic of his first book (in Karlsruhe) before his later work on water wheels and the general principles of mechanical engineering.

Redtenbacher's acuteness of mind grasped many helpful suggestions and practical experiences and amazing theoretical approaches for problems in machine technology. The factory of Escher-Wyss, under the influence of superior English technology with the leading engineers and technicians coming from England, guarded their know-how, which acted as a challenge for Redtenbacher. He wanted to strip off this knowledge secrecy and to place mechanical engineering as the foundation of new scientific principles. However, his main activities were focused on the school. In Zurich, Redtenbacher started thinking about the nature of the engineering school system which constituted the essential part of his lifework along with his scientific publications. Thus, it seems that the nearly 8 year-long restless occupation in Zurich constituted an important waystation for Redtenbacher's career. It let him mature and broaden his mind beyond mechanical engineering. The high reputation which he acquired very quickly brought him membership of the local association of Natural Science in 1834 and spread his reputation beyond Zurich. A token of increasing appreciation was, for example, the corresponding membership in the Lower Austrian association of industry in 1841. In Zurich, he also set the course of his private life: In 1836 Redtenbacher became engaged to his cousin Marie Redtenbacher and married her 1 year later. They had two children, a daughter Marie and a son Rudolf, to whom posterity owes a very informative biography (Redtenbacher 1879) of his father.

Appointment at Karlsruhe

In 1840, Redtenbacher received a call from the Polytechnic School of Karlsruhe. The basic concept of the new institution at Karlsruhe, the first of its kind in Germany, was to integrate the scientific and mathematical basics of engineering competence as an organic unity as part of the Polytechnic schools. The reform in 1832 enforced by Karl Friedrich Nebenius, merged the Civil Engineering School founded by Tulla, the Architectural School tracing back to Weinbrenner, the Industrial School initially domiciled in Freiburg, the School of Forestry, the Trading School and, above all, the Post School. Under Nebenius, the unity of these technical schools, on a unified basis with the preparatory had been much more elaborate than what was first formed when the Polytechnic School was founded in 1825. He had created a type of school somewhere between a grammar school and a university also spatially separated, possessing senate constitution, annular director election by the professors and featured an organization close to a department system of current universities.

Karlsruhe, the capital of the state Baden, with its 25,000 inhabitants, became the permanent home for Redtenbacher. By ministerial resolution of October 13, 1841, i.e. at the beginning of new school year, Redtenbacher was appointed as professor within the Mechanical Engineering Department. It was obvious that Redtenbacher was keen to play a part in Karlsruhe but, at the same time, to get flexibility and space for development to advance the school by pursuing the vision of his progressive concepts.

The subject of Redtenbacher's concern was the senior industrial school. When he started there, it was the technical section that was least developed of all and encompassed the same course of instruction in both engineering chemistry and mechanical engineering. There was no question that it was not mechanical engineering on a scientific basis. Everybody who was interested in becoming a mechanical engineer at that time, normally started with practical training. The industrial school taught theoretical knowledge quite apart from practical experience. One was content to become acquainted with machine elements, studied descriptions of machines and models of them. Dimensions were expected to be given by experience or were modified by empirical trial-and-error methods in the workshop. Strength calculations based on ideas of stress and strain were practically unknown.

During the 1830s of the nineteenth century, and also at the industrial section of the Polytechnic School of Karlsruhe, instruction primarily took place in the workshop in a handicraft-like fashion. Within a few years, Redtenbacher created a fundamental change in this type of education.

Considering the situation of industry in the German state of Baden at that time, the endeavor described in such a manner, at the beginning of Redtenbacher's tenure in Karlsruhe was definitely challenging for him. It is to Redtenbacher's credit that he introduced scientific methods in his lecture as a young 30-year old professor. The scientific treatment of practical engineering problems seemed to Redtenbacher to be not only more economic but also less erroneous than an investigation based on experience. At the same time, Redtenbacher knew that technical education was not sufficient with pure sciences alone, without attending to practical successes.

Herein, Redtenbacher differed from most Paris professors at Ecole Polytechnique. His lecturing was eventually directed to practice. What he had learned rudimentarily as a young student at the Vienna Polytechnic Institute, and what he had taken on as a successful link between science and application from the scientific work of the French polytechnician Jean Victor Poncelet (1826/1838) for his studies on water wheels and turbines during the Zurich time, was now combined by Redtenbacher into a far-ranging, coherent concept. Thus, the bottom line was to bring together both the education carried on by scientific study and practice. Therefore, Redtenbacher in 1846, began to separate the mechanical and the chemical program at the Industrial school into two single programs and in addition to the existing chemical laboratory, he installed a separate machine laboratory. Only after this step was mechanical engineering constituted as an independent department. This was the starting point for mechanical engineering under Redtenbacher and applied chemistry under Carl Weltzien for development into two autonomous and strong departments of international standing.

The fame of the mechanical engineering school of Karlsruhe propagated very fast. From everywhere, the prospective students came for an education at the Karlsruhe Polytechnic School in the mechanical engineering section under Redtenbacher. The number of students increased and at the zenith, Redtenbacher had 359 attendees, where 227 of them were regular students. After a while, Redtenbacher's work governed the scientific standard of his school. Accordingly, in 1857 he was elected as director. Under his directorship, the Karlsruhe Polytechnic School achieved international standing and was a model for the formation of other schools or re-organizations at home and abroad. As noted before, he received several calls from other institutions but he rejected them all. At the beginning of 1850, he received a call from the Austrian Department of Commerce with an offer of the directorship of a company which was the leading establishment of the Austrian railroad. About the same time, Redtenbacher received a prestigious offer for a professorship at the Royal Industrial Institute of Berlin. There were negotiations by letter over a long time, but on October 3, 1850 he decided to remain in Karlsruhe. On August 20, 1854, Redtenbacher also received an exceptionally prestigious call from the president of the Swiss education council, Dr. Kern, for a new professorship of mechanical engineering at the Swiss Polytechnic School of Zurich. It was planned that, under a generous general framework, Redtenbacher should not only undertake the direction of the mechanical engineering section but would participate in the organization of the whole school including the hiring of professors. Working conditions for Redtenbacher in Karlsruhe were already good before these recruiting calls, and the convenient life for him and his family in Germany (the economic situation obviously was further improved and he became privy counsellor so that in the future, some unpleasentnesses he could avoid) again caused him to stay. It must have given him the strongest satisfaction that for the internal organization of the Zurich school, Karlsruhe was taken as the prototype.

According to Redtenbacher's suggestions, the pre-school and the first annular mathematical course and also the Trade School, the Post School and the School of Forestry were abandoned. Instead, a Mining school was founded and philosophy, history, national economy and business, political science and law were included in the curriculum, besides literature and science which had been incorporated long before. The so-called "Education to Industry" already attested in the sense of Friedrich List by Karlsruhe's historian Franz Schnabel, was strongly promoted by these measures.

After the relocation of mechanical engineering in the new building was carried out in 1860, Redtenbacher was at the zenith of his productive life. By establishing humanities, a deeply felt desire of Redtenbacher had come true. Teaching the subjects of humanities at the Polytechnic School meant neither decoration nor luxury, they were a part of the technical studies themselves. What Redtenbacher demanded, or at least expected from his students, with respect to general education essentials beside the usual technical study, he did not excuse himself from either. He did not give up his artistic intentions in painting, music, theatre, poetry until his last years. In connection with his own research, he was inspired by the classical French mathematicians who were seen far above all their contemporarities, especially the English who focused more on practice. The logic and the methodologies of French science were the closest to his heart. From Justus von Liebig he learned to grasp beyond chemistry into adjoining areas. Kuno Fischer who was a recognized philosopher in Jena, gave him an understanding of the newer philosophy, from which he studied Kant and Hegel as well as the much noticed main opus of Hermann Lotze, “Micro Cosmos”, and the writings on aesthetics by Friedrich Theodor Vischer. In addition to all the time-consuming teaching and adminstration work and his own literary activities, he even got round to the reading of contemporary historians.

