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Contributions and support by more than 130 professors of polymer science in Germany, as well as industry representatives, scientific divisions and professional societies.

GDCh
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preface

The task of this white paper on polymer research is to contribute towards shaping and promoting of the research field and to draw attention to the expansion and integration of other sub-fields to one large scientific field of "Molecular Materials and Polymer Science", which has already been initiated. The authors are convinced that this is one of the most exciting and most influential scientific fields of the 21st century. However, due to its interdisciplinary interconnection its advancement is a challenge for universities and research institutes but also for future development of competitive support structures.

Rapidly developing integration of the research and lecture field of polymer science and other scientific areas with regard to molecular materials are the starting point. The appreciation of the research field in public and by the German research organisations does not go in line with its fundamental and technological importance. At the same time, the reputation of our research suffers from the prevalent concerns about health-related and ecological burdens, which are legitimate in individual cases (e.g., plastic waste). The white paper is not problem-oriented but intended to point out the major scientific changes and technological opportunities in a future-oriented manner. The variety and organic nature of (macro-)molecular materials opens up sustainable and ground-breaking perspectives, in particular in areas where developments are majorly triggered by the availability and mastery of material categories. The symbiosis of man-made material technology and nature that is possible with these kinds of materials is focussed on two aspects, (i) new and better performance with lower resource input and (ii) integration into our natural environment and closed cycles. In essence, the future developments of the research field will deal with control of the properties and generation of complex, hierarchically structured materials as a basis for novel products and process developments, on the one hand, and with understanding of the transition from dead to live matter as a special, fundamentally scientific challenge, on the other hand.

The verbalised future perspectives are first and foremost addressed to scientists, with the goal of promoting interdisciplinary cooperation and convergence but also to associations, the media, as well as funding agencies and supporters to illustrate the general importance of the progress perspectives on a larger scale.

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Part I: Synopsis and recommended actions

Taking H. Staudinger's concept of macromolecules (Nobel Prize in 1953 "for his discoveries in the field of macromolecular chemistry", Freiburg) as a basis, unique, world-changing scientific discoveries and technologies were developed. This is closely related to explosive increase of knowledge but also in-depth specialisation and diversification of the sciences that deal with different aspects of (soft) molecular matter. In this way, a number of scientific schools were formed, that are guided by synthetic macromolecules as polymer sciences, on the one hand, and research of the function and application of biomacromolecules as part of life sciences, on the other hand. The driver for this specialisation firstly was the unparalleled technical success of plastics, paints, elastomers, functional polymers and composite materials, and secondly the ground-breaking developments with regard to the molecular understanding in life sciences.

The significance of polymers is generally attributed to their structural properties and their use as materials. Through the last decades, the group of functional polymers and polymer-based additives has gained more and more importance. For example, approximately 20% of the BASF sales are due to plastics but more than 50% of the BASF products contain macromolecules or are largely based on macromolecules. The economic importance of polymers is even more significant with regard to the end products. The progress in connection with biomacromolecules is due to clarification of the interconnection of structural, functional and information properties but also increasingly allows for new synthetic approaches (cue: synthetic biology).

With regard to the capability of molecular storage and transfer of information, the synthetic macromolecules lag far behind despite the great progress in accurate synthesis. Polymer scientists have started systematically dealing with these challenges. The most important key words are: Supramolecular chemistry, self-assembly and the transfer from molecule to functional systems. While control of equilibrium-driven processes is frantically developed further and has meanwhile been incorporated in technical applications for materials from the field of materials, life, and bio-sciences, other aspects that are required for development of adaptive molecular systems are still at the very beginning. This refers to switchability through external influences, among others, as is required for future-oriented concepts, such as self-healing, reversible and switched changes in shape or for biomimetic robotics. Many aspects of these systems, also referred to as 4D materials (3D of space, 1D of time) are still in their infancy. Concepts for self-regulation, targeted adaptation in complex sensoric maps or even for "learning materials" are largely unknown. The background for these developments, that are sometimes also referred to as "bioinspired materials engineering", is our increasing capability and understanding of cross-scale correlations and handling thereof. The expression "cross-scale" refers to the spatial dimensions from molecules to components, on the one hand, and to time scale-dynamic processes of less than a pico second up to years, as well as the reach and cooperativity of the interactive forces. These are topics that are intensely worked at in the field of soft matter physics. For knowledge- and understanding-oriented research the result is that the underlying complexity of deterministic clarification of the structure-property relationships poses certain limits and may lead to emergent properties and meta material effects in extreme cases and thus represent a special scientific challenge. The critical phenomena already reveal that collective interaction of many units may result in behaviour of novelty quality. Such aspects are also considered central for understanding of collective non-equilibrium phenomena.

Development of unique (quantitative) structure-property relationships increasingly reaches its limits, also for polymer materials that seem to be simple at first glance. In this context, it is mainly the complex modifications and the resulting new morphologies or heterogeneities occurring during processing and under load that counteract development of universal structure-properties relationships. In addition, the materials should also be suitable for targeted modification, even after processing. Therefore, the aim should be a molecularly informed structure-process-properties control that, upon correct use, makes modifications of polymer materials predictable and thus controllable.

Consequently, management of the complexity of synthetic macromolecular materials, composites and functional units represents a challenge for chemists, physicists and engineers alike, that spans the entire field of research. Methodological key elements are further development of physical characterisation methods and handling of very detailed information, in addition to chemical synthesis. This particularly involves the capability for simulation of cross-scale structures and processes throughout the entire cycle, from material formation, its function and ageing through to metathesis for new applications.

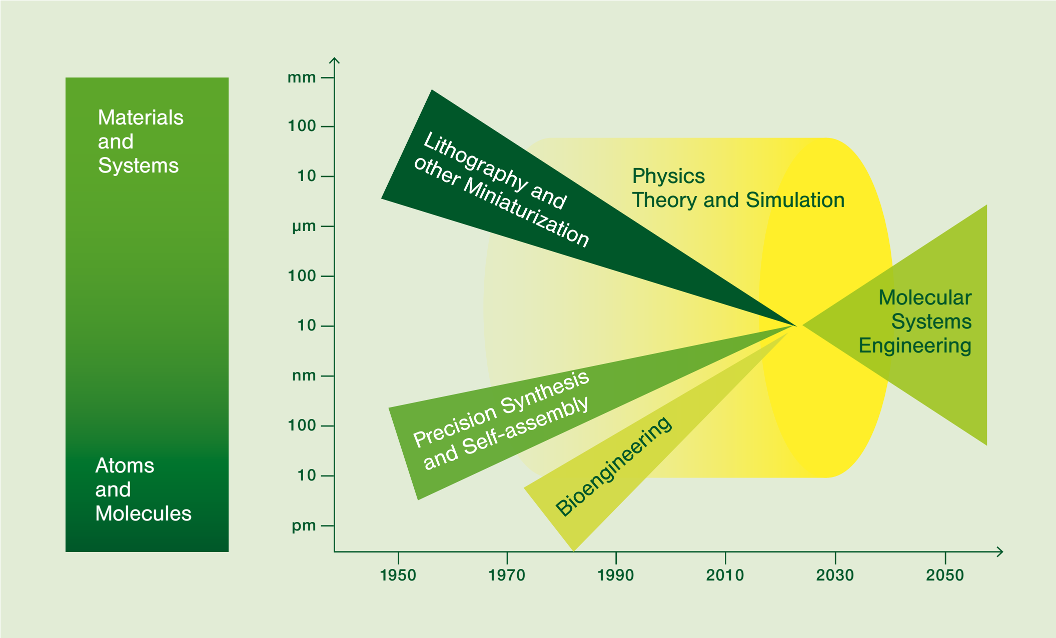


Figure 1: Overview of the drivers and interdisciplinary interconnections for development of molecular materials. In addition to control of length scales that become ever smaller (top-down) progress is defined by the increasing ability for synthesis and molecular simulation of ever growing units (bottom-up).

While in the past polymer sciences have become established as a separate and autonomous scientific field through development of special methods and insights, new issues and solutions increasingly distil from the task-oriented and multidisciplinary pooling of methods and processes. Consequently, the influence of polymer science on other disciplines is increasing and simultaneously the influence from other fields on polymer science through new developments and problems is growing. Therefore, it is important to pick up on these dynamics and consistently develop them. The growing trans-disciplinary cooperation of scientists involved in this field is characteristic.

Figure 1 is a schematic diagram that illustrates the way of developing a starting situation from cooperation and pooling of disciplinary successes, from which not only a better understanding for structure-property relationships can be derived but also the possibility for designing new properties and materials (from molecule to material & system).

