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# Hermann Staudinger and Polymer Research in Freiburg

**Hans-Joachim Cantow and Rolf Mülhaupt**

**Abstract** Between 1926 and 1956, Hermann Staudinger carried out his groundbreaking research on macromolecular chemistry at the University of Freiburg. He recognized that biopolymers and synthetic polymers are formed according to the same blueprint. Fighting vigorously against his numerous opponents, he established his concept of macromolecules. Since the pioneering days, his bioinspired molecular design of multifunctional polymeric materials has stimulated remarkable progress in materials science, biosciences, and engineering, accompanied by an extraordinary growth in polymer production. In 1940, Staudinger founded the Institute of Macromolecular Chemistry as the first European center for interdisciplinary polymer research. In 1999, his laboratory was honored as an International Historic Chemical Landmark dedicated to the foundation of polymer sciences. Today, macromolecular (bio)systems engineering, inspired by Staudinger's visions, plays a prominent role in sustainable development.

**Keywords** Bioinspired materials · Hermann Staudinger · History · International Historic Chemical Landmark · Macromolecule · Polymer · Polymer sciences

## Contents



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## 1 Staudinger's Laboratory as International Historic Chemical Landmark

On April 19, 1999 in Freiburg, the American Chemical Society and the German Gesellschaft Deutscher Chemiker jointly honored Hermann Staudinger's laboratory at the Albert-Ludwigs University of Freiburg as an International Historic Chemical Landmark dedicated to the foundation of polymer sciences by the Nobel laureate Hermann Staudinger (1881–1965). The goal of the landmark program of the American Chemical Society is to enhance the public's recognition and appreciation of the seminal achievements in the history of chemical sciences and chemical engineering with deep impact on society and modern life. Today, the landmark plaque (see Fig. 1), donated by the American Chemical Society, is on display at the entrance of the building "Hermann Staudinger Haus" in Stefan-Meier-Strasse 31, hosting the Institute for Macromolecular Chemistry. The institute was founded by Hermann Staudinger in 1940 as the first European polymer research center. The English translation reads:

> International Historic Chemical Landmark, Foundation of Polymer Sciences, Albert-Ludwigs-University Freiburg, State of Baden-Württemberg, 1926–1956. This building is named after Hermann Staudinger, who, between 1926 and 1956, carried out his path-breaking research on macromolecular chemistry in Freiburg. His theories on the polymer structure of fibers and plastics and his later research on biological macromolecules formed the basis for countless modern developments in the fields of materials science and bio-sciences and supported the rapid growth of the plastics industry. For his work in the field of polymers, Staudinger was awarded the Nobel Prize for chemistry in 1953 [1].

Once again, this late honor acknowledged Staudinger's remarkable courage during the 1920s, when he decided to leave the highly prestigious and safe harbor of classical organic chemistry, pushing his revolutionary but still unproven concept of macromolecules against the established doctrines of colloid chemistry and against the harsh opposition of his colleagues. Although in 1920 no experimental proof was at hand, he had postulated the existence of "high polymers," which he renamed in 1922 as "makromolekel" and "macromolecules." As first indirect experimental evidence for covalent bond formation in the polyisoprene backbone, Hermann Staudinger and Jakob Fritschi at ETH Zürich applied catalytic hydrogenation of polyisoprene. After complete hydrogenation, a highly viscous solution was retained, thus failing to produce distillable small molecules as expected for supramolecular assemblies of cyclic isoprene dimers [2]. Among his strong opponents, crystallographers favored colloidal assemblies as they were firmly convinced that large crystalline molecules could not exist because such large crystalline

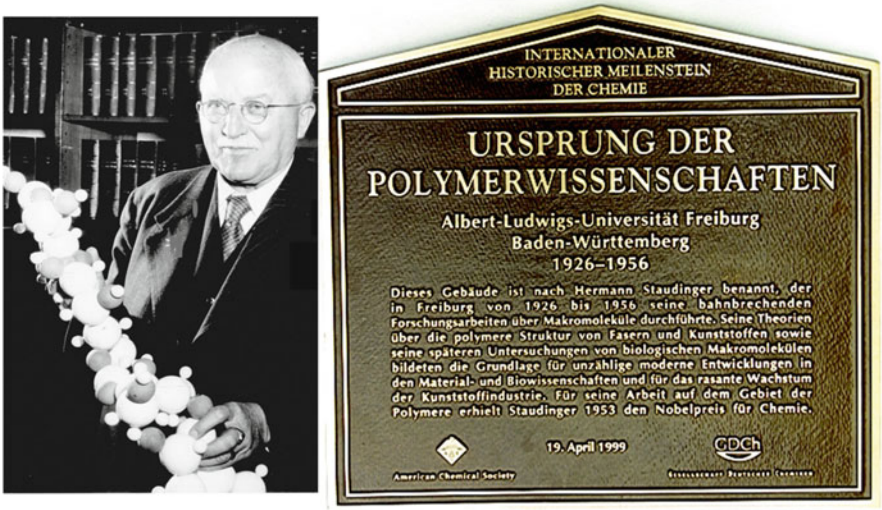


**Fig. 1** *Left*: Hermann Staudinger showing his favorite rigid rod cellulose molecule (source: University Library of the University of Freiburg). *Right*: The International Historic Chemical Landmark plaque of the American Chemical Society displayed at the entrance of the Institute of Macromolecular Chemistry in Freiburg (source: Archives of the Institute of Macromolecular Chemistry)

polymers would never fit into the extremely narrow confinement of the small crystallographic unit cell.