To his admirable self-discipline that he mustered during his studies, during his later years there was added an authoritarian rigorousness towards particular lecturers who became obstinate and were not inclined to follow his plans. He was not always a congenial colleague. He never made a secret of his convictions and he could mercilessly pack a punch in a faculty meeting when mediocrity and small-mindness emerged and when people clung to out-of-date and bureaucratic regulations instead of pursuing the objective requirements. All the time, however, he was backed up by the state authority which was needed to push through his reforms with both meticulousness and impatience against restrictions and obstructions of all kinds, sometimes surely with a good deal of obstinacy as well. Self-willed traits emerged when, for the school year 1861/62, there was simply no re-election of the director – since 1857 year after year, the faculty meeting had voted for him – but he directly pursued his official duties because, to his mind, it would be in the interest of the school to eliminate the previous annular director election by the lecturers of the school by a director appointment for life. The ministry had this opinion of Redtenbacher to prolong his directorship for life which was not explicitly confirmed but condoned and did not urge a re-election. Though some colleagues grumbled, they hesitated to undertake actions against this infringement of their perceived rights, especially because Redtenbacher was at this time starting to be troubled with a stomach illness which developed little by little into a deadly disease. Despite his malady, Redtenbacher still continued his classes during the whole school year 1861/62. In the fall of 1862, after a recuperation journey which should bring recovery, the illness exacerbated such that he had to cease lecturing at Christmas 1862 and also resign the directorate. On April 16, 1863 he silently departed this life blessed by restless work and great success.

These biographical notes, which are a shortened version of Wauer et al. (2008) substantially follow Mauersberger (1989a) and Fuchs (1959) with regard to personal biographical details by Ferdinand Redtenbacher himself (Bader 1858), as well by historical appraisals in Mauersberger (1980, 1985) and Schnabel (1925 and 1938).

List of Works

Theorie und Bau der Turbinen und Ventilatoren, 1844
Theorie und Bau der Wasserräder, 1846
Resultate für den Maschinenbau, 1848
Prinzipien der Mechanik und des Maschinenbaus, 1852
Die Luftexpansionsmaschine, 1852
Die calorische Maschine, 1853
Die Gesetze des Lokomotivbaues, 1855
Die Bewegungsmechanismen, 1857
Das Dynamiden-System. Grundzüge einer Mechanischen Physik, 1857
Die Bewegungsmechanismen, neue Folge, 1861
Die ursprüngliche und jetzige Temperatur der Weltkörper, 1861
Der Maschinenbau, 3 Bände, 1862–1865

Review of Main Works on Machine Science

Within the limits of this contribution, it is hardly possible to completely do justice to Redtenbacher's groundbreaking scientific work; it is too voluminous, too manifold in content and so broad in its scope. Lasting results concern the institutional establishment of mechanical engineering as a science and the formulation of trend-setting methodical design principles. They represent the German way to find a synthesis between the workshop-oriented English technical education close to practice and the highly theoretical machine science of French provenance. Above all, there was the final goal to combine theoretical knowledge, especially of mechanics, with extended practical experience in an appropriate manner. Within this approach, the intention was perceived to extend the brilliant successes of analytical mechanics, in particular to predict the planetary motions. Bearing in mind the fact that machine motion is dictated by terrestrial effects, Redtenbacher aspired to incorporate friction, impact restitution forces and other "noise terms" in a scientific method for predicting the behavior of machines. This could be accomplished not only through reliable knowledge of the mathematical-scientific fundamentals but also through firm workshop experience know-how.

As much as he planned to apply scientific methodology ideals, he did not forget the empirical basis of technology. Intuitively, he developed his knowledge stepwise and started both with the exploration of determinant phenomena and with the examination of different types of machines. In his opinion, every science should begin with induction and end with deduction. His debut publication was in 1844, a book on "Theory and Construction of Turbines and Ventilators" (Redtenbacher 1844), second edition 1860, followed 2 years later by "Theory and Construction of Water Wheels" (Redtenbacher 1846), second edition 1858. This unexpected order had essentially no technical reason. In a letter from his publisher Bassermann of

Mannheim (August 30, 1844), we learn that the “Water Wheels” at that time were ready to print but there was a time lag due to the time consuming production of 30 lithographic tables. Much of the material for both treatises can be traced back to his Zurich time and the collaboration with the company Escher-Wyss, but it was also advanced by study trips 1842 to the industrialized Alsace, 1843 down the Rhine till Cologne, in February 1844 to the Baden Black Forest and in August 1844 to Amsterdam and Haarlem via Cologne, back via Belgium (Figs. 2 and 3).

In the creation of new machines, conventional technical knowledge and the inherited wealth of workshop experience often failed. Therefore, analyses as exact as possible had to be found, in particular for further advancement of such machine innovations. In exemplary form, Redtenbacher tackled the problem. Even though, in the case of turbines, for example the constructions of Fourneyron, Jonval or Schott, seemed to be designed in all details but with respect to limited water resources, there was a need to look for an increase of power or a reduction of energy losses. Additionally, there was the demand for specific dimensioning rules depending upon the application and to harmonize the power requirements with the driven machinery. By his detailed calculation rules based on fundamental hydrodynamic balance equations, Redtenbacher helped to overcome tentativeness in launching such driving aggregates and presented lasting, acceptable construction standards for them.