Against this background, future research in the field of molecular materials does not only require reinforcement of the collaboration among chemists, physicists and engineers but also increasing integration of mathematicians, computer scientists, biologists and medical scientists. In this context, it is a challenge for the established methodology to consolidate and quantify deterministic, stochastic and heuristic methods. For the research work in this field, this results in the requirement to establish a **convergence of disciplinary competences as a new paradigm of the scientific strategy and organisation**.[1]

Scientists have long started to face the increasing requirements for convergence in research by numerous approaches (structured schemes of the DFG, such as CRCs, RTGs, the BMBF, the European Commission, etc.). In contrast to that, the structures of our scientific system continue to be largely discipline-oriented. The reason for this is the objective of preservation and further development of the established fields of competence and scientific methods as embedded in the theory. This results in a conflict between the necessity for discipline-specific tenet and the interdisciplinary scientific problems, which is resolved only

1 "Convergence: Facilitating Transdisciplinary Integration of Life Sciences, Physical Sciences, Engineering, and Beyond" by the Committee on Key Challenge Areas for Convergence and Health; Board on Life Sciences; Division on Earth and Life Studies; National Research Council, THE NATIONAL ACADEMIES PRESS 2014, ISBN 978-0-309-30151-0 | DOI 10.17226/18722.

hesitantly and rather late in Germany in comparison with international competitors. For polymer sciences the consequence is a dilemma between the established competence and its specific further development, on the one hand, and the necessity for consolidation of various disciplines, on the other. At the same time, active convergence represents a challenge for the presence and visibility of the discipline with regard to autonomous scientific methods and the related scientific doctrine. However, not all fields of polymer science are equally affected by the necessity to open up for convergence. While clear distinctions from other chemical/physical fields of molecular systems, such as supramolecular chemistry and colloid science are increasingly eliminated for many new approaches, important and discipline-defining developments in the core areas of polymer materials, macromolecular synthesis and physics of polymers are also expected in future. Nevertheless, there must also be close transdisciplinary intertwining in these areas, to prevent many new developments from grasping at nothing.

Taking the compiled analysis of the interaction of disciplinary and cross-disciplinary developments in the field of molecular and macromolecular materials in part II of this white paper as a basis, our goal is to illustrate the cornerstones and recommendations for future developments of this field of research. Clear definition of the objectives, opportunities and challenges within this discipline will be of great importance, both in the competition for the best brains and in seeking support from society. The latter is based on the understanding of the importance of macromolecular materials for all spheres of life but also on the belief that new developments can be designed in an environmentally friendly way. This also refers to translation into products, added value and employment, which takes place in added value networks and thus changes the business models of the companies involved, already today. We ask the question of how to formulate an extended definition of the scientific field that does not dilute development and progress of the polymer science's success story, on the one hand, and at the same time leaves enough room for supporting the successes resulting from convergence on an international competitive level expected in future, on the other hand. From this also results the requirements for developing new models for assignment of resources and administration/organisation of scientific work to foster convergence and thus obtain desirable knowledge networks in the width and depth required in the mid-run.

Part II of the present white paper includes five sections:

- **Section 1** gives a short overview of **the status and importance of polymer sciences** in Germany.
- **Section 2** concentrates on the **development of a widened research field of molecular materials whose limits and challenges extend beyond the core of polymer sciences**.
- **Section 3** deals with the **status of the extended research field in the universities.**
- **Section 4** analyses **integration of the extended research field into the support and examination structures of the Deutsche Forschungsgemeinschaft**
- **Section 5** sums up the **organisational challenges for future further development**.

Using the analysis of the development of polymer science in Germany and the experience from the various requirements and support schemes for polymer research in Germany, as well as its status with regard to international competition as specified in part II, the authors involved in writing this paper have formulated a number of principal and general recommendations for action.

Recommended actions

1 Understanding and control of the properties and generation of complex, hierarchically structured materials is one of the great scientific challenges that can hardly or not at all be mastered within the framework of the historically grown disciplinary structures. At the same time, progress in the development of molecular materials promises innovative product and process developments and thus become technology-defining. Support and sustainable improvement of the competitive position of this research in Germany must be a central concern of research politics, research support as well as education politics and the economy. Greater consideration and appreciation by German and European research promotion is essential.

2 The changes within the field of research must be taken into account. The progress made in the past and development of physics and chemistry that increasingly allow for control of the transition from molecules to systems require detailed and comprehensive definition of the research field that goes beyond the core area of polymer sciences. A suggestion is the expression of "Molecular Materials and Polymer Science". Synthesis may be taken as the connecting element - not in the sense of a chemical recipe but in the sense of a natural science construction and function principle of complex molecular systems ("biologisation" of materials science).

3 Convergence of the scientific disciplines must be supported by organisational and administrative measures with regard to the structure of research institutes and facilities. The interdisciplinary organisation of non-university science institutions could be taken as a model; however, this approach has only been adopted by few universities (e.g., Bayreuth) when it comes to the focus with regard to appointment proceedings. Another option results from the alliances with non-university science institutes (e.g., Aachen, Berlin-Potsdam, Dresden or Mainz) with regard to research and education.

4 The growing importance of convergence for future development of the research field must be taken into account in organisation of research support and funding. In this context, the application-oriented research must stay abreast of the long-term and sustainable significance of enablers, such as synthesis and catalysis, materials development, simulation and characterisation of material modifications during intended product life. For promotion of fundamental research it should be considered to establish a new interdisciplinary specialist forum within the DFG. This should also include further aspects of materials research, simulation, photonics, synthetic biosciences, etc..

5 The appreciation and visibility of the field of research as a fundamental challenge must be promoted with the aim of achieving stronger identification of the scientists involved:
a) By improved foothold within the teaching curriculum and through support of the sites' profiles. In this context, the basic disciplinary education that teaches methodological core competences of the subjects must be maintained by interconnection of common problems and methodological differences: Chemists, biologists, physicists and engineers as experts for molecular materials.[2] The boundary areas of physics, chemistry and biology must be made more penetrable with regard to master's theses and dissertations. This can be achieved by structured education of postgraduates that focuses on elaborating fundamental coherences of disciplinary findings and including aspects of interdisciplinary relationships in tests and exams. An example for this are PhD schemes established in the US.
b) By improved collaboration among scientific divisions in representation of the scientific field to the public and organisation of events (GDCh, Bunsen Society, DPG, Dechema, VDI).
c) Through European internationalisation of the work performed in the scientific divisions. In view of the dominant international role of US associations in "Promotion of Science", Europeanisation should also make European integration a priority and provide appropriate support.

2 White paper – Chemistry as a driver for innovation in materials research.

Part II: Polymer sciences in Germany

1. Status and importance of polymer science in Germany

1.1 Research field

Notwithstanding its great economic and scientific success, polymer science only evolved around 100 years ago and thus is a fairly new discipline in comparison with other classical disciplines in chemistry and physics. That is characterised by its high degree of interdisciplinarity. As a sub-field of polymer science and with its strong orientation focusing on structure-properties relationships, macromolecular chemistry combines insights and research problems from organic chemistry with rather special approaches of physical chemistry and colloid chemistry. These are combined with side relations to inorganic chemistry, such as catalysis (from polymer synthesis to polymer carriers), composite structures and inorganic polymers. Also, the interconnections with biotechnology and biology are evident due to synthesis / expression of highly defined bio-macromolecules (e.g., proteins, DNA). In addition to physical chemistry of polymers, physics of soft matter with a much broader footprint has evolved. This sub-field in turn contributes towards further development of physics through polymer physics, biophysics, colloid physics, non-equilibrium physics and basic approaches on critical phenomena. On the basis of biological compatibility of macromolecules and function of bio-macromolecules, connection points of polymer science with the disciplines of biology, biochemistry, as well as medicine and pharmaceutics are evolving more and more.

In the light of its diverse significance for technical developments, strong application orientation and practical focus is characteristic for many fields of polymer science. However, due to this application orientation, conflicting priorities between molecule-related considerations (chemistry/physics) and technical orientation towards macroscopic properties have developed. In future, the development of the discipline will benefit from the combination of engineering, heuristic modelling with scientific insights. This is due to the molecular understanding enabling new engineering and scientific solutions, on the one hand, and these engineering and scientific solutions helping in management of the complexity of materials, on the other hand.

Currently, the scientific discipline is suffering from the fact that the sub-fields involved do not "do enough talking". This also becomes evident by the discrepancies in the terminology found in various publications, which makes networking and mutual citation very difficult.