In 1926, Hermann Staudinger followed Heinrich Wieland and became the director of the Chemical Laboratory at the Albert-Ludwigs University in Freiburg. His relocation from Zurich to Freiburg marks a distinct transition in his science and also in his private life [3–6]. When he moved to Freiburg, Hermann Staudinger rigorously abandoned his prosperous and highly successful field of small molecule organic chemistry. Fighting tough battles with his numerous opponents, he boldly took the risk of embarking on an, at that time, uncertain journey into the stormy and dangerous seas of the emerging polymer sciences. After his divorce from his wife Dora in 1925 and his move to Freiburg, he left behind in Switzerland three daughters and one son. In 1928, he married Magda Woit, a highly cultured woman born in Latvia, who soon became his fierce and most feared ally in his never-ending struggle for macromolecules. Holding a PhD in biology and as experienced botanist, Magda Staudinger shared and encouraged his visions concerning the prominent role of polymers in biology.

When Hermann Staudinger left the Swiss democracy in 1926, he exposed himself to the political and economic turbulences of postwar Germany, that was soon followed by the Nazi tyranny of the Third Reich, which finally led to the suffering and devastating destructions during World War II. In spite of the manifold political, economic, and wartime obstacles, Staudinger made significant progress in macromolecular chemistry. Several books and reviews have addressed Staudinger's role in polymer sciences [3–11]. Today, polymeric materials prepared according to Staudinger's molecular design principle, are indispensible in daily life. At the beginning of the twenty-first century, we are living in the "Plastics Age." As highly cost-, eco-, resource-and energy-efficient materials polymers are pacemakers for the progress in modern sustainable technologies, bringing great benefits to society. Polymers secure health, mobility, communication, shelter, clothing, protection, resources, and reliable supplies of food and energy. Above all, the versatile polymeric materials with tailored property profiles render high-technology products affordable for those living in industrial and developing countries. They contribute to substantial savings in energy and resources and help meet the demands of the rapidly growing world population.

## 2 Staudinger: Pioneer of Bioinspired Chemical Research

When Hermann Staudinger moved to Freiburg, he shifted his entire research focus and thrust toward macromolecular chemistry, preparing and characterizing a wide variety of macromolecules. These included biopolymers such as cellulose, natural rubber, and chemically modified biopolymers as well as a wide variety of new synthetic polymers ranging from polystyrene and polyoxymethylene to polysilicic acid. Inspired by his close affiliation to botany, learning from nature was an integral part of his research for decades. In fact, originally Staudinger had planned to study botany. However, his father, the school teacher Franz Staudinger, advised him to study chemistry first "in order to be able to understand botanical problems better." As an organic chemist, he carefully studied nature, successfully isolated natural ingredients, identified their structure, and developed chemical syntheses for preparing them in the laboratory. This led him to the development and temporary wartime commercial use of synthetic surrogates for the flavors of pepper and roasted coffee, which were not available in Germany during World War I. Together with Leopold Ružička and Staudinger's former PhD student Tadaeus Reichstein, he identified pyrethroids as natural biodegradable insecticides produced by the chrysanthemum flower. Due to their very low mammalian toxicity, pyrethroids are in high demand today as common household insecticides. It was extremely fortunate for the polymer community that Staudinger's synthetic efforts failed to produce the appropriate stereochemistry of three-membered ring in the pyrethroid structure, thus enabling him to move to new horizons and pioneer macromolecular chemistry.

It was Hermann Staudinger who recognized that biopolymers and synthetic polymers are assembled according the same blueprint, linking together a huge number of small monomer molecules by covalent bond formation. This approach toward bioinspired research and molecular bionics was revolutionary, because at that time the formation and properties of natural and synthetic polymers were thought to be vastly different. In Staudinger's view, synthetic polymers represent excellent model systems for achieving a better understanding of biopolymers and the much more complex biosystems. In 1927, jointly with Gustav Mie, the Freiburg physicist and expert in scattering and X-ray diffraction, he published his research on "the polymeric formaldehyde, a model for cellulose" [12]. This highly successful interplay of polymer chemistry and physics in Freiburg clearly demonstrated that purely synthetic polymers can form fibers that resemble natural fibers. At that time, fiber formation was thought be an exclusive domain of biopolymers and living organisms such as spiders. Without any doubt, this paradigm shift in scientific conception has stimulated the development of synthetic fibers, as started by Wallace Carothers, who during the 1930s pioneered synthetic polyamide and polyester fibers at Du Pont. Staudinger's bioinspired molecular polymer design opened a new dimension for the development of advanced polymeric materials in chemistry and biotechnology, going well beyond the scope of the purely "trial-and-error" development typical of the very early days of polymer technology. Moreover, the insight that he gained into the crystallization behavior and crystal structure of polyoxymethylene clearly proved that only a very small section of the polymer chain is allocated in the crystallographic unit cell of a crystalline polymer. At the end of the 1920s, crystallographers gave up their opposition and vividly engaged themselves in polymer research.