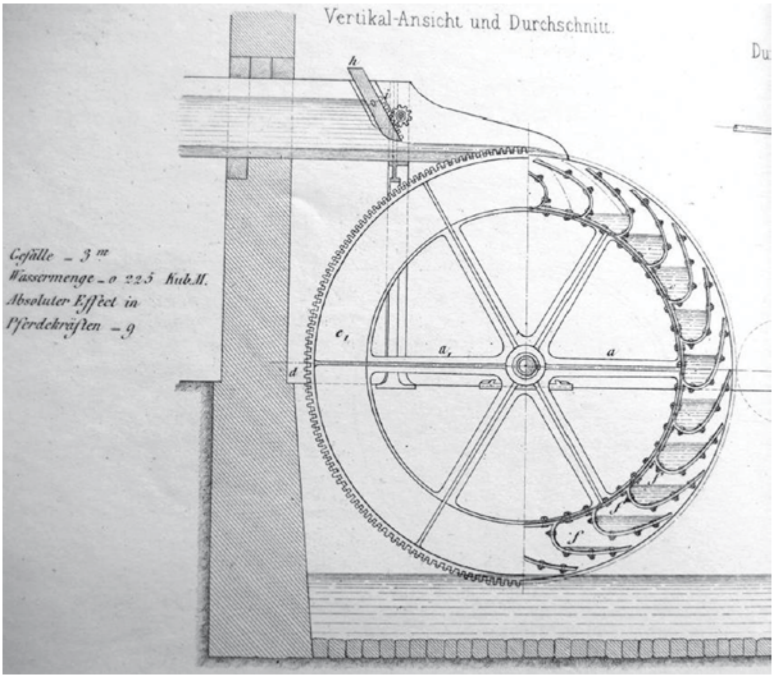


Fig. 2 Water wheel design of Redtenbacher

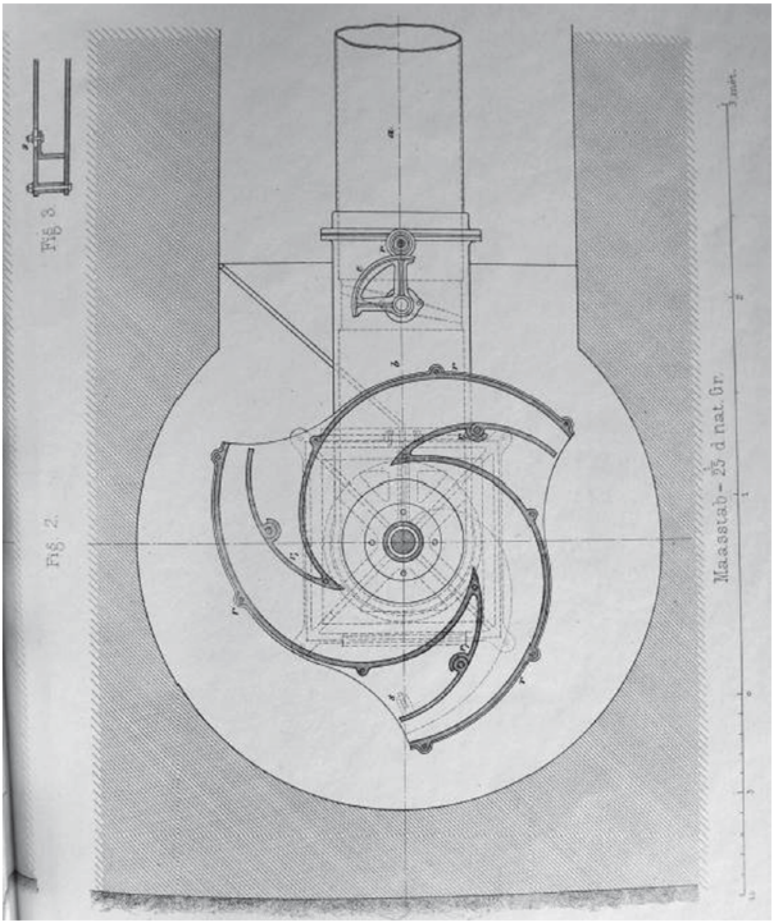


Fig. 3 Water turbine design of Redtenbacher

Moreover, he showed, by comparing issues regarding energy aspects, the advantages and drawbacks of the different designs.

In a report strongly structured according to basic scientific principles, he succeeded in coming up with such effects and to take into account such economic-technical determinants not yet exactly computable in the sense of confirmed scientific knowledge. In this way, Redtenbacher's understanding of sufficiently accurate approximation results was formed to bring them through further research experiments, step by step to a higher level of generality and closeness. Of course, the analytical machine theory vis a vis the French deductive method, was still in its infancy, and there were still too many unknowns in the knowledge basis of the young engineering sciences. For the time being, only use of well-proven technology helped. Recourse to a reliable reference book was among the popular instruments in engineering during that time, as is still true today.

The completion of a design reference book was realized by Redtenbacher in 1848 in his most popular work “Results for Mechanical Engineering” (Redtenbacher 1848) (see Fig. 4) a real manual for students, practically working engineers, designers and industrial managers likewise. It had four German editions and one French edition in his lifetime and two other German ones posthumously. In this work, he presented all those tools and rules in a half-empirical manner, multiply tested and well-established for the practical applications to be indepensible for a beneficial design. He referred therein to accepted standards to dimension all essential machine elements such as gearwheels, pulleys, chains, screws, cables and belts, journals, shafts, rivets and bolts, linkages, stuffing boxes and pistons and transferred them to other scales. This “method of ratios”, once borrowed from architecture and, already applied during the time of James Watt, was an elementary method of calculation characterizing scientific mechanical engineering during the early stage of the field.

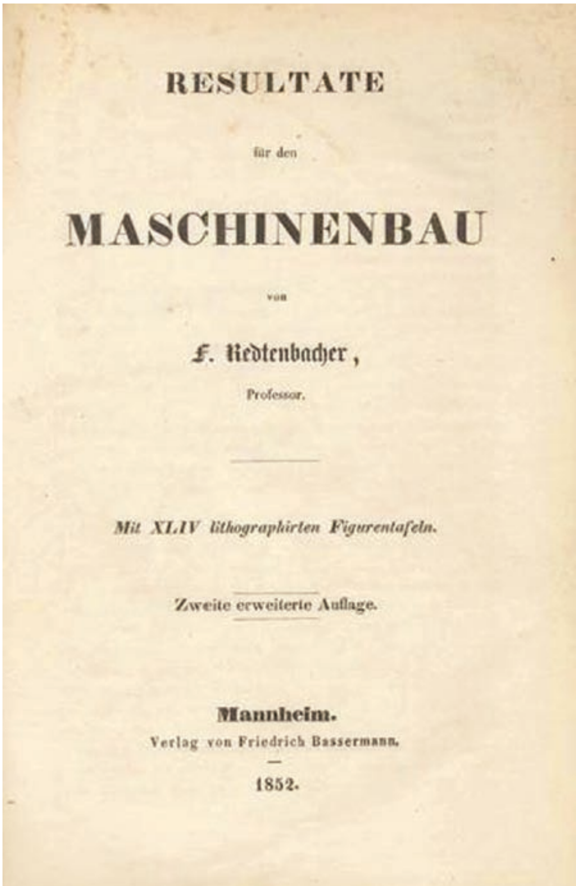
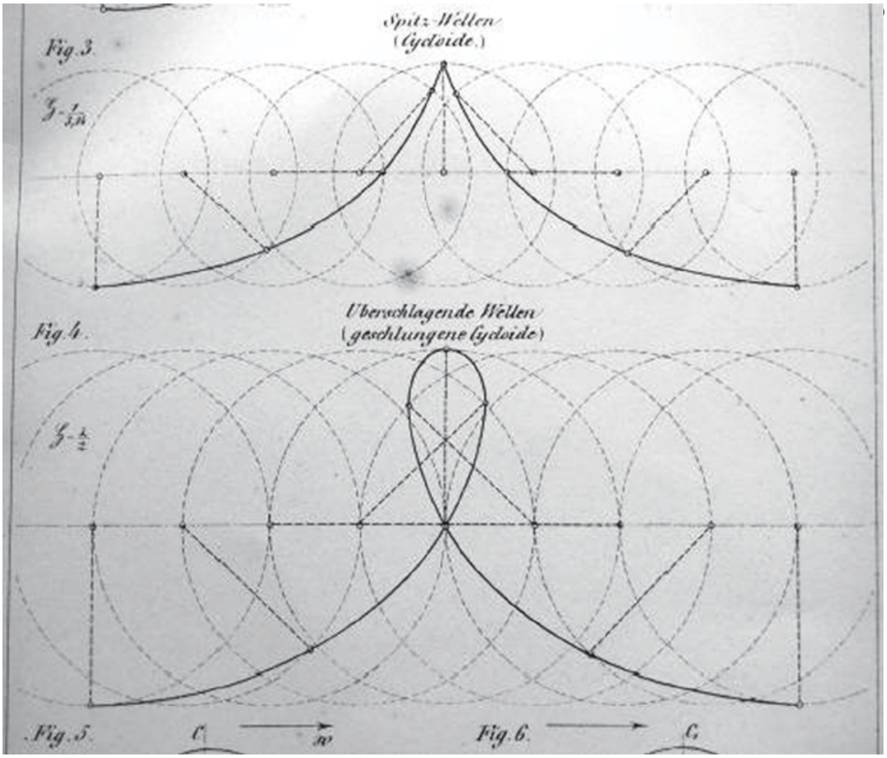


Fig. 4 (**a**) Book facing page “Results for Mechanical Engineering”. (**b**) Cycloid mathematical curves from “Results”. (**c**) Kinematic mechanism design from “Results”