1.2 Applications

In the field of plastics manufacturing and processing, of rubbers and textiles technology, as well as mechanical engineering for plastics, polymer science is a major innovation driver. For other industries, polymer science also plays a central role due to the wide range of applications of molecular materials. Polymers are basic elements in paints and coats, used as additives, e.g., in concrete and in food or as adhesives in joining technology. Electronic components would not be existent any more without polymers. A comparable role is assumed by elastomers in the field of mobility (e.g., tyres, drive belts and damping elements). Polymers are used for membranes and as precipitation and absorption agents in environmental technology and in cosmetics and/or medical formulations. In the latter industries they are also used as carriers for active agents. A list of key words of application fields is provided in Figure 2. Moreover, the requirements for environmental and biological compatibility increasingly represent new challenges with regard to production, properties and complete integration into economic and natural cycles. This necessity becomes particularly evident through the fact that plastics have so far only been recycled in an insufficient manner (less than 10% in 2015).[3] Uncontrolled release results in environmental pollution, particularly of the oceans – degradation of plastics may take up to several centuries. This also goes in line with the problematic situation

3 R. Geyer, J. R. Jambeck, K. L. Law, *Sci. Adv.* **2017**, *3*, e1700782.

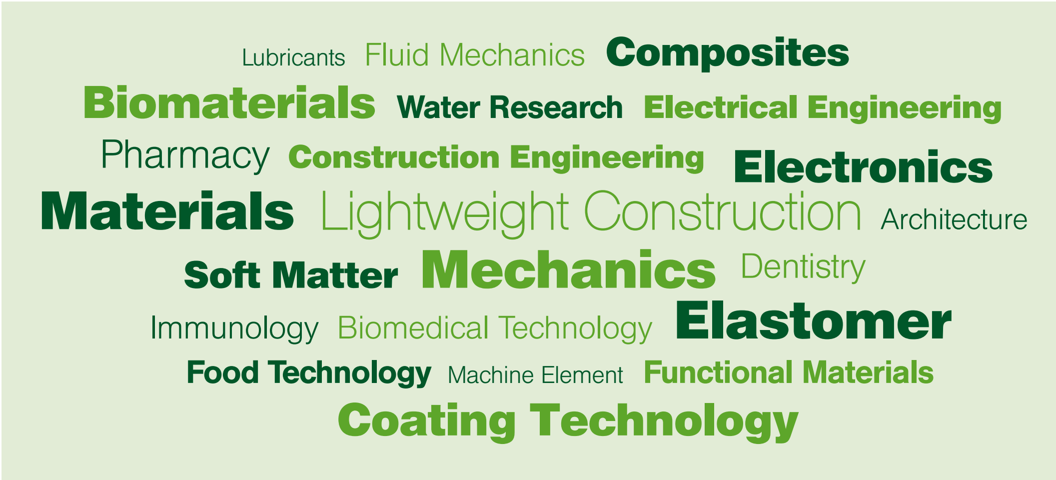


Figure 2: List of keywords for the fields of application of polymers.

of microplastics[4] that may arise through the degradation process, on the one hand, or as primary particle through washing of synthetic fibres or abrasion from tyres.

The polymer industry enabling and promoting these diverse applications is a major player both in Germany and in Europe. Of the 322 M tonnes of plastics produced globally, the European share is as much as 60 M tonnes. This results in a European turnover for the plastics industry of 350 billion Euro per year, with Germany achieving 90 billion Euro. The plastics sector's share in the industrial production in Germany is 6%. Approximately 6,000 companies employ an overall of 393,000 persons. The German rubber industry (tyres and technical elastomer products) has been employing a consistent 75,000 persons for years, with a turnover volume of 11.3 billion Euro, overall. It is the highly specific properties of rubbers and elastomers that enable modern transport and logistics concepts. The national consumption of synthesised rubbers, including high-performance special rubbers in 2016 was 41,400 tonnes of a total of 674,500 tonnes (incl. natural rubber).

However, the highest-revenue polymer materials have already been developed as early as the 1930s to 1950s (ranging from polyamides, to polyolefins and polycarbonate). In the subsequent years, it was mainly new special polymers and highly significant polymer improvements that development focused on. These were based on fundamental chemical innovations. Rubbers and elastomers are examples for mass productions. Only their highly developed properties enable modern transport, traffic and logistics concepts. High-performance polymers, polymer additives for lubricants, paints, cosmetic applications and others demonstrate that molecularly controlled properties of polymers significantly contribute towards development of complex formulations and components.

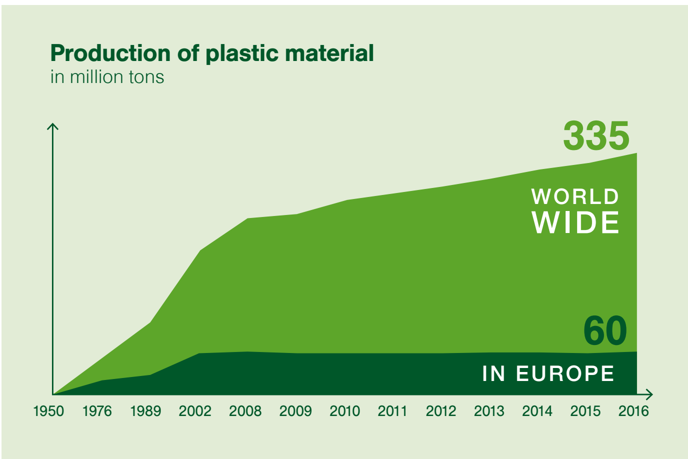


Figure 3a: Plastics production quantities.

Figure 3 also reveals that there is an increasing shift in produc-

4 Small plastic particles of a few mm in size.

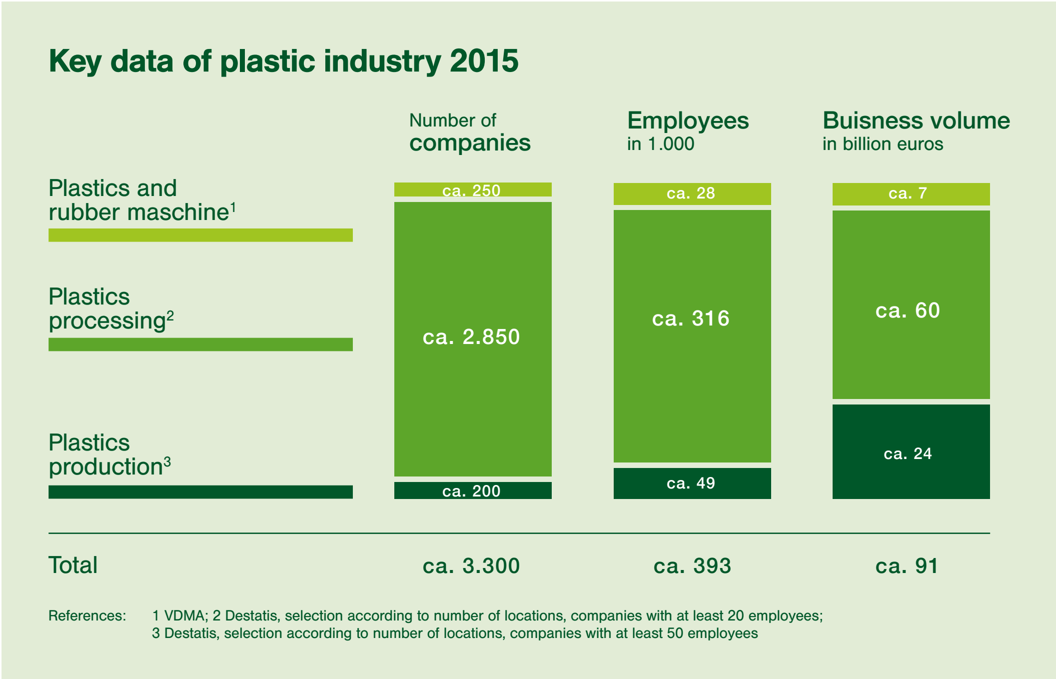


Figure 3b: Overview of employees working in the German plastics industry. [5]

tion shares to sites outside Europe. However, this chart does not include the production shares in special polymers for formulations and other "hidden" applications. Especially in development of particularly high-quality polymers and specialised polymers used as system components, the shrinking share in production of basic plastics is opposed by an ever growing economic success.

Developments beyond basic polymers towards special polymers and innovations in the production processes are characteristic for the years after the turn of the millennium. This also holds true for new polymerisation methods that allow for significantly more accurate structure control, as well as new processing methods that represent the basis for enormous quality improvements. The latter mainly refers to temperature resistance, failure and fatigue behaviour and functionality for use. Control of an ever growing variety of combinations using components of varying degrees of hardness and softness continues to remain a fundamental basis. In this way it has been possible to integrate properties into polymer materials that were previously considered impossible, so that macromolecular materials could be developed and refined to conquer new fields of application that in the past were restricted to other material categories (e.g., construction materials in aircraft construction, OLED displays, car window panes, complete housings for lights, flexible electrodes for sensors, as well as medical implants, optical elements and solar cells). However, this increasing variety of components simultaneously results in new scientific challenges. For example, predictability of property changes throughout the useful life of complex composites is insufficient in most cases.

In summary, it can be said that an ever growing, high degree of diversification and specialisation of polymer products is a major pillar of the economic success in Germany. The polymer and methodology competence ensures an internationally outstanding competition position for Germany as a knowledge and industry location.

5 www.plasticseurope.org: "The plastics industry in Germany" 09/2016.