In Freiburg, Giulio Natta from the Polytecnico di Milano, Italy, learned how to use the tool of crystallography, This new experience was essential to his research when he identified the molecular architecture of isotactic polypropylene. In his Nobel speech, in 1963, Giulio Natta stated [13]: "After I had the luck to meet Professor Staudinger in Freiburg in 1932, I was attracted by the study of linear high polymers and tried to determine their lattice structures. To this end I also employed the electron-diffraction methods which I had learned from Dr. Seemann in Freiburg and which appeared particularly suitable for the examination of thin-oriented films. I applied both X-ray and electron-diffraction methods also to the study of the structure of the heterogeneous catalysts used for certain important organic industrial syntheses." Staudinger is the father of macromolecular chemistry, but he also is the pioneer of bioinspired chemistry and molecular bionics [14].

## 3 Staudinger's Viscosity Law

In the pioneering days, an important shortcoming hampered the progress in polymer sciences, which was the lack of methods for molecular weight determination. Staudinger's solution viscosity measurements were prone to be sensitive to the molecular weight of polymers, solvent interaction, and to formation of colloidal aggregates. Significant progress was made in 1926 when Svedberg and Fåhraeus developed the ultracentrifugation technique for protein characterization. They measured the equilibrium sedimentation of hemoglobin [15]. This research afforded clear experimental proof for the existence of high molecular weight proteins.

In 1929, Staudinger tried to bring an ultracentrifuge to Freiburg. However, his proposal was rejected by the Notgemeinschaft der Deutschen Wissenschaft, the precursor of the Deutsche Forschungsgemeinschaft (DFG). Therefore, he intensified his efforts, aiming at finding a correlation between molecular weight and the viscosity of non-spherical colloid particles. He tried to adapt Einstein's viscosity law, established for spherical particles, to polymer chains. This led him to a relationship that became known as the Staudinger law, correlating the polymer molecular weight with the specific viscosity of dilute solutions, and extrapolating it to infinite dilution ("Staudinger index" or intrinsic viscosity) [16]. Using a calibration with polymer samples of known molecular weight, it became possible to estimate the molecular weight. This concept was refined by Kuhn, Mark, Houwink and others, who substantially improved this correlation. Today, this correlation is known as the Mark–Houwink and also as the Kuhn–Mark–Houwink–Sakurada equation. This valuable and robust viscosimetry technique is still in use today in academia and industry. It is well known as very reliable and facile method for molecular weight determination. Unlike ultracentrifugation and gel permeation chromatography, no costly investment is needed. Moreover, using this method it was possible to distinguish between spherical and rod-like conformations of macromolecules in solution. It should be noted that Staudinger clearly favored a rod-like fully stretched polymer conformation, resembling a Mikado stick (see Fig. 1). In his view, highly ordered polymers rather than spaghetti-like random-coil polymers account for the specific functions of polymers in nature. For many years and also for other reasons, he heavily opposed Werner Kuhn and Hermann F. Mark, who pushed forward the concept of random-coil polystyrene. A detailed description of the dispute between Staudinger, Mark, and Meyer concerning the size and shape of macromolecules is given by Priesner [4]. During his "habilitation" in Staudinger's laboratory, in the 1930s, Günter Victor Schulz introduced osmometry as an accurate measurement for molecular weights.

## 4 Imaging of Single Macromolecules

In Freiburg the Staudinger group successfully made early attempts at characterizing the morphology of polymers using ultraviolet phase contrast microscopy and also transmission electron microscopy (TEM), which was invented in 1931 by Max Knoll and Ernst Ruska. It was Magda Staudinger who started research on microscopic imaging of polymers in Freiburg during the late 1930s. In 1940, Elfriede Husemann in collaboration with Helmut Ruska, working at the laboratory of electro-optics of Siemens & Halske AG, successfully employed TEM to visualize a single spherical glycogen macromolecule with molecular weight of around 1.5 million, as determined by osmosis, and an average diameter of 10 μm [17].

They achieved substantial improvement of contrast when they examined the *p*-iodobenzoyl derivative of glycogen with a much higher molecular weight of six million. From the molecular weight, using the Einstein viscosity law, they calculated an average diameter of the *p*-iodobenzoyl glycogen macromolecule to be 30 μm, which is in remarkably good accordance with the diameter measured by

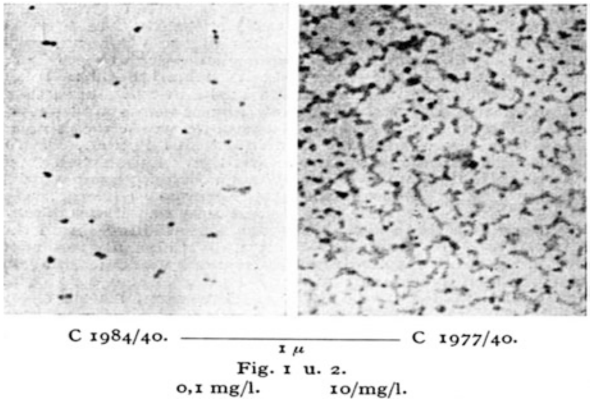


**Fig. 2** Visualization of a single *p*-iodobenzoyl-modified glycogen molecule of six million molecular weight and its supramolecular assembly at elevated concentration (Husemann and Ruska [18], with permission of Springer)

TEM (see Fig. 2) [18]. Although single glycogen molecules were detected only at low concentration, supramolecular assemblies of glycogen macromolecules were observed upon increasing the glycogen concentration. This exciting ground-breaking research came to an abrupt end when Staudinger's laboratory was destroyed by bombing in 1944. In 1964, Bittiger together with Husemann published fascinating microscopic images of cellulose tricarbanilate single molecule single crystals [19].