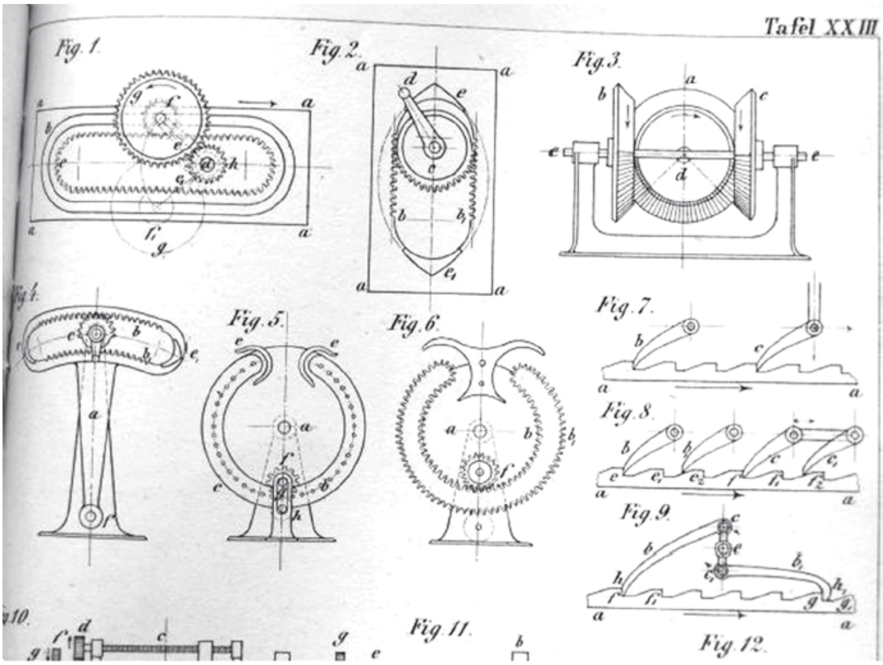


Fig. 4 (continued)

Besides Redtenbacher, the French polytechnician Artur Morin had succeeded cultivating this calculation type theoretically and using it as a practicable tool. Its publication motivated Redtenbacher, for the most part, to retreat from his high scientific ideals but it corresponded to the actual needs of mechanical engineering to have available a large variety of new mechanisms and design concepts for power and work machines fully functional in the developing industry. It helped to define mechanical-constructive orientation of the machine design.

Mechanics was omnipresent in Redtenbacher's work: "All-around where something budges, mechanics has a finger in the pie but the spirits do not stir by mechanics", could be read in the 1856 caption of a Redtenbacher portrait. During his time in Zurich, Redtenbacher had indicated that he was not interested in leaving design to half-empirical recipes. Already, his objective was aimed at a machine science that would match the achievements of modern mathematics and mechanics. The French experts of mechanics were so highly distinguished in his mind that their shining example inspired him to emulate them. He had manifested, for a long time, the desire to comprehend the machine problems totally in their highest generality.

His scientific ideas were published in 1852 in the book "Principles of Mechanics and of Mechanical Engineering" (Redtenbacher 1852a) (see Fig. 5). This became a

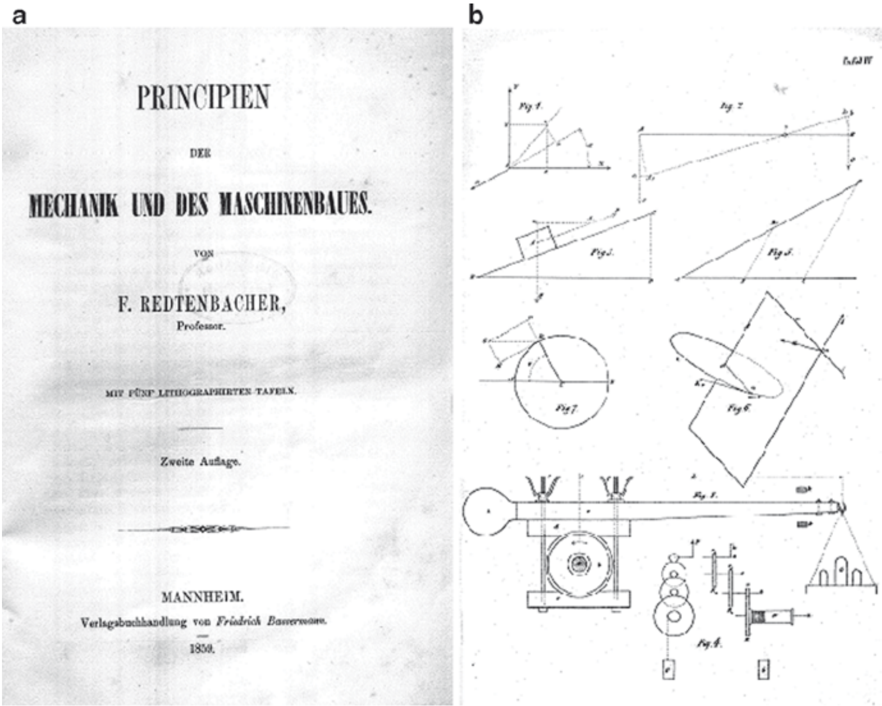


Fig. 5 (**a**) Book facing page "Principles of Mechanics and of Mechanical Engineering". (**b**) Drawings of equilibrium problems from "Principles"

principal part of his machine theory and a milestone in composing technical-scientific theories. In the book, he compellingly developed the modeling ideas for the design of a machine. With a consequent orientation to the interactions of technical function, constructional shape forming and economic feasibility, he broke new ground in design methodology. Consequently, he incorporated that vocabulary which had already heralded a specific dynamic-energetic dimension of approach under the French triumvirate Louis Marie Henry Navier, Gustave Gaspard Coriolis and Poncelet, starting with Charles A. Coulomb and his theory of simple machines during the second half of the eighteenth century. Work, energy and efficiency factor were among the main properties within the structure of categories of his machine theory, where he always tried to explain the context descriptively. By avoiding cumbersome mathematical expansions, straightforward and applicable procedures were his ultimate goal. Herein, the specific usefulness of technical coefficients outcropped, e.g., describing the strength behavior of machine elements made of metallic material or concerning the outflow of fluids from containers or reservoirs but also such geometrical properties of shape and cross-section tabularly ascertainable as moments of inertia, etc. Such comparisons gave directions to the engineer for an effective design.

Redtenbacher's approach was captured in a systematic method that was based on the machine's type of motion – changing the position and deformation of machine parts led to the determination that beneficial layouts and culminated in an analytical machine theory. Its framework was geared to a technical–economic optimal solution, the essential determining properties were then represented by a set of primary and secondary equations. With respect to the purpose of the machine and the technological process, considerations were finally given to the dependencies between the constructional elements and their technical functions. This part of Redtenbacher's procedure to design machines is the one that is based the least on scientific principles but on economic, industrial and societal issues. Here mechanical design practice totally dominates.

With the development of mass production, scientific mechanical engineering became more intensively devoted to the manufacturing processes. The temporary priority of the design process as an object of scientific examinations was emphasized by the key role which Redtenbacher attributed to technical drawing. Despite all specialization, he still considered engineering activities as an organic procedure, also involving a certain artistic creativity. The recognition that the design abilities of technicians as well the aesthetic appeal of their product were part of the process began to emerge within the evolving engineering sciences. The use of aesthetics in machine design was later embraced by Redtenbacher's student Franz Reuleaux (see, e.g., Moon 2007).

Redtenbacher saw the conscious use of engineering thinking as an expression of human power, and a chance to create a bridge between nature, technology and society and, furthermore, a basic approach for a reconciliation between the differences of the neo-humanistic and technical education. The psycho-emotional moment in the process of an original design became a central part of the inventive process of an engineer as well as the basic principles of mechanics.

Redtenbacher believed that, among the important virtues of a mechanical engineer, should be an artistic nature, including phantasy, play instinct, artistic abilities and virtuosity. Incidently, he felt that technical drawing would considerably advance keenness and clarity of thoughts of an engineer. Without it, many a trend-setting idea might be pushed ahead of its time, many a keen approach could not completely be realized. The use of descriptive geometry and technical drawing was introduced by Gaspar Monge of the Ecole Polytechnique showing again the French influence on Redtenbacher.

On the one hand, advances in the theory of machine sciences were so notable that they were beyond the means of the engineering practice, on the other hand, there were huge gaps of knowledge in such elementary problems as lubrication, tightness or fit accuracy of machine components. Increasing the speed rates and the pressure as well the enlargement of the reciprocating masses were other factors accounting for such discrepancies between theory and design rules. Only the next generation of engineering scientists could overcome the hiatus between program and reality. Nevertheless, Redtenbacher tried to verify his guiding principles during the fifties. By his essay “The Air Expansion Machine” (Redtenbacher 1852b), which was already published as a second edition in an extended form and new title “The Caloric Machine” (Redtenbacher 1853) 1 year later, he could manage a validated conformation of his conceptions from Redtenbacher (1848) in a original format. Using the example of Ericson’s air expansion machine, a strange forerunner of the combustion engine and strongly debated in the literature, Redtenbacher – surely knowing the contributions of the French polytechnician Sadi Carnot – raised the question on the perfect motor. During that time, the thermal behavior of heat-power engines came more and more the vision of the engineers. Increasing the power by higher cylinder pressures and temperatures, multi-utilization of steam, minimal fuel consumption and advantageous arrangement of the thermal process were the focal points of many scientific debates.