2. Development of a widened research field of molecular materials whose limits and challenges extend beyond the core of polymer science

Molecular materials offer the basis for new solution approaches for the great challenges of the 21st century as no other material system can do. These include energy-efficient infrastructures, efficient recycling economy and new healthcare technologies. In all fields where technological developments are majorly triggered and enabled by the availability and control of material categories, the variety and organic nature of molecular materials offers new perspectives. At the same time, the technological need is increasingly shifted from exclusive requirements with regard to the material in the context of its use towards ecological consequences connected with the production and utilisation of the materials and the technologies used (ecological footprint), among others. This involves, availability, energy usage and future-oriented balance between technological benefit and the influence on variety and function of natural cycles (both in view of the production and the disposal). Particularly against the background fact that human civilisation has long changed the earth and increasingly determines natural cycles (our time is referred to as a new era, the “Anthropocene” for nothing) the question for a new material technology extended by natural concepts and components (materials for a better life) has arisen.

Solution approaches that are oriented towards preservation of nature and natural resources are of great importance but generally still incorporate a contrast between technology and nature that needs to be overcome. The symbiosis of man-made material technology and natural systems mainly focusses on two aspects: (i) improved performance with lower resource input and (ii) integration into our natural environment (learning from nature and hybridisation with natural systems). Apparent challenges with regard to the first point are light-weight construction, further improvement of functionality, efficient production processes and control of aging and wear processes, controlled/accelerated degradation of polymer materials after use (e.g., photo degradation, biological degradation, chemical degradation) as well as more efficient recycling of used products. This includes prevention of uncontrolled release into the environment, increase of the portion of reused materials and new approaches for more efficient recycling (e.g. stabilisation of complex polymer blends). The challenge of “learning from nature” is closely in line with the afore-said. The natural structures and systems developed through evolution are role models for new solutions and the natural cyclic processes set the boundary conditions for our spheres of life. Against this background and in view of the complexity of natural structures and the processes that partly take place simultaneously, the need for hybridisation, i.e. integration of natural elements into technical components and processes, and vice versa, arises. This is described by the expression of “biologisation of materials research”.[6]

International benchmarks for this research field with its rapid upheavals mainly are the Harvard Wyss Institute (founded in 2009) and the Institute of Molecular Engineering, University of Chicago (founded in 2013). Other centres of competence are the newly founded soft matter centres in Asia, such as the “International Research Center for Soft Matter” in Beijing, China (2014), and the “Center for Soft and Living Matter” in Ulsan, South Korea. Moreover, a variety of research approaches can also be found in Germany and Europe; however, these are rather specific and mainly do not aim at long-term concepts, with the exception of relatively small non-university science institutions.

6 Cf. also “Biologisation of engineering”: https://www.vdi.de/technik/fachthemen/technologies-of-life-sciences/artikel/innovations-potenziale-an-der-schnittstelle-biologie-und-technik-1/ (last accessed on 26.02.2018).

2.1 The complexity of macromolecular materials as a guiding principle of polymer research

An aspect that all requirements for better and more efficient polymer materials and the search for an advanced new material class with adjustment capabilities and active properties have in common is that the properties and functionality of molecular materials can only be grasped and determined through cross-scale coherences. The function resulting from the composition of individual molecules also affects the transition from the molecular structure to molecular aggregation and supramolecular association, spatial organisation and interaction of these nano-structures, as well as the processes taking place at the inner boundary areas, structuring and heterogeneities in the visible area. Formation of non-equilibrium structures and dynamic interaction through a frequency spectrum of more than 20 scales are characteristic in this context. Complex structures are often formed by various interacting processes that take place on different spatial and temporal scales that cannot be clearly differentiated from one another. This makes reasonable theoretical approximations very difficult. To achieve understanding of these complex coherences, large numbers of different characterisation methods that ensure detailed time-resolved, structural and morphological exploration of such structures are required, on the one hand. On the other hand, the great and diverse amount of information can only be interpreted and processed by sophisticated mathematical models and simulations. For polymer technology and processing, non-destructive, and particularly real-time, characterisation in connection with data evaluation throughout the entire production process and the life cycle of a product becomes more and more important. Also, synthesis and production of polymer structures of increasing complexity utilising specific interactions can only be very successful with the help of new theoretical models and numeric simulations that ensure determining all coherences and correlations on the various **length and time scales**.

In this context, a special aspect deals with defects and contamination of polymers. Due to their non-uniform structure (non-uniform molecule structures, multiple phases and non-equilibrium conditions) only simple polymer melts are more or less homogeneous. Already during transition into glassy condition, and even more during crystallisation but also during cross-linking, distinct heterogeneities that largely determine the material's properties arise. This is not only of major importance for the failure and ageing behaviour but even more so for the electronic properties, particularly of conjugated polymers. For research and development of such functional materials, management of contaminations and definition of defect structures become more and more important. Defects may be both disadvantageous and intended, since they may targetedly modify the material properties.[7] Examples from nature show that functional structures may also be composed of non-uniform components.

In the core area of polymer science, i.e. polymer materials, functional and special polymers, new impulses and options arise for further development of macromolecular chemistry[8] and for polymer process and material engineering. For example, the transition away from petroleum-based resources and reduction of the environmental burden requires new orientation towards material flows that are based either on recycling of largely heterogeneous biomass or on a power-to-X technology the development of which currently merely is an initial approach. At the same time, new requirements for bio-compatibility and bio-reabsorption capacity, as well as material recycling or reuse within the sense of efficient recycling economy emerge. This also results in an interest in new monomers and polymers as competitors of established, highly powerful polymers. Examples for this are furandicarboxylic acid, 1,3-propanediol, but also CO_2 and CO. For previously established biologically based and biodegradable products, such as PHAs and polylactide acid, there still is a requirement for consistent further development of their property ranges. Due to the wide range of effects of monocultures on symbiotic communities and living conditions in tropical cultivation areas for different raw materials, there is additional requirement for finding a concept leaving behind plantation economy and towards production of biological and/or chemical synthesis facilities.

7 K. Muellen, "Molecular Defects in Organic Materials", *Nat. Rev.* **2016**, *1*, 15013.

8 C. K. Ober, S. Z. Deng, P. T. Hammond, M. Muthukumar, E. Reichmanis, K. L. Wooley, T. P. Lodge, "Research in Macromolecular Science: Challenges and Opportunities for the Next Decade", *Macromolecules* **2009**, *42*, 465-471.

The end of development options for the market-dominating polymers, such as polyethylene, polystyrene, and others, is still not in sight. New and refined polymerisation methods are required to make available further improved products and products that are customised for their applications with a low degree of resource input. The options for control of molar mass distribution, control of monomer sequence and chemical functionalisation are still limited. In this context, the challenges are not only of chemical nature but increasingly due to aspects of polymer technology. An example for this is the development of ultra-high molecular polyethylenes that did not become high-performance materials until new processing methods were available.

Moreover, the close interconnection of polymer chemistry and polymer technology is necessary to perform chemical structure forming processes outside of chemical factories that are safeguarded against the environment. Water-based varnishes and coats, adhesives and applications in the building and cosmetics industry are well-established examples for this. The prerequisites are new pre-polymers, water-based, non-toxic chemical processes and control of physical transitions and self-assembly processes. A fundamental challenge for resource-saving technologies is the control of ageing and failure or fatigue behaviour. New and advanced solutions for stabilisation, predictability and self-healing but also controlled ageing (from novelty to vintage) can only be achieved in close collaboration between macromolecular chemistry, polymer technology, polymer physics and mathematical simulation. Particularly the developments in the field of high-performance computing will open up new perspectives to make predictions *in silico*.

Great research and development potential is also still manifested for hybrid materials, in which polymers are alloyed with finely dispersed inorganic particles in such a way that macroscopically homogeneous appearance and property pattern is achieved.[9] Particularly for finely dispersed systems, the influence of structure and dynamics of the bulk properties of the individual components is increasingly superimposed by the influence of the inner boundaries. In contrast to the established dispersion systems, such as high-impact polystyrene or soot- and silicate-reinforced elastomers, examples from nature, such as mother of pearl from mollusc shells,[10] wood or bone structures reveal more great potential for development of designed and anisotropic hybrid structures. The option of producing nano-composites with well-defined superstructures, opens up the path to new materials with specific electronic, optical and mechanical properties. New approaches result in this context (i) though further developed self-assembly methods (phase morphology of block polymers, controlled crystal formation, core-shell structures, as well as complex and mesoscopic grids) but also (ii) increasingly through top-down structuring processes with which ever smaller size scales are achieved (layer-by-layer techniques, lithographic processes and ink jet printing). The triumph of 3D printing that is due to these aspects and other additive production technologies will continue. New monomers and polymer systems alongside advanced printing processes will provide essential contributions towards digitalisation of material synthesis and pre-assembly within the sense of industry 4.0. A special, boundary-spanning and future-oriented area opens up in the field of personalised healthcare technology in the research field of biomedical hybrid systems and development of tissue preparations (ATMPs).[11]

9 G. Wegner, M. M. Demir, M. Faatz, K. Gorna, R. Munoz-Espi, B. Guillemet, F. Gröhn, “Polymers and Inorganics: A Happy Marriage?”, *Macromol. Res.* **2007**, *15*, 95-99.

