Preprint article from *Philosophy of Technology and Engineering Sciences*, ed. Anthonie Meijers
(*Handbook of the Philosophy of Science*, Vol. 9) Elsevier, 2009, pp. 1031-1068.

Aesthetic Values in Technology and Engineering Design

Authors

Joachim Schummer

Department of Philosophy, University of Darmstadt, Schloss, 64283 Darmstadt, Germany; js@hyle.org

Nigel Taylor

Department of Planning & Architecture, Faculty of Environment and Technology, University of the West of England, Bristol, Coldharbour Lane, Bristol, BS16 1QY, U.K.; Nigel.Taylor@uwe.ac.uk

Bruce MacLennan

Department of Electrical Engineering and Computer Science, University of Tennessee, 414 Ferris Hall, 1508 Middle Drive, Knoxville, TN 37996-2100, U.S.A.; mclennan@cs.utk.edu

Table of Contents

Keywords

Aesthetic values; Aesthetics; Architecture; Art; Beauty; Chemical engineering; Chemistry; Elegance; Modernism; Post-Modernism; Product design; Software engineering; Symmetry; Urban landscape planning; Visualization

Published in A. Meijers (ed.): *Philosophy of Technology and Engineering Sciences*, Elsevier, 2009, pp. 1031-68

1. Introduction

Author: Joachim Schummer

With few exceptions, most notably in architecture and product design, engineers have been used to pay little explicit attention to aesthetics. Most philosophers of technology have followed that model and excluded anything related to aesthetics from the philosophy of technology. The neglect seems to be justified on basic conceptual grounds. Indeed, many definitions of technology start with discussing the ambiguity of the term "art", in order to distinguish the useful arts from the fine arts: While both kinds of arts are productive or poiëtical in the Aristotelian sense, it is said that they fundamentally differ from each other by their values. The fine arts are governed by aesthetic values and thus constitute the proper realm of aesthetics, whereas the useful arts, i.e. technology, are governed by functional values, such as product performance, durability, cost, safety, and so on, as well as by epistemic values in so far as they produce technological knowledge. From such an approach it follows that aesthetic values play only a marginal and at most additional role in certain engineering fields such as product design, in order to please consumers and increase sales.

There is a long philosophical tradition of defining the fields of science, technology, fine arts, and ethics in terms of their dominating goals and values, with prominent examples by Aristotle and Kant.[1] However, even if certain values are dominating in or characteristic of a certain field, it would be naive to exclude them by definition from other fields in order to maintain a pure systematics. The distinctions between the useful and fine arts and between science and technology have always been debated and indeed redefined many times in the course of history, frequently reflecting the changing social status of the corresponding professions. Moreover, pure science that ignores any functional and ethical values is as hard to find as fine arts that completely exclude these values. Such as ethical values have always played a role in engineering, for instance by inspiring technological ideas of human progress or by prohibiting harmful technologies in codes of conduct, such have aesthetic values been influential by informing design processes, whether knowingly or not. Thus, the question is not *if* aesthetic values do or should play a role in technology. Instead, the question to be dealt with in this article is *how* aesthetic values inform technology and how they compete or harmonize with other values.

Aesthetic values are difficult to define and to identify in engineering activities for several reasons. One reason is that the professional aesthetics discourse has been too narrowly focused on the fine arts including literature, such that, particularly for many Anglo-Saxon aestheticists, aesthetics has become equivalent to the study of the fine arts or art criticism (e.g. Cooper [1992]). Unfortunately that makes their conceptual apparatus largely inappropriate for other fields of aesthetics, including engineering aesthetics. Another reason is that scientists and engineers frequently use terms such as "beautiful", which would otherwise be typical indicators of aesthetic appreciation, to express epistemic or functional approval or to popularize their activity to a broader public. It is useful therefore to start with a broad concept of aesthetic values by considering any values that are not of epistemic, functional, or ethical nature. The remaining values typically include familiar aesthetic values such as beauty, elegance, harmony, (non-epistemic) simplicity and clarity, and familiarity, as well their opposites on which aesthetic disapproval is based. In addition, something can aesthetically please or displease by resemblance to something else that pleases or displeases for aesthetic reasons only, which is typically expressed by analogies or metaphors and which sometimes leads to the formation of aesthetic styles. Whenever such aesthetic values contribute to preferences in engineering decisions, there is evidence that they inform the engineering activity.