## 5 Hermann Staudinger and the Third Reich

As probably the only German chemist during World War I, Staudinger publically opposed the use of poisonous gas as a chemical weapon of mass destruction and even proposed to the German High Command to stop the war because of the imbalance of power when the overwhelming US military and economic power joined the allied war effort. Many Germans questioned Staudinger's loyalty and accused him of anti-German sentiments. Hence, members of the selection committee of the University of Freiburg visited him in Switzerland, thoroughly checking on his patriotism and national spirit before accepting him as candidate. Details on Staudinger's experience with German politics and his difficult time in the Third Reich are reviewed by Priesner [5]. It should be noted that both Staudinger's father and brother and his first wife had very close left-wing political affiliations. Staudinger's younger brother Hans, who was an economist and Social Democrat member of the German Reichstag 1932–1933, opposed the Nazis and was arrested. He managed to escape from Germany in 1933 and became a professor of economics at the New School for Social Research in New York City. Hence, it is not surprising that Staudinger was not considered a trustworthy follower of the Nazi movement.

Shortly after the Nazis seized power in 1934, the Dean of Freiburg University and famous philosopher Martin Heidegger, new member of the Nazi party and at that time deeply impressed by the Nazis, denounced Hermann Staudinger. He proposed the immediate dismissal of Hermann Staudinger by claiming without any proof that Staudinger would be an opponent and was only pretending in public to support the Nazi movement [15]. Staudinger was summoned by the secret police (Gestapo) and questioned for many hours. They forced him to sign his own dismissal request without dating it, threatening him that they would immediately seize him as soon as he opposed the regime. The Nazis imposed on him a ban on foreign travel, which massively disabled his scientific activities. Staudinger understood this clear message. In public he demonstrated his obedience and his Nazi-conforming attitude. However, his application for Nazi party membership was rejected. Although Staudinger tried hard to acquire the reputation of an anti-Semite, expressing his concerns about the presence of too many non-Aryans in academia, in his institute he helped his half-Jewish assistants like Gerhard Bier to survive. He pointed out to the Nazi government their important contributions to the German war effort, thus enabling them to carry on their work in his institute. Among others, Hermann Staudinger's coworker Elfriede Husemann also suffered under the Nazi rule. Her career was delayed on purpose because the Nazis saw the primary role of women in motherhood but not in academic careers [20]. On November 27, 1944 the Allied bombing destroyed a large part of the city of Freiburg, including Staudinger's laboratory and the entire chemical laboratory. Although his institute was rebuilt, the difficult situation and shortages typical of the German postwar period severely impaired Staudinger's research.

## 6 Staudinger and His Institute of Macromolecular Chemistry

For many years, Staudinger's macromolecular chemistry was an unloved and alien daughter of organic chemistry. Since most industrial polymers have fairly broad molecular weight distributions and frequently ill-defined composition, comprising complex multicomponent and multiphase systems, most hard-core organic chemists considered polymer chemistry to be *Schmierenchemie* (goo chemistry). Soon, Hermann Staudinger realized that a new platform was in urgent need to foster interdisciplinary research on polymer sciences, train students, and communicate research results. In 1940, Staudinger founded the Institute of Macromolecular Chemistry in Freiburg as the first European research center devoted exclusively to research on polymer sciences. At the beginning, his institute was embedded in the organic chemistry department, but became an independent research institution of the state of Baden in 1945. Then, in 1956, it was integrated as an independent institute into the University of Freiburg. Figure 3 shows an artist's contemporary view of a Staudinger laboratory in the 1950s.

**Fig. 3** Staudinger's chemistry laboratory in the 1950s (lithography by the artist Helmut Philipp, property of R. Mülhaupt)

Many of Staudinger's students took the lead in industrial polymer research, among them prominent directors like Adolf Steinhofer at BASF AG, Hans Batzer at Ciba-Geigy AG, Gerhard Bier at Hoechst AG, and Ernst Trommsdorff at Röhm & Haas AG. When the University of Mainz was founded after World War II, the two chairs of physical and of organic chemistry were taken by G.V. Schulz, who did his habilitation in Freiburg, and by Werner Kern who was a former Ph.D. student of Hermann Staudinger. Later, two other former Staudinger students joined the Mainz faculty, namely Helmut Ringsdorf and R.C. Schulz. In an early version of a public–private partnership, Staudinger rallied prominent representatives and research directors of polymer industries in an association (Förderverein für Makromolekulare Chemie e.V.), supporting and advising the activities of Staudinger's institute in Freiburg.

In order to communicate polymer research results, Staudinger founded the first polymer journal, *Journal für Makromolekulare Chemie* (*Journal of Macromolecular Chemistry*), in 1943 as a new branch of the *Journal für praktische Chemie* (*Journal for Practical Chemistry*), for which he had served as the editor-in-chief since 1939 with the Barth publishers in Leipzig, Germany. In the postwar time, at the beginning of the cold war, Freiburg in the French zone, was cut off from access to East Germany, which was occupied by the Russian army. Therefore, Staudinger's journal was published under the new name of *Die Makromolekulare Chemie* (*Macromolecular Chemistry*) by the publishers Wepf & Co. in Basel, Switzerland. Today this journal is renamed *Macromolecular Chemistry and Physics* and, together with a family of sister journals, is published by Wiley. In several textbooks published by Staudinger, among them the "bible" of polymer chemistry entitled *Makromolekulare Chemie und Biologie* (*Macromolecular Chemistry and Biology*) [21], are taught the basic principles of polymer sciences, serving for decades as an entry to the fascinating world of macromolecular chemistry.