10 U. G. K. Wegst, H. Bai, E. Saiz, A. P. Tomsia, R. O. Ritchie, “Bioinspired Structural Materials”, *Nat. Mater.* **2015**, *14*, 23-36.

11 https://www.pei.de/DE/arzneimittel/gewebezubereitungen/gewebezubereitungen-node.html;jsessionid=08A49878E280EF01135F96F01C886B1C.1_cid319.

2.2 Where will the increasing control of complexity lead us?

The complexity of the material structure and structural dynamics that is characteristic for molecular materials thus also provides an inherent fundamental, scientific challenge: Control of the transition from materials to material systems, whose properties develop through their formation or production processes, are defined by functional hierarchic heterogeneity and change through use and/or are adapted to requirements.

The complexity of the structures and functions of polymer materials is not only a challenge for understanding but also leads to new scientific problems that reach far beyond a deterministic structure-properties understanding. This is the case if we view the diversity of potential components, their dynamics and the hierarchy of interaction forces as starting point for new properties. Biological systems whose functions are determined by the interaction of a variety of sub-units act as role models for this. Natural materials in many cases reveal that their properties result in synergetic processes through evolutionary development and intelligent combination of individual components and may be changed in reaction to external impacts. In the same way, progress in the synthesis and control of molecular interaction as well as the defined superstructures are able to ensure transition from molecules to active functional systems, such as polymer actors or self-healing and adaptive polymer materials. This scientific challenge does not only open the path to more efficient materials but also to intelligent materials with active and adaptive properties. The prerequisite for development of such increasingly complex, adaptive polymer systems are (i) properties ranging from self-assembly of molecules through achievement of equilibrium and advanced lithography methods to "build" structures across scales, (ii) increasing availability of switchable molecular structures, (iii) control of bi-stable structures and hysteresis effects, as well as (iv) control of dissipative structure forming processes and (v) integration of hierarchic feedback mechanisms (Figure 4). Literature has revealed dramatic development on all of these aspects in the past years.[12]

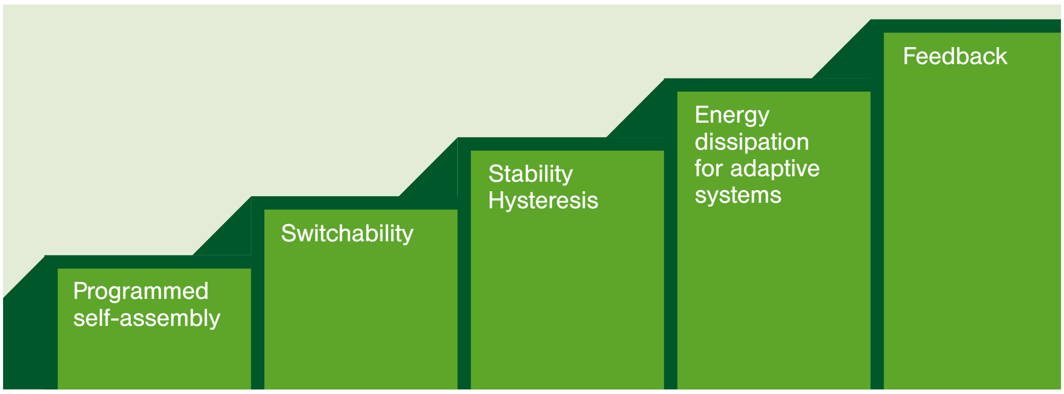


Figure 4: Coding of system properties based on structural and information properties of polymers.[13]

This results in two fields of action for the area of physics. On the one hand, physics needs to explain correlations, describe new phenomena and develop universal paradigm concepts. In this context, physics as a science field for polymers also is a clear "end in itself" as a promoter of new scientific developments. However, this purpose is slightly underestimated in the competition with other modern areas of physics (e.g., quantum optics). On the other hand, the goal of physics must be to achieve better understanding of the connection between structure and special mechanical, optical and electrical properties for the given materials and systems through suitable experiments and quantitative analysis. In this context, the contribution of physics is in the development and provision of experimental methods and in the expertise for utilisation thereof.

12 R. Merindol, A. Walther "Materials Learning from Life: Concepts for Active, Adaptive and Autonomous Molecular Systems", *Chem. Soc. Rev.* **2017**, *46*, 5588-5619.

13 Self-assembly: Thermodynamically promoted process; self-organisation: Structure formation by energy dissipation in non-equilibrium processes.

An underlying challenge for physics is the understanding of non-equilibrium phenomena and active processes. Also in general statistical physics, there are no universal approaches available for that. We have to admit that we have not even been close to understanding non-equilibrium. Soft matter, particularly polymers, are an interesting basis for this, since polymers are already capable of forming highly complex equilibrium phases. Since in the contrast to 'hard matter' energy and entropy are of similar importance, it is relatively easy to manipulate soft matter. E.g., through variation of temperature and molecular size, time and length scales can be shifted into experimental windows so that advanced concepts of theoretical non-equilibrium physics can be examined. Polymers that are additionally subjected to "metabolic" processes, e.g., actively driven dynamic cracking or fusion, could lead to dynamic phase structures that reach near-biological complexity.

Advanced multi-scale simulation methods allow for direct access to many of the stated properties and sizes so that unprecedented proximity of theory and experiment up do direct coupling of experiments with simulation is almost tangible. In short, the connection of multi-phase structures of polymers with proactively driven processes represents an ideal model system for materials that overcome the conventional borders between "solid" and "liquid", on the one hand, and are capable of storing memory and information in their properties, on the other. Consequently, soft matter is bound to become a driving agent of modern physics. Moreover, the connection of multi-scale simulations with data-driven methods, such as machine learning, opens up completely new options that are not foreseeable for the time being.

Challenges for structural exploration involve neutron and X-ray control, as well as volume and boundary area properties. Especially the new options within the scope of CFEL (Continuous Free Electron Laser) must be mentioned in this context. They enable direct mapping of nanoscopic regions or droplets. The experiments from the field of biomolecules envisaged here that have in part already been performed, can be extended to universal problems of soft matter physics and lead to unprecedented precision (e.g., mapping of individual mini-emulsion droplets or individual defects). In electron microscopy, highly sensitive, ultra-fast detectors in combination with cryo-technologies increasingly enable clarification of molecular structures and modification processes down to atomic levels. Further developments in chemical labeling allow for time-resolved tracking of processes with molecular resolution under normal conditions within the scope of highest-resolution light microscopy. The combination of conformation, composition and morphology with electronic properties does not only result in new options for electronic components but also new insights into current-day issues of semiconductor physics. Organic semiconductors are examined using the entire range of instruments of modern solid-state physics and with their possibilities offer a long-term option for replacing conventional semiconductors in specific applications. AFM and STM experiments combine this with a very high local resolution. New spectroscopic approaches, that have partly been developed for multi-dimensional processes of NMR spectroscopy, enable detailed insights into boundary areas that in turn are of universal importance, since soft matter is full of internal boundary areas in the most cases.

For macromolecular chemistry, this results in new incentives to promote "perfection" of the synthesis of polymers and to achieve better understanding of the interaction of highly defined and structurally flexible components. Examples for progress in polymer synthesis are metallocene catalysis, living and controlled polymerisation reactions[14] and progress in polycondensation chemistry and in precision polymer synthesis.[15] In this field, the synthetic approaches are still far behind the accuracy and precision of natural systems. Biomacromolecules, such as DNA, proteins and glycanes have uniform structures but at the same time are built of a variety of different components. This also ensures encoding of "information" for control of formation of suprastructures through to hierarchic structures. Against this background, strategic positioning of monomers[16] and supramolecular chemistry will increasingly play a

14 a) P. B. Zetterlund, S. C. Thickett, S. Perrier, E. Bourgeat-Lami, M. Lansalot, "Controlled/Living Radical Polymerization in Dispersed Systems: An Update", *Chem. Rev.* **2015**, *115,* 9745-9800; b) K. Matyjaszewski, "Controlled Radical Polymerization: Mechanisms", *ACS Symp. Ser.* **2015**, *1187*, 1-17.

15 J.-F. Lutz, "Sequence-controlled Polymerizations: The Next Holy Grail in Polymer Science?", *Polym. Chem.* **2010**, *1*, 55-62.