In contrast to his student Reuleaux, Redtenbacher’s contribution to machine theory therefore moved into the forefront of technical thermodynamics. Starting with fundamental considerations in which, strongly following his principles, he formed a theory of an effective hot air engine, he optimized its main parameters. However, the problem was not yet completely solved and he addressed the key question of the practicability under which the required high temperature gradient brought back down to earth all speculation to exceed the limits of the classical steam engine. With less resonance, the work “Laws of the Locomotive Construction” (Redtenbacher 1855) was addressed in 1855, even though there was an urgent need for such a book of rules. Railroad construction had been a catalyst for the growth of powerful machine factories. The novelty and complexity of this technical system required scientific principles and from March 1854, he declared in several letters that this technology, driven by the English with their long empirical knowledge, would require a scientific basis. He thereby entered the new field of interia forces, vibrations and impact loading, but was not able to cope with the complex driving system, called a locomotive, in all details. Critical comments by experts in this field could not be ignored.

His series of books was extended in 1857 by the contribution “Motion Mechanisms” (Redtenbacher 1857a), a book of detailed designs for models of kinematic mechanisms. In 1861, it was expanded by a new issue (Redtenbacher 1861a), to be collected in 1866 as one volume (see Fig. 6) which essentially presented and explained the teaching model aids collection of the mechanical engineering section constructed in the workshops of the Polytechnic School under Redtenbacher. These models (see Figs. 7 and 8) supported his lectures to the professional community from models of a simple pair of wheels or a slider crank mechanism through kinematic models of the complex non-uniformly transmitting gear boxes.

a

b

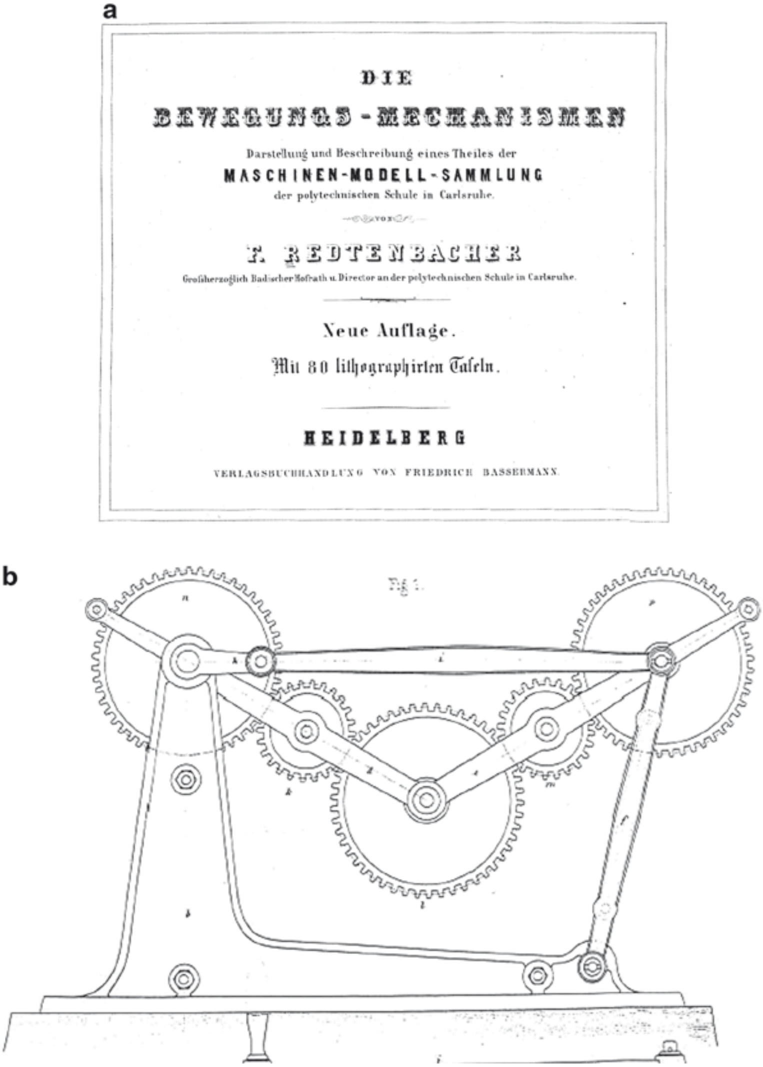

DIE
BEWEGUNGS-MECHANISMEN
Darstellung und Beschreibung eines Theiles der
MASCHINEN-MODELL-SAMMLUNG
der polytechnischen Schule in Carlsruhe.
von
F. REDTENBACHER
Großherzoglich Badischer Hofrath u. Director an der polytechnischen Schule in Carlsruhe.
Neue Auflage.
Mit 80 lithographirten Tafeln.
HEIDELBERG
VERLAGSBUCHHANDLUNG VON FRIEDRICH BASSERMANN.

Fig. 6 (**a**) Book facing page of Redtenbacher's "Motion Mechanisms". (**b**) Drawing of gear train mechanism from "Motion Mechanisms".

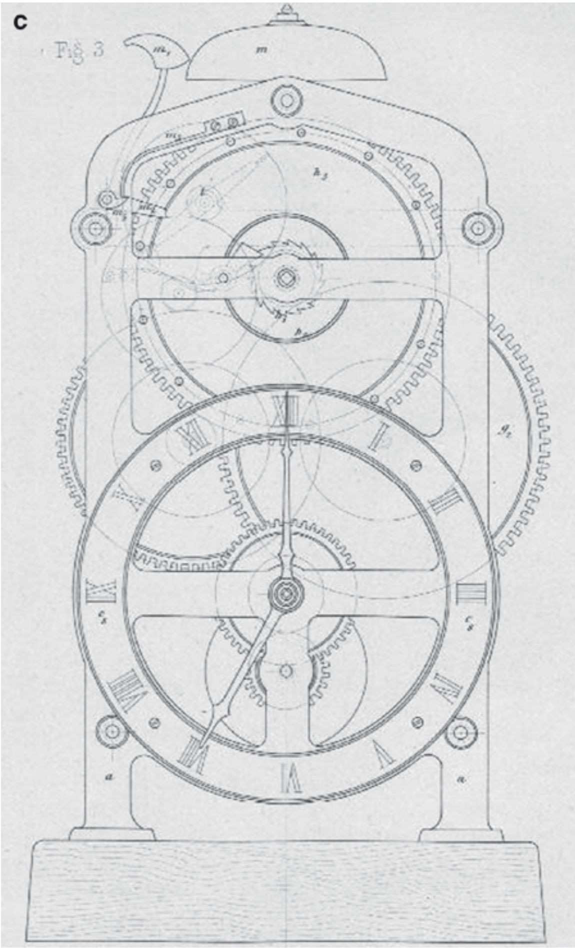


Fig. 6 (continued) (**c**) Drawing of gear train mechanism from "Motion Mechanisms"

Again and again, Redtenbacher was interested putting his explanation of the interaction between nature and technology on a consistent basis. Such wide-ranging thinking permanently inspired his research activities and led him to a complex and variable methodology. His world picture was particularly rooted in the predictability and in the logical precision of classical mechanics. Redtenbacher, who contemplated writing a history of mechanics, picked up nature-philosophical discussions and tried to translate them into a technical-scientific question. His intentions in 1857 culminated in the presentation of his opus "The System of Dynamides, Main Features of a Mechanical Physics" (Redtenbacher 1857b). What he already had implied in his "Principles", here it attained the most mature expression: an attempt