**Fig. 4** Hermann Staudinger and his successor Elfriede Husemann (source: Archives of the Institute for Macromolecular Chemistry, Freiburg)

In 1950, Staudinger opened his internal macromolecular colloquium to the public, converting it into a national polymer conference. Since then his "Makromolekulares Kolloquium" has turned into one of the largest European polymer conferences, held annually in the last week of February and attracting around 800 participants. In 1951, he retired from the University of Freiburg, was followed by Arthur Lüttringhaus in organic chemistry, but remained the managing director of his independent Institute for Macromolecular Chemistry until 1956. All his attempts to bring a Max Planck Institute for polymer research to Freiburg had failed. Hence, he was somewhat frustrated when he retired. Known for his very strong personality and his extremely low level of tolerance regarding opinions deviating from his own, Staudinger's rule in the institute and the chemical laboratory resembled that of an ancient warlord.

In the aftermath of Staudinger's Nobel Prize of 1953, his successor Elfriede Husemann (affectionately called "Husefrau") was awarded the new chair for macromolecular chemistry, which was installed in 1956 when the institute was finally reintegrated into the University of Freiburg. In contrast to Staudinger, Husemann was open-minded, accepting and responding to different views from different people and different scientific disciplines. In 1962, under her leadership, the institute moved to a new building located in the nearby Stefan-Meier-Strasse 31. Figure 4 shows Elfriede Husemann, who was a passionate motorcyclist, driving together with Hermann Staudinger in front of the the new building of macromolecular chemistry, which was undergoing construction during the early 1960s. On September 8, 1965, Hermann Staudinger passed away and is buried in the central cemetery of Freiburg (see Fig. 5).


**Fig. 5** The grave of Hermann and Magda Staudinger in Freiburg

## 7 Staudinger's Visions Toward (Bio)System Integration

In his Nobel lecture on December 11, 1953 [6] Hermann Staudinger stated [22]: "With a few bricks it is impossible to erect a great variety of buildings; nevertheless, provided that 10,000 or 100,000 bricks are available it is quite possible to construct the most diverse buildings, . . . The existence of macromolecules and the steadily deepening knowledge of their properties have revealed the nature of the building units which the living cell requires to create matter". .. Today his vision is inspiring many researchers in chemistry, materials science, and biotechnology to tailor multifunctional polymeric materials with complex functions and architectures. Hermann Staudinger concluded his Nobel speech with the statement [22]: "In this way macromolecular chemistry appears today to fit between low molecular organic chemistry and cytology. It is the connecting link between them, growing systematically out of low molecular chemistry but, with the incomparably larger wealth of its chemical scope, forming living matter. ... In the light of this new knowledge of macromolecular chemistry, the wonder of Life in its chemical aspect is revealed in the astounding abundance and masterly macromolecular architecture of living matter". Going well beyond the scope of tailoring single macromolecules, Hermann Staudinger has foreseen the unique opportunities of the emerging macromolecular systems engineering, which is not at all restricted to biosystems. Advanced synthetic, biological, and biohybrid polymer systems can be tailored to exhibit features typical for living organisms such as sensing, recognition, learning, stimuli-response, adaptation, energy autonomy, self-assembly, self-healing, and even self-replication. Although polymer sciences and engineering has more than just one father, Hermann Staudinger has successfully created inspiring visions that will continue to stimulate progress in science and technology for many years to come.

## 8 The Days After Hermann Staudinger in Freiburg

The history of the Institute of Macromolecular Chemistry and polymer research in Freiburg reflect the growth and paradigm shift in polymer science and engineering and the impact of individual researchers. The gallery of the research directors and today's collaboration partners from other faculties is displayed in Fig. 6. Originally, polymer properties were varied by tailoring single macromolecules through varying monomeric units, chain length, and shape of polymer chains. In the second half of the twentieth century, polymer properties were tuned via controlled nanostructure formation in bulk and at surfaces, exploiting assembly of macromolecules at interfaces, controlled nanostructure formation, and functional processing. In the early days of polymer sciences, the search for surrogates of natural materials such as silk, ivory and the strategically important natural rubber had claimed top priority, exploiting predominantly biobased raw materials such as carbohydrates.

Under the leadership of Elfriede Husemann (1956–1974), whose special field of research expertise was carbohydrate chemistry with a focus on starch and glycogen research, Freiburg became an "Eldorado for polysaccharide chemistry" [20, 23]. As an excellent organizer and manager, Elfriede Husemann substantially broadened the horizon of polymer research in the Institute, bringing together the fields of polymer chemistry with biopolymers, physical chemistry, and modern electron microscopy. In 1962, the new building significantly improved the polymer research facilities in Freiburg (Fig. 7). Her student and coworker Beate Pfannemüller became a distinguished female scientist in starch research, well known for her contributions such as the enzymatic synthesis of amylose [20]. Another student and coworker of Elfriede Husemann was Walter Burchard, who in 1956 introduced static light scattering and in 1978 dynamic light scattering. He made significant progress towards a better understanding of the conformation of linear and branched polymers as well as gelation [24].