16 G. Gody, P. B. Zetterlund, S. Perrier, S. Harrisson, "The Limits of Precision Monomer Placement in Chain Growth Polymerization", *Nature Commun.* **2015**, *7*, 10514.

role in polymer science.[17, 18] Step-wise self-assembly and new adaptive properties require new processes for functionalisation and function modification as is possible e.g., through click reactions. Top-down methods (lithography, layer-by-layer) and bottom-up processes can be more and more combined for the purpose of structure formation and thus open up possibilities for combinations across scales of structural components.[19]

New challenges arise from the field bordering with biology but mainly in biomedical technology and pharmaceutics. For polymers with applications in pharmaceutics and medicine accurate sequence analysis would significantly improve the possibility for registration and for protection of the fields of use ("Polymeromics").[18] However, particularly great potential evolves from the combination with biological systems; i.e. in hybridisation with biological components, as well as control and regeneration of biological functions. Biohybrid implants, *ex-vivo* models of organs, synthetic scaffolds for tissue engineering, targeted transport and release of active agents, diagnostics and many more are examples for this aspect. The research field of molecular materials and polymer science overlaps with developments that are jointly referred to as synthetic biology. In contrast to the approaches by biologists who generally apply biological mechanisms to synthetic systems with new properties, the focus here is on non-biological elements and systems with active properties derived thereof. Key words are adaptive, responsive and interactive. Since active properties are mainly known from nature, this area is also referred to as biomimetic chemistry. Overlapping results from the fact that biomimetic chemistry not only contributes to understanding of the biological processes but follows the same fundamental physical rules as biology. However, overlapping particularly results for hybrid structures in which synthetic function elements are combined with biological components. These overlaps clearly reveal that both scientific approaches highly depend on one another. Consequently, modern polymer science provides valuable impulses for the area of synthetic biology through use of new components and processes for production of bioactive macromolecules.

The requirements for technological transition into efficient, sustainable processes and procedures are highly varied. Development and properties of boundary areas are the central point of materials development. Particularly control of boundary layer and surface properties largely defines the functionality of a material and results in great utilisation potential for adaptive and responsive capacities (ranging from dirt-repellent, self-cleaning to self-healing and active opto-electronic properties), even for very thin coats. Thin films used as functional elements and membranes with customised and adaptive properties are the precondition for innovations in energy, construction and environment technology. In addition, polymers used as energy materials pave the way for new application options, for example in polymer-based batteries.

However, from this also completely new challenges result with regard to technological transition into efficient, sustainable processes and procedures. In this context, nature can be considered a good and a bad example at the same time. Natural structure-forming and growth processes are highly self-regulating and allow development of complex hierarchic structures; at the same time, such processes are very slow on large length scales and ultimately inefficient. In most cases, structure forming takes place in combination with dissipation, which is promoted by energy and/or material flow. In nature there are only few systems that are fixed in equilibrium or a static structure. This is the case in load-bearing structural materials for energy-saving reasons (e.g., wood). However, it is the entire orientation of biology towards energy-driven formation of non-equilibrium structures that enables the highly adaptive behaviour of biological systems at all. Synthetic examples for such dynamic-dissipative self-organisation are still in their very early development. Of particular interest in the field of equilibrium-oriented self-assembly are top-down controlled self-assembly processes that are used in many areas for development of special, mostly meta-stable structures and processes (spinning processes for fibres and membranes, stratification and pigment orientation in paint and surface-coating technology, templates) and for which new perspectives arise thanks to 3D printing processes.

17 a) E. Krieg, M. M. C. Bastings, P. Besenius, B. Rybtchinski, "Supramolecular Polymers in Aqueous Media", *Chem. Rev.* **2016**, *116*, 2414-2477; b) T. Rossow, S. Seiffert, "Supramolecular Polymer Networks: Preparation, Properties, and Potential", *Adv. Polym. Sci.* **2015**, *268*, 1-46.

18 W. H. Binder, M. Schunack, F. Herbst, B. Pulamagatta, "Biomimetic Principles in Macromolecular Science", in *Bioinspiration and Biomimicry in Chemistry: Reverse-Engineering Nature* (Editor G. F. Swiegers), John Wiley & Sons, Inc., Hoboken, NJ, USA **2012**.

19 L. Persano, A. Camposeo, D. Pisignano, "Integrated Bottom-up and Top-down Soft Lithographies and Microfabrication Approaches to Multifunctional Polymers", *J. Mater. Chem. C* **2013**, *1*, 7663-7680.

20 E. Altuntas, U. S. Schubert, "'Polymeromics': Mass Spectrometry based Strategies in Polymer Science toward Complete Sequencing Approaches: A Review", *Anal. Chim. Acta* **2014**, *808*, 56-69.

3. Significance of the extended research field in the universities

The numerous aspects of this field are mirrored by the research and education programmes of the universities, in particular by differing institutional assignment of professorships for macromolecular chemistry, physical chemistry of polymers and colloids. Important professorships for this field of research are mainly connected to non-university science institutions (exceptions: Halle, Mainz, Freiburg, Berlin-Potsdam, Bayreuth). Within the field of engineering sciences, polymer science is mainly represented in the area of mechanical engineering and in some cases in process engineering and material sciences.

The latest university guide for "Macromolecular Chemistry in Germany" provides a summary of the situation in Germany and the research institutes of the working groups (see Annex "University Guide").[21] It becomes evident that the main working fields of the university groups are in the areas of polymer synthesis and analytics, as well as physics (Figure 5, on the left). Moreover, there are 46 application-oriented university and non-university science institutions active in the field of polymer and materials research. In addition to traditional applications in the form of materials, issues with regard to functional and new active properties are increasingly of interest for scientists. The focus here is on hybrid materials and biomaterials, with the latter concentrating on medical applications (see Figure 6). Also, there is comparatively new interest in the development of polymers with adaptive and switchable properties.

The overview also reveals local diversification of the respective research priorities. It becomes clear that polymer science is not represented at all universities by research and education. Diversification of polymer science with simultaneous concentration to a limited number of university is also mirrored by the range of courses offered. Figure 7 gives an overview of the offer of curricular education within the traditional chemistry courses (bachelor and masters) and the range of specialisation courses (e.g., elective and specialist courses) in the field of polymer sciences. In very few cases, specialised masters studies are offered for macromolecular chemistry (e.g., Bayreuth – Polymer and Colloids Chemistry; Freiburg/Strasbourg: Int. M.Sc. Sustainable Materials: Polymer Science; or Hanover – Further Education Studies in Rubber Technology; Berlin-Potsdam – M.Sc. studies in "Polymer Science").[22]

21 Link to university guide for macromolecular chemistry: https://www.macrochem.org.

22 An overview of the universities in Germany can be found at: http://polymerscience-plasticsengineering.de/#.

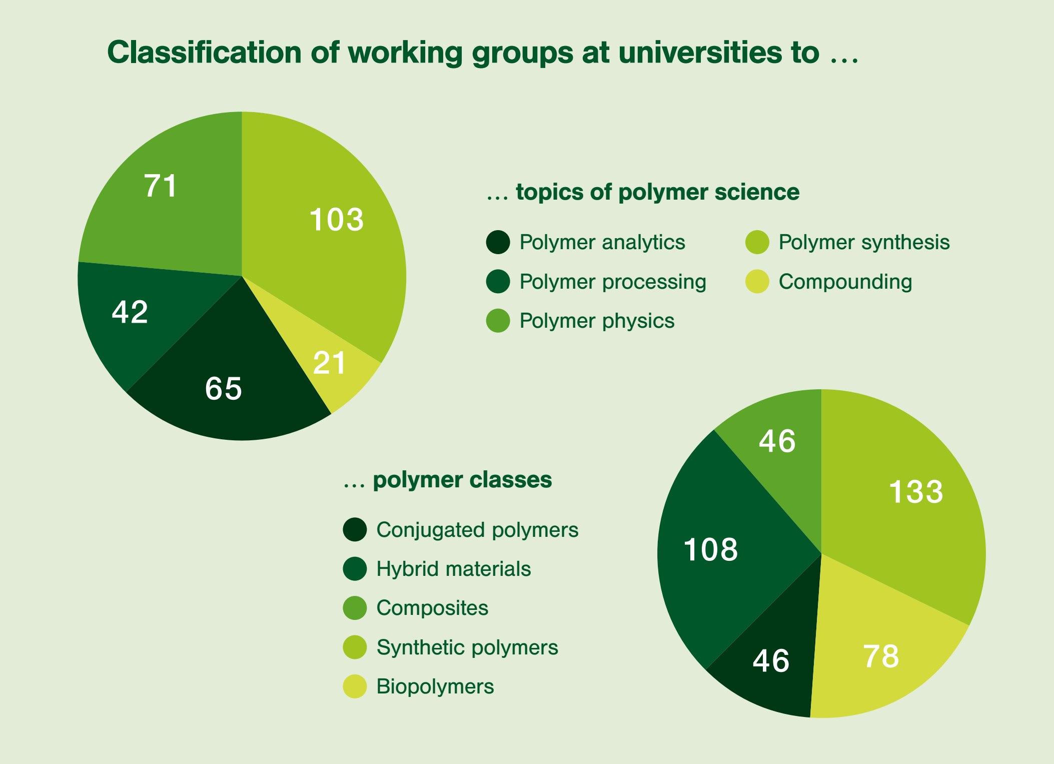


Figure 5: Assignment of the university working groups to subareas of macromolecular chemistry (LH) and polymer categories (RH).[23]