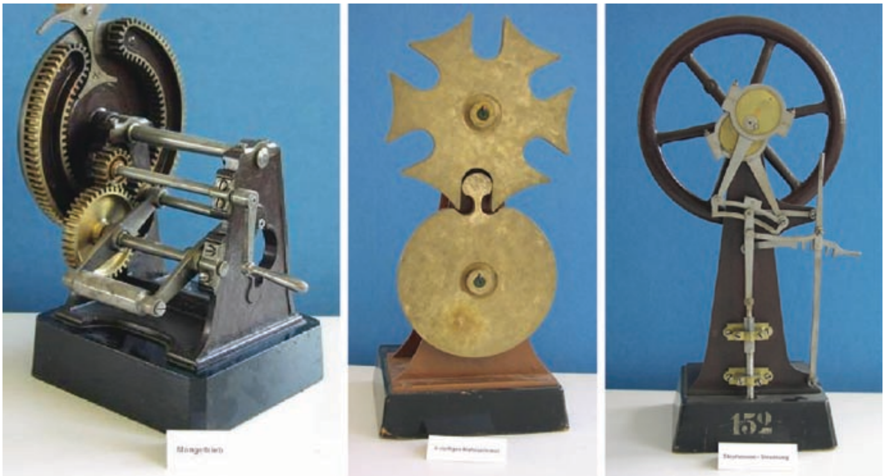


Fig. 7 Photographs of kinematic models from the Redtenbacher Model Collection of Karlsruhe University. (**a**) Reciprocating gear mechanism. (**b**) 6-part Geneva wheel intermitted mechanism. c. Stephenson valve gear mechanism

to yield a contribution to the scientific and philosophic progress of knowledge. Therefore, evidence of the theoretical influence of the flourishing technical-scientific thinking should be furnished. In the process of fermentation between different concepts of nature which loomed in the course of the accomplishment of the classical physics, Redtenbacher's contribution to continue the thoughts of Dalton Poisson and Augustin Louis Cauchy was an attempt to match the existing atomistic molecular-theoretical models with the specifics of technical-scientific styles of thinking. The center of his ideas were the so-called "Dynamides", i.e., body atoms with its enclosing aether hull, he aspired to explain graphically the connection between micro- and macro-cosmos, a venture which must fail on the mathematical explanation of complex processes of aether oscillations. By this "System of Dynamides" which was denoted a patchwork theory by Redtenbacher – obviously he appreciated the deficiencies of his constructs – he wanted to set a marker to bring forward – beyond the attempt to the self-image – the acceptance of the status of engineers. In this respect, the book had deserved broader attention from his contemporaries, especially as it dealt with important ideas in physics, e.g., such of James Clerk Maxwell. His affinity to natural-philosophical topics was expressed in 1861 a second time in his work "The Initial and the Actual Temperature of the Heavenly Bodies" (Redtenbacher 1861b). Both books are important in understanding the broadness of Redtenbacher's scientific work, but for the development of machine science, they are contributions with no impact.

Obviously, several factors came together to inspire Redtenbacher's final masterwork "Mechanical Engineering" (Redtenbacher 1862). As Redtenbacher himself explains in the preface to the first volume, the complete three volumes should summarize the essentials of all his lectures on mechanical engineering at the Polytechnic

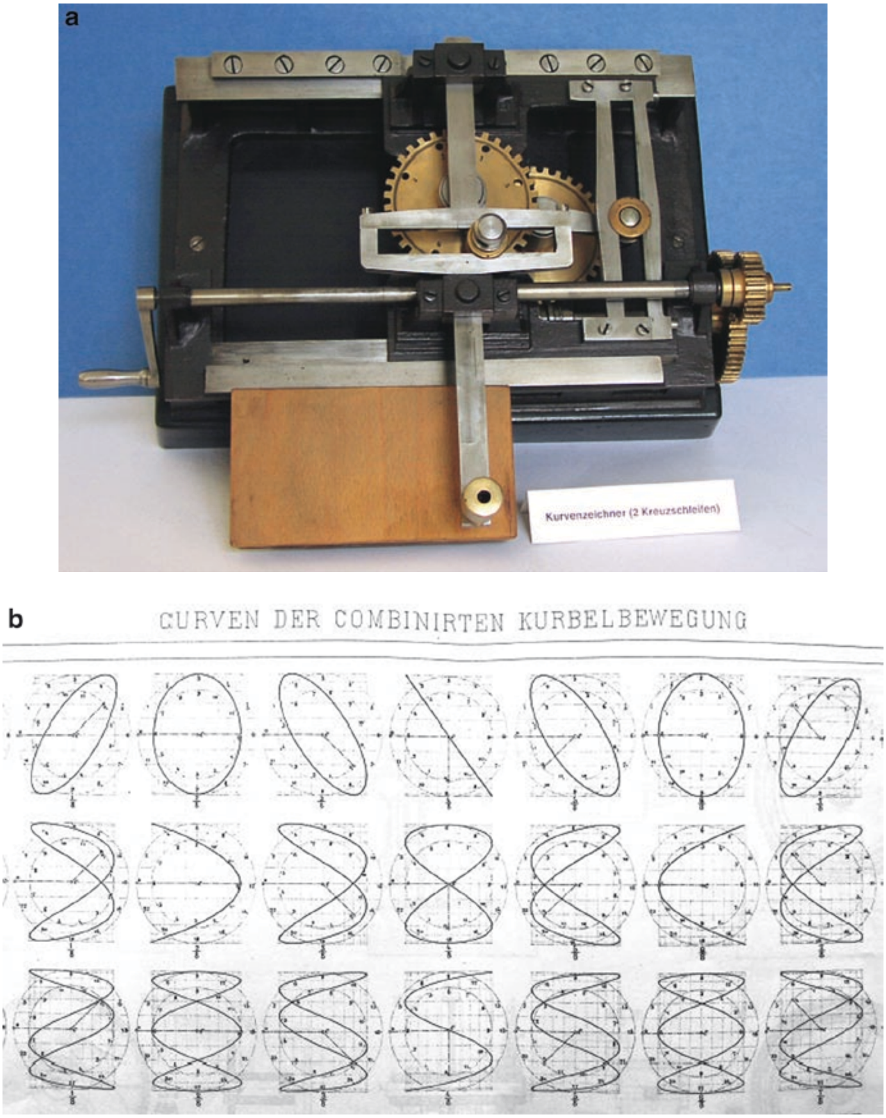


Fig. 8 (**a**) Photograph of kinematic model of a function synthesizer from the Redtenbacher Model Collection of Karlsruhe University. (**b**) Lissajous curves drawn with Redtenbacher's kinematic function generator

School of Karlsruhe. "This work composes for all students of mechanical engineering the bridge between the other works which I have published many years ago, namely the 'Principles of Mechanics and of Mechanical Engineering' and the 'Results for Mechanical Engineering'. The present work shortly called 'Mechanical Engineering' essentially is the derivation of the results from 'Principles' for application. This means that the 'Principles' are a general formalism describing what the essence of every machine is, how the motions and operations work, what conditions influence the machine and how these constraints can be traced, what ideas are important in order to develop the design to a real machine that functions in practice. With one word: The 'Principles' try to tell and to teach everything what is necessary for understanding, for design and for realization of machines, i.e., the 'Principles' are the general machine science which is taught within the first three months of engineering study. On the other hand, 'Mechanical Engineering' is intended to teach all specialities which are necessary for practical realization of all general principles and treats a series of concrete work and power machines." But Redtenbacher's desire to write this summary work, however, was urgent due to the misus of his ideas by others and the exploitation of his lectures. The final statement within the foreword to Volume 1 states explicitly "that the publisher already often was impelled to intervene against this circulation of my work and that hopefully this misapplication will not happen again in future". Only the first volume was published in Redtenbacher's lifetime. Volume 2 was ready to print when he died, volume 3 was finished according to available notes by his co-worker Josef Hart; the publication took place in 1865.