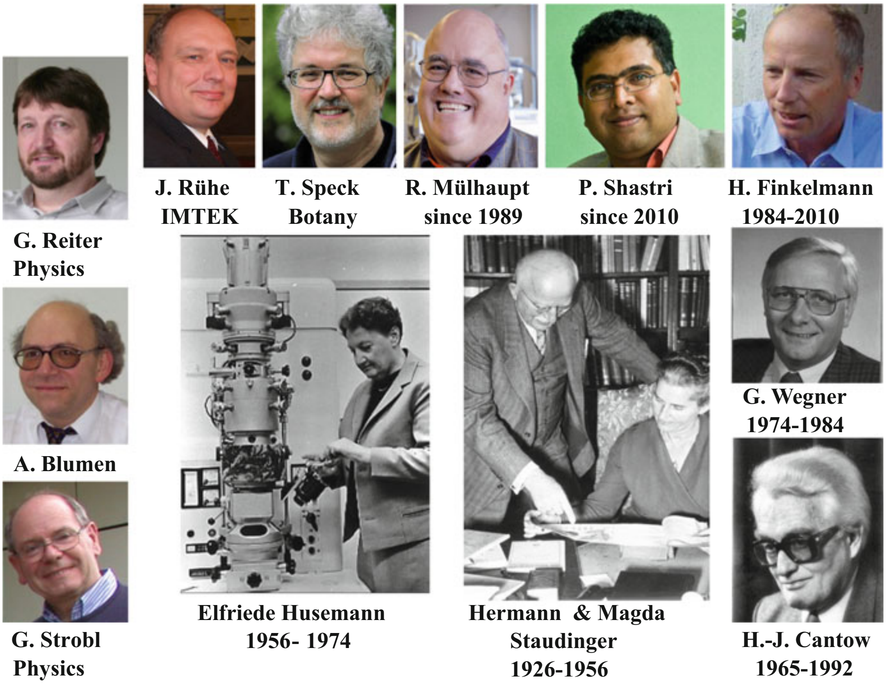


**Fig. 6** The research directors of the Institute of Macromolecular Chemistry and their partners in physics, microsystems engineering (IMTEK) and the Freiburg Botanic Garden

**Fig. 7** The Institute of Macromolecular Chemistry (*left*), the Freiburg Materials Research Center, FMF (*center*) and the new Freiburg Institute for Interactive Materials and Bioinspired Technologies (FIT), which is currently under construction

In 1965, Hans-Joachim Cantow, at that time a young industrial chemist at Chemische Werke Hüls (now Evonik) who had just completed his habilitation at the University of Mainz, took the new chair of physical chemistry of macromolecules. Since then, the Institute has had two directors. Going beyond the traditional polymer characterization methods, Hans-Joachim Cantow introduced supraconductive nuclear magnetic resonance spectroscopy, pyrolysis–gas chromatography, thermodynamic approaches, rheology, element-specific transmission electron microscopy, environmental scanning microscopy, scanning tunneling microscopy, and atomic force microscopy, thus enabling new insights into the role of nanostructure formation in multiphase polymers and blends. Surfaces and interfaces were studied not only in macromolecular, but also in inorganic crystalline systems. Besides model polymers, stereocomplexes and amphiphilic block copolymers, thermoreversible elastomers containing cellulose and donor-acceptor groups were synthesized, and their structure–property interplay studied. In cooperation with colleagues in the "regio basiliensis," Cantow started the regio symposia and founded the "Graduiertenkolleg Polymerwissenschaften" (Graduate Training Program in Polymer Sciences). He was assisted by Hans-Adam Schneider and Wolfram Gronski. In 1974, Gerhard Wegner followed Elfriede Husemann, shifting the focus of the Freiburg polymer research from carbohydrate chemistry towards self-assembly of functional macromolecular materials, conducting polymers, hairy rod polymers, formation of ultrathin layers, and topochemical polymerization in single crystals [25]. This marked the beginning of the new age of advanced macromolecular materials and systems.

After Gerhard Wegner had left Freiburg to become the co-founder and director of the Max Planck Institute for Polymer Research in Mainz, Heino Finkelmann joined the Institute in 1984. In his research, Heino Finkelmann successfully combined the anisotropy of liquid crystals with the viscoelasticity of polymers [26]. This led him to the discovery of new generations of liquid crystalline elastomers, tunable lasers, and stimuli-responsive "smart" macromolecular materials.

In view of the increasing demand for advanced polymeric materials and bioengineering in regenerative medicine, Prasad Shastri from Vanderbilt University in Nashville, USA, followed Heino Finkelmann in 2010 as director of the Institute, professor of biofunctional macromolecular chemistry and cell signaling environments, established jointly with the Center for Biological Signalling Studies (BIOSS). In the emerging field of health sciences and nanomedicine, his research focus is placed upon bioactive macromolecular systems and bioengineering.