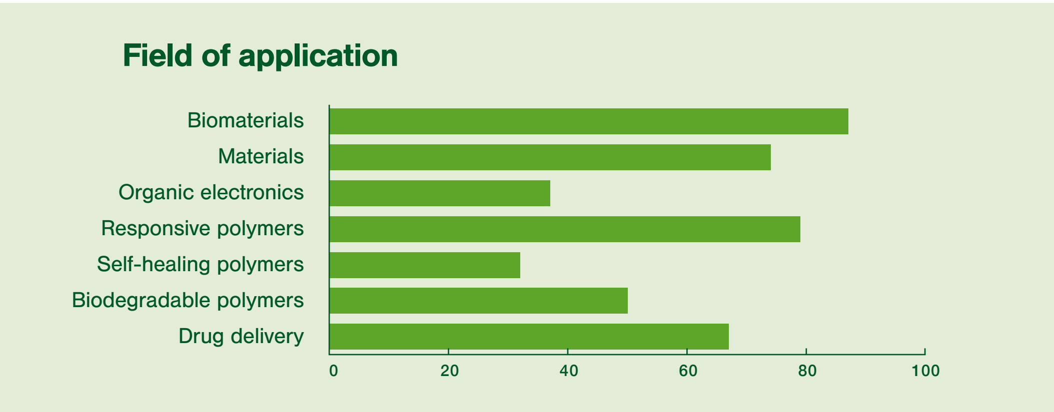
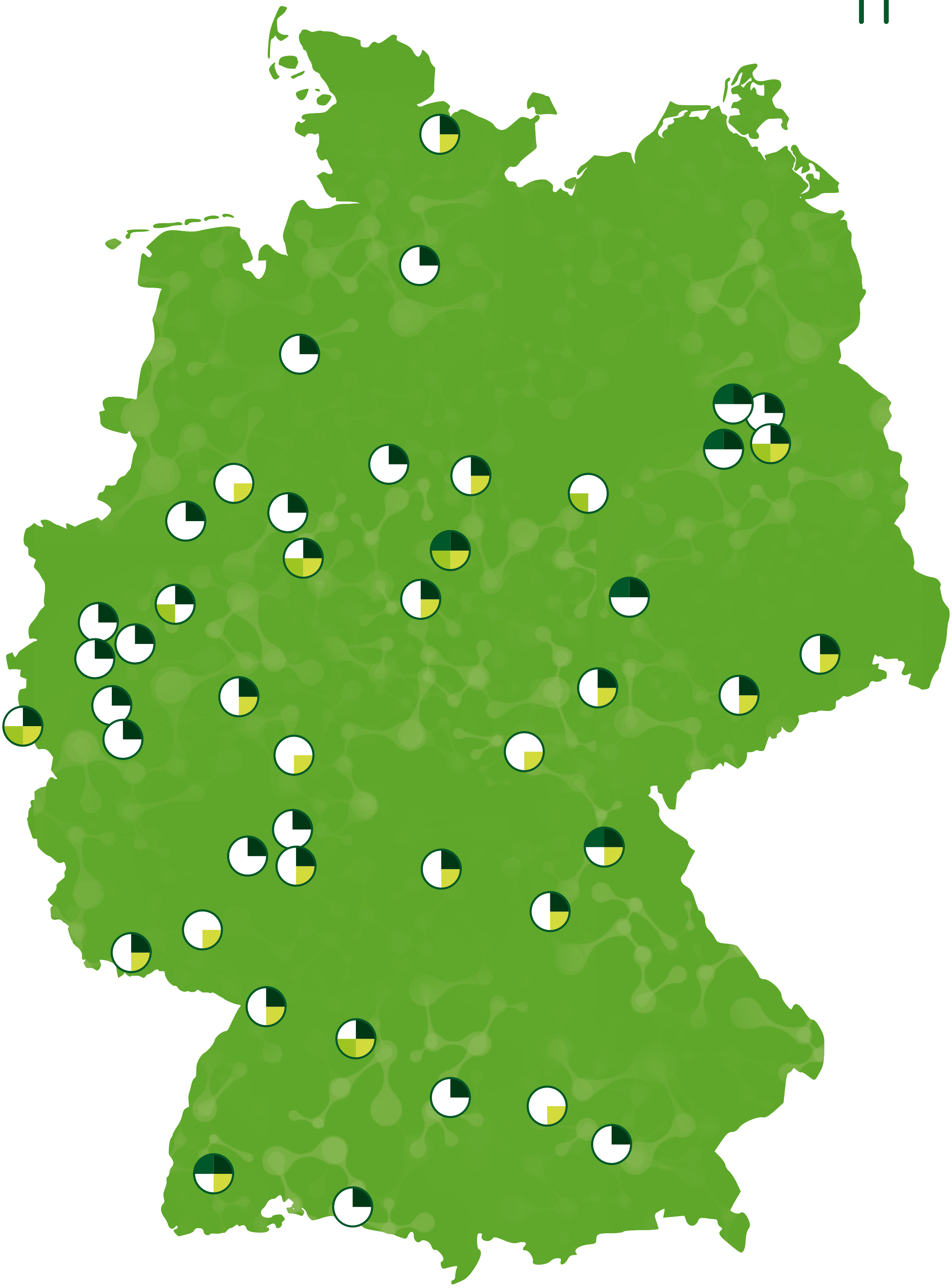


Figure 6: Fields of application of polymer materials that are currently examined by university working groups.[19]

Within the scope of education, the following must be considered: "The spectrum of the basic chemistry studies, with an emphasis on material-science issues, must be maintained to reinforce the role of chemists as experts for molecular materials."[24]

23 Based on feedback messages (overall number 183), multiple answers possible.

24 White paper – Chemistry as a driver for innovation in materials research.



Education in macromolecular chemistry (polymer chemistry)

Separate course of studies in the field of polymer chemistry

Engineering studies, incl. polymer education and/or polymer engineering

Material science

Figure 7: Courses offered by German universities within the field of macromolecular chemistry.

4. Integration of the extended research field to the support and review structures of the Deutsche Forschungsgemeinschaft

Polymer science and molecular materials represent a sub-area of research in view of the issues of development and function of (macro-)molecular matter. Within the organisational structure of DFG support and promotion (Figure 8) that includes four main fields, topics such as molecular materials assume a wide cross-sectional function since they involve both issues of life science, natural science and engineering science. The breadth of this field reveals the fundamental importance, on the one hand, and results in low level of visibility and coordination of such basic issues beyond specialist limits, on the other.

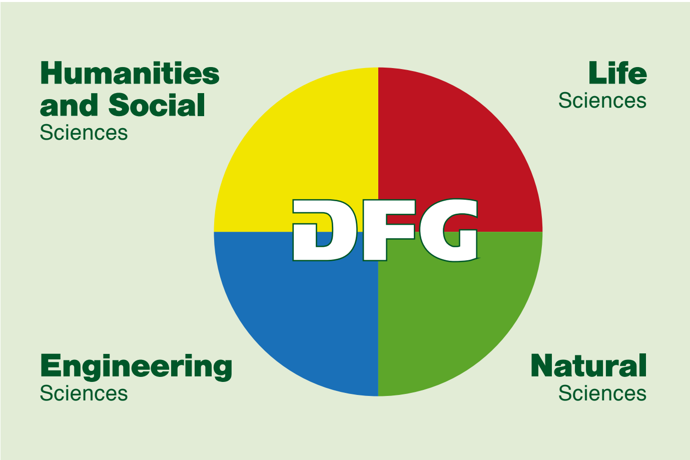


Figure 8: Organisational structure of DFG in four support categories.

Structural differentiation of polymer science and the science of molecular materials from life science results from the different motivation aspects and objectives of the scientists involved. While life science mainly pursues the goal of understanding highly complex living systems and interfering with their development and reactions (decisions) (from systems to molecules), research in the field of molecular materials is oriented towards the fundamental physical understanding of comparatively simple structures, particularly with the goal of developing new materials (from molecules to systems). It is in the nature of these tasks that they cannot be clearly differentiated from one another but complement each other. Key words are biophysics, biomimetic material development and biomaterials for life sciences.

Research projects in the fields of molecular materials oriented towards synthesis and application, in their capacity as sub-fields of molecular materials are mainly carried out by four expert boards within the DFG:

- 306-1 Preparative and physical chemistry of polymers
- 306-2 Experimental and theoretical polymer physics
- 306-3 Polymer materials
- 401-4 Plastics engineering

In this context, the problems of colloids sciences are generally assigned to the field of polymer sciences (306). Furthermore, research projects on molecular materials also involve other expert boards, such as:

- 310 Statistical physics, soft matter, biological physics, non-linear dynamics
- 403 Process engineering, technical chemistry
- 301 Molecular chemistry
- And the interdisciplinary medical engineering section combining the expert boards 205, 306, 402, 404, 407, 409 and 410

An effect of this allocation is that appreciation and visibility of the field of research on molecular materials and polymer sciences do not reflect scientific and economic reality. This comes along with restrictions; a problem for intra-science communication but also for external representation of the importance of the field of research.