Following the intentions mentioned, the first volume spanned a wide selection of topics including strength of materials, design of machine elements, friction in machine elements, kinematics of mechanisms, clock escapements, and the design of construction cranes. His second and third volumes cover hydraulics, water wheels and turbines, locomotive design, steam engines and mining machines. The structure of the text consists of short descriptions of each topic, many formulas, some derived using differential and integral calculus, and a few line drawings at the end of each volume.

On the Influence of Redtenbacher's Works

For the evolution of mechanical engineering in central Europe from its workshop-oriented tradition into a science, Redtenbacher's three books "Results", "Principles" and "Mechanical Engineering" composed a type of comprehensive framework. To understand concrete applications, the publications "Water Wheels", "Turbines" and with some restrictions "Caloric Machines" and "Locomotives" are useful, too. To understand how Redtenbacher taught his students, explaining to them theoretical and methodical connections with the use of real models, the book "Motion Mechanisms" had additional significance. Therefore, these works will be included in the following discussion.

The influence and the renown of Redtenbacher's works were already wide spread during his lifetime. Six German editions and an additional French edition (from 1848 through 1875) of his most popular work "Results" as well three editions of "Motion Mechanisms" (between 1858 and 1866) give evidence for his wide reputation. In addition, there were two editions of “Water Wheels”, “Turbines” and the “Principles” while, on the other hand, there was only one edition of the large three-volumed comprehensive work “Mechanical Engineering”. The latest edition of “Results” edited by Redtenbacher’s successor, Franz Grashof, in 1875 was in the library of the well-known American engineer-professor Robert Thurston of Stevens Institute and later Cornell University, i.e., Redtenbacher’s work also circulated in America as well as in Germany and France. We can obviously conclude that practical handbook knowledge, rules of thumb and tabular results were most important for engineers and technicians during that time of early industrialization. But even nowadays such collections of scientific and technological facts in a short form without proofs are very important for students and practicing engineers as compendia as “Hütte” or “Dubbel” show. And a comparison with the early editions of “Hütte” in the nineteenth century verifies that it was definitively based on Redtenbacher’s “Results”.

The design experience represented by his precise technical drawings one can find both within the “Results” and also the tables accompanying the text of “Motion Mechanisms”, and are a further step in the didactic realization of the practical-mechanic knowledge of his time. Machines and their components were visualized in all details where the machine elements and even the motion of mechanisms were displayed in their statical and strength constitution. The kinematic principles that governed machine engineering was the typical style of the French Monge school in which they demonstrated the conversion of motion and represented a catalog of mechanisms for intuitive selection of proper gear shapes for example. It was far away from a modern mathematical–geometrical analysis or even a synthesis of such units.

Redtenbacher’s Kinematic Models

There is evidence that Robert Willis used such models as early as 1840 in Cambridge, as did Johann Andreas Schubert at Dresden around the same time (see, e.g., Moon 2003a, b, Mauersberger 1989b, 1997). Likewise, Redtenbacher developed one of the most extensive model collections of his day at Karlsruhe with as many a 100 different models which was only surpassed after his death by his student Franz Reuleaux at Berlin. Most important for the evolution of mechanical engineering is the fact that Redtenbacher documented the construction of these teaching models in his two monographs. This offered an opportunity for others to copy these models as did a famous commercial model-maker of the time, the Schroeder Company of Darmstadt. Unlike Reuleaux’s original 800 model collection at Berlin that was destroyed in World War II, the Redtenbacher Collection is remarkably preserved at the University of Karlsruhe. Recently, has become the entire collection available on the web, appropriately alongside the Reuleaux Collection, at the website KMODDL (http://kmoddl.library.cornell.edu). Reuleaux’s designs for models survived because he set Gustav Voigt to copy and make reproductions of around 350 of his models. However in competition with Voigt, I. Schröder of Darmstadt, Germany, also produced copies of Ferdinand Redtenbacher's models from (Redtenbacher, 1857a, 1861a) as well as copies of models based on Reuleaux's books. The Schröder-Redtenbacher models were quite popular because they came in two sizes, small and large. Several museums such as the Science Museum in London and the Musée des Arts et Métier in Paris purchased the larger models. A large collection of these copies of Redtenbacher models can be found in Italy at the Foundation for Science and Technology (FST) in Florence. Another large collection can be found at the University of Porto in Portugal. Cornell University has about 18 Schröder models to be found illustrated in Redenbacher's textbooks. Schröder exhibited these at many world exhibitions including the Centenial Exhibition in Philadelphia in 1876 at which Reuleaux was on the judging panel that awarded Schröder's models a prize. Thus unwittingly, Redtenbacher's influence extended beyond Karlruhe through his designs for teaching models of machines. The Redtenbacher models largely consist of kinematic mechanisms including linkages, gear systems and straightline mechanisms. However, there are cutaway models of steam-engine valve systems as well as mathematical function synthesizers.

The representation of engineering knowledge in the mid-nineteenth century began with mathematical codification in the form of coefficients, tables, dimensionless characteristic numbers, etc., and was typical for the methodical approach in the evolution phase of mechanical engineering science. In particular for the instruction of the early mechanical engineers, this type of procedure introduced drastic simplifications, and was the only practicable method. Within the conflicting goals of practicability and scientific content, Redtenbacher tended to propose a didactically-illustrative method – similar to his contemporary colleagues Julius Ludwig Weisbach at the Mining School of Freiberg in Saxony and the Scottish engineer William John Macquorn Rankine – but the scientific background had to be foremost. The benefits of such a unity of exact scientific conceptions and a realization intelligible to all were obvious: The different demands on scientific methods in research, education and engineering practice became apparent. Even in that period, the emerging of these levels of engineering-scientific activities within a scientist personality such as Redtenbacher proved its worth. Excellence in science mainly occurred where new technologies pioneered and technical problems could not be solved via conventional aids. However, it cannot be ignored that, essentially, engineering practice could be handled very well by handbooks and know-how and also workshop traditions.

Redtenbacher's posthumous fame was considerable at least in the German-speaking regions of Europe. A notable number of students alone has ensured that his name would not fall into oblivion. Already within early writings in the history of engineering science, Redtenbacher's lifework was acknowledged by well-known historians. He made history not only for his pioneering work in scientific mechanical engineering, but also as one who brought about its realization in the training of engineers. There was some continuity within the work of Gerstner (Vienna), Schubert (Dresden), Weisbach (Freiberg) and Redtenbacher (Karlsruhe) to introduce scientific methods into mechanical engineering where Redtenbacher possibly outstood and had in Grashof a coequal successor. Grashof was successful in continuing Redtenbacher's educational intentions and plans. One year after his relocation to Karlsruhe, at the annual meeting of VDI (Association of German Engineers), he delivered a lecture, "On the basic principles for the organization of polytechnic schools". Based on this speech, a new organization status for the Karlsuhe Polytechnic School was granted in 1865 as the first institution in Germany holding a university constitution with self-management and appeal proceedings to be equated in rank with the state universities.

But it is also correct to say that Redtenbacher's work is clearly less spectacular and less controversal than that of his most famous student, Reuleaux. Based on a solid disciplinary development of the scientific mechanical engineering, Reuleaux and others tried a theoretical consolidation that spurred strong pedagocical debates. The major subjects were sufficiency of theoretical models, practical relevance of theory, the role of mathematics and the variety of methods within the flourishing engineering science. Therefore, it is not surprising that Reuleaux's work received much more attention in America than Redtenbacher's although the latter's work was wider in scope than either of Reuleaux's two major works including his "Kinematics of Machinery".

Modern Interpretation of Main Contributions

To appreciate Redtenbacher's contributions to machine science, it is helpful to read the opinions of his colleagues and later educators in similar institutions.