In 1990, initiated by Hans-Joachim Cantow, the Freiburg Materials Research Center (FMF; Fig. 7) was founded as a resource center of the University of Freiburg, serving as a highly dynamic platform for interdisciplinary and interfaculty research on new materials, technologies, and advanced systems. In the FMF, research groups from chemistry, physics, biology, earth and environmental sciences, medicine, and microsystems engineering work together. The FMF technology laboratories substantially expanded the Freiburg polymer research in the field of functional processing and technology, ranging from extrusion and injection molding to 3D printing and scale-up of specialty polymers. In 1989, Rolf Mülhaupt, who for several years had worked in industry at Du Pont/USA and Ciba-Geigy AG/Switzerland, joined the University as professor for macromolecular chemistry and followed Cantow in 1992 as director of the Institute of Macromolecular Chemistry and as the managing director of the Freiburg Materials Research Center. In his research, Rolf Mülhaupt combined polymer chemistry and polymerization catalysis with polymer processing and polymer technology. Under the roof of the FMF, jointly with the Institute of Macromolecular Chemistry, a team of scientists from different faculties has built the Freiburg chain of knowledge spanning from synthetic polymer chemistry and polymerization catalysis to polymer physics, nanotechnology, bionics, biobased plastics, and processing. Today an important focus of applied polymer research in FMF is placed upon the development of sustainable materials for applications in lightweight engineering, energy technology, medicine, and microsystems technology.

Inspired by Staudinger's vision concerning macromolecular system engineering and macromolecular biometics, the new Freiburg Center for Interactive Materials and Bioinspired Technologies (FIT) was founded in 2010. A new research building will be completed by 2015 at the campus of the University of Freiburg near Freiburg airport (Fig. 7). The primary research objectives of FIT include the development of adaptive and responsive macromolecular materials and surfaces, biobased and biomimetic materials and their biosystem integration, as well as advanced embedded energy autonomous microsystems, which do not require external power supply because they contain built-in power harvesting and storage.

During Staudinger's era, the Institute of Macromolecular Chemistry was just an isolated tiny island hidden in the organic chemistry department. In the days after Hermann Staudinger, the Institute of Macromolecular Chemistry has been turned into a world-class polymer research center. Today, interdisciplinary polymer science and engineering have top priority at the University of Freiburg, creating a unique interdisciplinary and interfaculty research environment for basic and applied polymer sciences by bridging the disciplines of chemistry, physics, biology, medicine, and microsystems engineering. Since the mid-1980s, several chairs have been established in other faculties. These include the chairs of experimental polymer physics (Gert Strobl, 1985–2006, followed by Günter Reiter in 2008) and theoretical physics (Alexander Blumen since 1991) in the Faculty of Mathematics and Physics, as well as the chairs for chemistry and physics of surfaces and interfaces (Jürgen Rühe since1999) and process technology (Holger Reinecke since 2004) in the Department of Microsystems Engineering (IMTEK) of the Engineering Faculty. Polymer sciences also play a prominent role in bionics research (Thomas Speck, professor of botany, functional morphology, and bionics in the Faculty of Biology, and director of the Botanic Garden of the University of Freiburg since 2006). The aspects of forestry-based biomaterials and bioresources are addressed by Marie-Pierre Laborie, who holds a chair of forest biomaterials in Faculty of Environment and Natural Resources. Inspired by nature, the focus of the interdisciplinary polymer research at The University of Freiburg is placed upon the sustainable development of highly energy- and resource-efficient multifunctional polymeric materials for modern technologies.

The unique polymer research environment in Freiburg has stimulated scientific achievements in top-notch polymer research. Moreover, it has motivated and enabled numerous young scientists to start a successful career in industry and academia, among them German professors like Günter Victor Schulz (Mainz), Werner Kern (Mainz), Rolf C. Schulz (Mainz), Helmut Ringsdorf (Mainz), Gerd Greber (Vienna), Ernst G. Klesper (Aachen), Hartmut Seeliger (Ulm), Hans R. Kricheldorf (Hamburg), Walther Burchard (Freiburg), Manfred Hallensleben (Hannover), Claus Eisenbach (Stuttgart), Reimund Stadler (Bayreuth), Martin Möller (Aachen), Robert Schuster (Hannover), Alfred Saupe (Halle), Jörg Kressler (Halle), Walter Richtering (Aachen), Kai Saalwächter (Halle), Claudia Schmidt (Paderborn), Bernd Tieke (Bonn), Jörg Tiller (Dortmund), Holger Frey (Mainz), Stefan Mecking (Konstanz), Rainer Haag (Berlin), and Sabine Ludwigs (Stuttgart).

In Staudinger's time, Freiburg was isolated in the outmost southwestern corner of Germany, close to the borders of France and Switzerland, which were impermeable during war times. Today, Freiburg is located in the heart of Europe, without any restrictions by frontiers between the adjacent countries. The upper Rhine valley is the trinational region of the neighboring cities of Basel in Switzerland, Freiburg in Germany, and Strasbourg in France, forming an European high-tech triangle in academia and industry with one the highest densities of top-notch research in chemistry, polymer sciences, and life sciences. There are many very close interactions between Swiss, French, and German polymer research groups, owing to the highly complementary expertise in polymer sciences and the very close proximity of Basel, Strasbourg, and Freiburg, which enables an exchange of students and staff even on a daily base. In 2010, the International Research Training Group "Soft Matter Science – Concepts for the Design of Functional Materials," funded by the Deutsche Forschungsgemeinschaft, was established to promote international graduate training and research on advanced macromolecular materials and systems.