This problem is due to a fundamental dilemma between promotion of evolved disciplinary competence and development of new research fields that think outside the disciplinary box. The DFG faces this challenge through continuous further development of the structure of expert associations and in some cases also through establishment of interdisciplinary sections (see medical engineering). The DFG also counteract disciplinary limits through interdisciplinary selection of experts and reviewers. However, the current situation raises the question of the influence the different levels of coverage within the inherently wide and interdisciplinary field of molecular materials and the discipline-oriented composition of the DFG bodies have on the decision-making process for promotion of projects. Not least, the disciplinary allocation also results in certain pressure for the applicants for funds to orientate their research goals towards the respective expert boards. It is striking that among the coordinated schemes of the DFG (research groups, priority programs, special research areas, postgraduate colleges) the discipline of polymer sciences is visibly underrepresented (see www.dfg.de). In this case it is up to the scientists, themselves, to make new efforts and regularly contribute topics from polymer science. Another noteworthy fact is the decrease of young scientists (up to 35 years) with regard to the granted research scholarships and support/funding within the scope of the Emmy-Noether scheme, which is clearly visible in the statistics lists.

5. Organisational challenges for future further development

Despite the fact that Germany assumes a very competitive position in polymer research compared with other countries, not least due to its significant share of non-university science, major challenges have to be met in future.

The progress from the past has resulted in circumstances where focussing on the limited area of synthetic macromolecules, their properties and applications in the plastics, rubber, paint, and fibre industries has long ceased to meet the development needs in this research field. On the one hand, polymer scientists keep exploring new and innovative functional properties, on the other hand, there is an increasing number of evolving cross-border commuters from other disciplines. This broadening of the research field becomes evident in the participations and contributions at the research centres, such as Aachen, Berlin-Potsdam, Bayreuth, Dresden, Freiburg, Halle, Stuttgart and Mainz. Furthermore, and in connection with the progress of computer-aided modelling and simulation, new methods for synthesis, molecular characterisation and mapping procedures, the understanding of optical and electronic properties, progress in stochastic process physics and complex systems, nano-technology, as well as new options of bioengineering have significantly changed the research field.

At the same time, another area of research dealing with the “from molecule to system” issue is establishing as a new, fundamental scientific field with exceptional potentials. This field differentiates from the areas of life sciences by the fact that problems are not oriented towards the molecular understanding of natural systems but towards the structure of technical systems. Key words in this context are (i) scale-spanning control of structure-properties and structure-process relationships, (ii) development of materials with active and adaptive properties and (iii) combination of synthetic and biological systems. This comes along with the socio-economic requirements for new materials management in accordance with nature. In this context, it is of minor importance whether the expression “system” demarcates a molecular function system in a very close sense, or the use, processing and function of molecular elements in a superordinate system, in a broader sense.

These aspects result in high claims for transdisciplinary procedures that cross the traditional borders between physics, chemistry, biology, computing science and polymer science as well as medicine and engineering science; and it shows that the necessity for research organisation oriented towards convergence is evident. It can be said that within the core area of polymer science the culture of disciplinary convergence has been present ever since. This has been promoted and supported for a long time by large research laboratories from the industry where interdisciplinary groups of researchers also work on fundamental scientific problems in a task-oriented manner (BASF, Bayer, Hoechst, Dupont, IBM, Xerox, Bell Labs and many more). Due to restructuring of large industrial companies and their increasing focus of research structures on short-term product development, this push-pull mechanism between academic and industrial research today is contributing less towards development and evolvement of science. At the same time, convergence among scientific disciplines is not in line with the traditional organisation of our scientific system and represents a challenge for disciplinary organisation and management of research. Ultimately, convergence requires new models for assignment of resources and administration/organisation of scientific work. This aspect has so far mainly prevailed within the institutes of non-university science. These facilities are the most likely to meet the condition for bringing together in one site a critical number of researchers who extensively represent the broadening field. Despite the great interdisciplinary and practical significance, polymer science, even in its widened form, remains a field where convergent research strategy is not always possible. For reasons of fundamental perspectives and importance of the research field for the German industry, it is reasonable and necessary to strengthen polymer science at the few sites it is offered and to expand networking with other material-oriented research activities. This should also be represented in the appointment policies of German universities.

In this context, identification of the scientists involved with their scientific field is very important. Only this can result in clear visibility. And visibility, in turn, is the precondition for further integration of the field, definition of joint objectives, common terminology, new cooperation projects, and not least adequate funding reflecting its significance. Disciplinary cultural and methodical limits evolve between engineers and natural scientists, on the one hand, and among natural scientists between chemists, physicists and bio-scientists. Convergence brings about the necessity to dismantle borders without giving up the specific disciplinary competences. An aspect of visibility is the rating of research results. On the one hand, rating is performed on the basis of the typical scientific criteria (impact; which underlies largely differing definitions, depending on the special field), on the other hand, on the basis of visible social and economic benefit. In both cases, material developments suffer from the fact that they are often protracted within a component development project by being used as enabler. The prerequisite for improvement is detailed discussion, development of common quality benchmarks and evolvement of an understanding for cross-discipline problems. A special approach for cross-discipline development results from digitalisation of the material understanding and from the joint challenge posed by the complexity of material structures and material processing procedures. For physics, this means that polymers with their special connectivity and complexity raise new fundamental questions.

Against this background, the question for expansion of the term of polymer research is raised: "(Condensed or Soft) Molecular Materials and Polymer Science". This expansion has already become a tradition in France and in many areas modern research in the field of polymer semiconductors is equal to solid-matter physics in its best classical sense. The challenge for both national and international representation of the field of research is an important task for national organisations, such as the division of Macromolecular Chemistry of the Gesellschaft der Deutschen Chemiker (GDCh), the Bunsen Society, the Deutsche Physikalische Gesellschaft, DPG, and the engineering scientists involved.[25] Organisation on a European level and international networking are still at a very early stage in comparison to North America. Also, the industry is increasingly in demand to strengthen their locational advantage for the field of research. However, improvement of visibility and integration are a prerequisite for clear commu-

25 Exemplary activities have been initiated by the division of macromolecular chemistry: new brochures, a university guide, a new website giving an overview of the working fields of the working group leaders, together with an overview of the studies and courses offered in Germany in the field of polymer sciences. For improvement of visibility, the upcoming anniversary of polymer sciences (100 years of macromolecular chemistry in 2020) should be intensively used. For this purpose, close interaction of the university lecturers for polymer sciences, the respective review board member at the DFG, the board of the division of macromolecular chemistry and the industry will be targeted. Within this scope the "modern terminology" of polymer science should also be communicated ("beyond plastic bags").

nication of innovation potentials to decision-makers and supporters/funders. For research institutes, this particularly refers to representation of the research field within the DFG, towards the BMBF, the BMWi and towards politics and the public.

Within the framework of the organisational structure of the Deutsche Forschungsgemeinschaft, polymer science projects are mainly recommended by the "Fachforum Chemie" (chemistry expert board). Consequently, these projects are managed separately from statistical physics projects or engineering science projects. The reviews are specifically obtained for every project by experts from various subjects but the final recommendation always remains chemistry-, physics-, or engineering-focused. The disadvantage of this classification is exclusion of engineering science projects and the limited coordination with physical and materials science requirements. Even within the chemistry expert board, delimitation of interests and competences for evaluation of projects becomes evident in many cases. This is due to the interest in structure-reactivity relationships on the one hand, and in structure-properties relationships on the other. Even for synthetics projects within macromolecular chemistry and physical-chemical characterisation of macromolecules, the convergence of competences is limited. This is revealed quite clearly in the support and promotion of young scientists. Young researchers, who proved to be very successful in their later professional life, have been rather underrepresented in the line-up for Emmyy-Noether scholarships/funding.[26]

Against the background of the above-stated development as fundamental challenge in research, the special need for convergence of the research fields involved and future further development of polymer science to become a Soft Matter Chemistry and Physics, there is the question about the extent to which a specific interdisciplinary experts forum is capable of promoting the field of research. In contrast to the area of medical engineering, the common interests here are fundamental rather than primarily application-oriented.

Another precondition for future internationally successful development of the research on molecular materials and polymer science is strong educational anchoring of the field. With regard to scientific convergence, the future challenges will be to promote transdisciplinary development within the scope of education; on the one hand, i.e. students will be given the possibilities for interdisciplinary working. On the other hand, the traditional competences need to be strengthened particularly during education to maintain the established fields of competence.

Within the field of education, it needs to be discussed to which extent a range of subjects similar to the field of technical chemistry and chemical engineering (DECHEMA) could be established to ensure comparative educational standards in all polymer science studies.

26 To achieve accurate clarification it would be interesting to evaluate the careers of the applicants for Emmy-Noether projects of the past 12 years with regard to their scientific disciplines.

notes

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