What Redtenbacher achieved for the mechanical engineering cannot be stated more incisively than by the words of Professor Kammerer within his directorate speech discoursed in 1908 at the Technical University of Berlin, i.e., in a time when his school had become the largest and most important institution of this kind in the German empire: "…in the emergence of a mechanical engineering art from mechanical engineering craft, scientific methods had to be found to determine machine dimensions as well as economic efficiency. The leadership was firstly taken by the Karlsruhe Polytechnic School. There, in the year 1841, Ferdinand Redtenbacher started his lectureship who had got to know the mechanical engineering undertaking from his own personal experience and at the same time also governed the scientific mechanics. In place of aimless rules he placed a theory based on experience… Justifiably, he may be seen as the originator of machine science in Germany" (Keller 1909).

As another person of importance in this context, Franz Reuleaux has to be surely named as one of Redtenbacher's master students. Reuleaux was also impressed and influenced by Redtenbacher in his 2 years of study at Karlsruhe, 1850/51 and 51/52, where he had learned from Redtenbacher's books published between 1844 and 1857 and summarized in the three-volumed opus "Mechanical Engineering" in 1862–65. In his famous work of 1875 "The Kinematics of Machinery: Outlines of a Theory of Machines" (Reuleaux 1875), within the third paragraph of chapter 1, Reuleaux puts machine science in the framework which was filled out by Redtenbacher 30 years earlier in Karlsruhe. Thereby, he ascertained that the general basics of machinery, the theory of machines, machine design and kinematics, in a sense, could be extended compared to that of Ampere in order to define a machine as a whole. Reuleaux explicitly credited Redtenbacher with a key role in promoting the first three ingredients for scientification of mechanical engineering departing from the traditionals stating for example, "that in the general basics of machinery a descriptive representation was usual until the thirties and Redtenbacher first removed the stigma of indistinctness from the matter."

There is some debate among historians of machine engineering as to the relative contributions to mechanical engineering of Reuleaux and his professor Ferdinand Redtenbacher who, as noticed before, has been called one of the pioneers of German engineering education. Both men published influential books in machine design and both developed kinematic model collections for teaching. Redtenbacher's summarizing three volume work "Mechanical Engineering" followed a year after Reuleaux's own "The Constructor" (Reuleaux 1861) was published. The Redtenbacher work is wider in scope than either of Reuleaux's two major works, including his "Kinematics of Machinery" (Reuleaux 1875) of 1875/76. However, unlike his pupil, Redtenbacher did not attempt to develop a general kinematics theory of machines or mechanisms. His chapter on kinematics classified mechanisms as to the type of motion they performed and was clearly influenced by the earlier French classification schemes of Monge. Nor did Redtenbacher review the history of machines and there are not many references to the literature or machine practice.

Lasting effects emanated from Redtenbacher's main theoretical work "Principles". However, it is difficult to find his name associated with theorems, methods or even formulas in mechanical science and engineering. Examples of his theoretical paradigms showing his use of definitions and names in the sense of Newton's *Principia* were introduced in the development of machine theories and are still found in the framework of modern machine theory, albeit in a modified and extended form. In this meaning, Redtenbacher might be compared with Euler who had a similar impact on natural science. Redtenbacher reinterpreted the theorems of theoretical mechanics in such a way that they could be readily applied to problems in engineering. With regard to progress in knowledge and development of methods, Redtenbacher's "Principles" constitute a milestone in the history of mechanical engineering and are, at the same time, a credo for scientific methodology. It was not sufficient to simply mathematize problems, but the development of theoretical models took a key role in engineering science. The complexity of real machine problems and the large number of parameters within the design process preclude exact methods according to the ideals of natural science and require a limitation to the use of essential principles. The modelling has to consider the concrete purpose of use, the function and the boundary conditions. Practical experience, specifically for mechanical engineering, is the reference field for setting up of adequate theories. Nevertheless, the developing machine sciences borrowed their methodical approaches from natural science. Failing self-contained methods this approach was legitimate at the time. Deductive methods and the search for closed-form solutions were the long-term objective of all attempts for scientification by Redtenbacher and his students. At the same time, it was intuitively clear to them that the path for generalization could only be followed inductively, studying the specific features of the individual case.

How should such a theory of machine science finally look, what factors had to be taken into consideration within the modelling? In general, according to the principles of Galilei, the essentials had to be distinguished from the non-essentials. For this purpose, practical judgment and experience were required. However, the main parameters for an analytical machine theory were fixed; mostly there were key economic constraints on designing a machine as related to function, weight, power and costs. In his concept of a machine theory where one had to find efficient design proportions and the choice of appropriate machine elements and materials, Redtenbacher began with design parameters which he described as functions of geometric secondary quantities. The solution of a specific dimensioning problem then arose from maximizing or minimizing the main design parameters by step-by-step elimination from the governing system of equations.

Some fruitful approaches were created but there were some limits to such a strictly composed deductive theory. Often the economic solution could not be technically realized; due to the complexity of the machine problem, simplifications had to be introduced which diminished the applicability. Furthermore, mathematical solutions existed which avoided a technical interpretation. Altogether, Redtenbacher therefore stuck to approximate approaches. The basic principle of transfer of proven traditions onto new circumstances and, in parallel, the balancing of possible factors and disturbances, was in accordance with the requirements of that time. It is to Redtenbacher's credit, that he used the "method of ratios" borrowed from architecture for mechanical engineering and cultivated it. Initiated by practical problems, Weisbach and Redtenbacher maintained the introduction and the use of technical parameters. These had the advantage of being measurable and could be calculated. The tabulation of such coefficients provided a basis to consolidate the structure of the concept of machine science and, by the permanent usage in reference books, it became the prevalent tool of the working engineer. Such practicable parameters also conveyed their theoretical background. Redtenbacher committed himself to establish non-dimensional parameters which had the advantage of being independent of specific measurements. Furthermore, such ratios were easily committed to memory and formed the intensive thinking of engineers for the correct design rules. Such a simplified machine calculation began in the first place with the geometry of motion of the mechanisms (later object of kinematics and gearings). The second step in the design process was the consideration of the strength of materials which resulted in the specification of design rules for machine elements.

Although Redtenbacher, who had a distinct appreciation for the theoretical formulation, attached great importance to their verification, he continually tried to improve them. With a view to approaching the high aims of his "Principles", at least partially, he formulated modified specific theories for special machines. For corresponding optimization problems, he even discarded the "exclusive computing method". Consequently, Redtenbacher proposed a deductive-axiomatic procedure, e.g., treating the design of hydraulic machines where he structured the calculation as follows:

1. Listing the requirements
2. Definition of the variables
3. Development of theory
4. Formulation of constraint equations maximizing a certain effect
5. Derivation of dimensioning rules
6. Consideration of constraints (noise, losses)
7. Generation of general laws for construction and operation of the machine by comparison with experiments
8. Selection of material and cost calculation

Taking into account the imperfection of the introduced ratios which were based on static principles, Redtenbacher again and again evaluated the pros and cons of approximate methods. But ultimately he had only one essential criterion of his scientific theory which was to accurately describe real conditions in a machine. The necessary simplifications of theoretical formulations led to the practical realization that these models were not precise but which were consciously accepted. But Redtenbacher did not stop with a new theory, he tried to improve it by error estimations and reflections on the neglected effects. Such a procedure sharpened his ability to deal with existing technical solutions and to judge and to estimate trends of mechanical engineering. Even today, such a procedure seems to be very modern and shows how strong his methodical thinking influenced the later theory of mechanisms and machines. But an explicit example may be difficult to find.

Contemporary "mechanism and machine theory" was originally defined within the English-speaking area as a conglomerate of machine-scientific disciplines focused on machine kinematics and only included dynamics and design in recent years. Willis seemed to advance the view of machine theory as largely kinematics, see, e.g., Moon (2003a, b)). Rankine, however, see Rankine (1887), seems to have pursued a wider vision of the theory of machines. Redtenbacher in his time, pursued by all means a very modern concept of machine science looking much more from a holistic perspective. Traditionally, constructive and technological aspects were approximate and one tried to evolute the established machine engineering into a machine science. To realize it, Redtenbacher and his students brought together kinematics and gearings as Reuleaux did, as well as strength of materials with an intensive study of the machine elements as did Bach and fluid dynamics/thermodynamics as did Weisbach, Zeuner and Stodola.

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