In 2013, the universities of Strasbourg and Freiburg started a joint master degree training program in polymer sciences, paralleled by the new national master degree program in Freiburg, entitled "Sustainable materials – polymer sciences," as well as the master degree in chemistry with specialization in macromolecular chemistry. At the University of Freiburg, the unique training and research environment in polymer sciences is built upon the chain of knowledge in polymer sciences and engineering. Interdisciplinary research combined with multicultural training is the prerequisite for creating innovations and for achieving significant progress in the emerging field of macromolecular (bio-, micro-) systems engineering. This is essential for the sustainable development of advanced functional materials with high energy- and resource-efficiency and of modern technologies to meet the urgent needs of the growing world population.

## References

1. American Chemical Society International Historic Chemical Landmarks (2013) Foundations, foundations of polymer science: Hermann Staudinger and macromolecules. http:/portal.acs.org/portal/PublicWebSite/education/whatischemistry/landmarks/staudingerpolymerscience/index.htm. Accessed 7 July 2013
2. Staudinger H, Fritschi J (1922) Über die hydrierung des kautschuks und über seine seine Konstiution. Helv Chim Acta 5:785
3. Jostkleigrewe E (ed) (1987) Makromolekulare chemie – das werk Hermann Staudingers in seiner heutigen Bedeutung, Katholische Akademie Freiburg. Schnell & Steiner, Munich and Zürich

4. Priesner CC, Staudinger H, Mark H, Meyer KH (1980) Thesen zur Größe und struktur der makromoleküle. Ursachen und hintergründe eines akademischen disputs. Weinheim, Verlag Chemie
5. Priesner CC (1987) Hermann Staudinger und die makromolekulare Chemie in Freiburg. Dokumente zur Hochschulpolitik 1925–1955. Chem Unserer Zeit 21:151–160
6. Staudinger H (1961) Arbeitserinnerungen. Dr. Alfred Hüthig, Heidelberg
7. Deussing G, Weber M (2012) Life and work of Hermann Staudinger (Part 1,2,3,4), K International trade fair for plastics and rubber, Düsseldorf. http://www.k-tradefair.com/cgi-bin/md_k/custom/pub/content. Accessed 17 July 2013
8. Ringsdorf H (2004) Hermann Staudinger and the future of polymer research jubilees—beloved occasions for cultural piety. Angew Chem Int Ed 43:1064–1076
9. Mülhaupt R (2004) Hermann Staudinger and the origin of macromolecular chemistry. Angew Chem Int Ed 43:1054–1063
10. Morawetz H (1985) Polymers-the origins and growth of a science. Wiley, New York
11. Furukawa Y (1998) Staudinger, carothers, and the emergence of macromolecular chemistry. University of Pennsylvania, Philadelphia
12. Staudinger H, Johner H, Signer R, Mie G, Hengstenberg J (1927) Der polymere Formaldehyd, ein Modell der Cellulose. Z Prakt Chem 126:425
13. Nobelprize.org (1964) Hermann Staudinger – Nobel lecture: macromolecular chemistry. In: Nobel lectures, chemistry 1942–1962. Elsevier, Amsterdam. Accessed 14 July 2013
14. Mülhaupt R (2010) Bioinspired macromolecular chemistry—paying tribute to the pioneering advances of Hermann Staudinger and Helmut Ringsdorf. Macromol Chem Phys 211:121–126
15. Svedberg T, Fåhraeus R (1926) A new method for the determination of the molecular weight of the proteins. J Am Chem Soc 48:430–438
16. Staudinger H (1933) Viscosity investigations for the examination of the constitution of natural products of high molecular weight and of rubber and cellulose. Trans Faraday Soc 129 (140):18–32
17. Husemann E, Ruska H (1940) Versuche zur sichtbarmachung von glykogen molekülen. J Für Praktische Chem 156:1–10
18. Husemann E, Ruska H (1940) Die Sichtbarmachung von Molekülen des p-Jod-benzoyl-glycogens. Naturwissenschaften 28:534
19. Bittiger H, Husemann E (1964) Elektronenmikroskopische Abbildung von Einmolekülkristallen bei Cellulosetricarbanilaten. Macromol Chem Phys 75:222–224
20. Mischnick P (2005) Zum Beispiel Beate Pfannemüller. Nachrichten aus der Chem 53:1076–1078
21. Staudinger H (1947) Makromolekulare chemie und biologie. Wepf, Basel
22. Nobelprize.org (1972) Giulio Natta – Nobel lecture: From the stereospecific polymerization to the asymmetric autocatalytic synthesis of macromolecules. In: Nobel lectures, chemistry 1963–1970. Elsevier, Amsterdam. http://www.nobelprize.org/nobel_prizes/chemistry/laureates/1963/natta-lecture.pdf. Accessed 7 July 2013
23. Zugenmeier P (2009) Contribution to the historical development of macromolecular chemistry – exemplified on cellulose. Cellulose Chem Technol 43:351–378
24. Huber K, Richtering W, Schmidt M (2005) Tribute to Walter Burchard. Macromolecules 38:5857–5858
25. Spiess HW (2000) Gerhard Wegner. Adv Mater 12:249–250
26. Komb A, Sanchez-Ferrer A, Severing K (2010) Heino Finkelmann: 65 years of devotion to science. Macromol Chem Phys 211:373–374

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