---

1 For instance, Aristotle: *Metaphysics*, 980a ff.; Kant: *Critique of Judgement*, §§ 43ff.

The focus of this article is on how aesthetic values inform the process of functional engineering design. Rather than looking at how the engineering products are aesthetically received by consumers, we look at how they are designed by engineers and what role aesthetic values play in the research and design process. Of course the distinction is not always clear-cut because, depending on the engineering field, the design is frequently influenced by the anticipated reception by consumers. For instance, in industrial design, the anticipated aesthetic reception by consumers has become an important part of ergonomics that essentially informs design decisions. Moreover, our focus is less on the product itself than on the process of designing the product. That is, we are interested in how aesthetic values have an impact on the various activities and steps that contribute to the design process. That particularly includes the initial choice of the engineering problem to be solved, different steps of the cognitive process of functional design, and various representational tools and media that engineers use in their design process for visualizing and structuring the engineering problem, the strategies to solve it, and the final product.

Unlike the frequently assumed uniformity of technology, the various engineering fields have quite different historical traditions and methodologies, so that it is perhaps not surprising that the impact of aesthetic values, as well as the kind of aesthetic values that matter, differ accordingly. Since this article cannot cover all the engineering fields, we have made a selection of three fields that might represent to some extent the diversity of aesthetic values and traditions. The rationale behind the selection is that the size and visibility of the engineering product makes a crucial difference in how the product is designed, both regarding the cognitive processes involved and the representational tools used in that process, and that the role and kind of aesthetics might differ accordingly. Thus the first section, written by Nigel Taylor, deals with aesthetic values in the design of large-scale objects, exemplified by urban landscape planning and architecture. The second section, by Joachim Schummer, investigates the aesthetics of chemistry, which is usually not considered an engineering field, but fits well in our systematics because it has a major focus on the design of small-scale molecular objects. Finally, the subject of the third section, written by Bruce MacLennan, is the role of aesthetic values in the design of virtual objects as performed in software engineering.

Both our selection of the engineering fields and our focus on the design process are clear departures from the few classical treatments of aesthetics and technology, which are largely confined to architecture and industrial design. Of course, in architecture, and more recently in industrial design, aesthetics is frequently part of the standard curriculum, either in the form of historical accounts of styles or in the normative-didactic form of teaching students the principles of aesthetically preferred products. That tradition indeed goes back to Vitruvius who, in the oldest extant textbook of architecture from the first century BC, devoted a whole chapter to that topic (*De architectura*, III.1). The other classical topic is the "aesthetic assimilation" of machinery by modern artists (e.g., Mumford [1934, ch. VII.3]) and the complementary view of how industrial production has enabled a kind of mass art and influenced a mass aesthetics (Benjamin 1936), which became a standard critique of modern civilization. That has inspired many later sociological, frequently Marxist, studies on industrial design products and the social, political, and economical contexts that have determined their aesthetics (e.g., Haug [1971], Gartman [1994], Brummett [1999]). Furthermore, many critics of modern culture have argued that technology, because it would focus on functional values alone and ignore aesthetic values, drives our culture into an aesthetic vacuum. In so far as the critique was directed at the functionalist movement in 20th-century architecture and industrial design, it turned out, however, that functionalism is an aesthetic style in its own right, which tries to express functionality in its products by aesthetic elements, sometimes to the degree that its products become dysfunctional.

References

Benjamin, W. Das Kunstwerk im Zeitalter seiner technischen Reproduzierbarkeit (The Work of Art in the Age of Mechanical Reproduction). *Zeitschrift für Sozialforschung*, 1936.

Brummett, B. *Rhetoric of Machine Aesthetics*. Praeger, 1999.

Cooper, D. (ed.) *A Companion to Aesthetics*. Blackwell, 1992.

Gartman, D. *Auto-Opium: A Social History of American Automobile Design*. Routledge, 1994.

Haug, W.F. *Kritik der Warenästhetik*. Suhrkamp, 1971 (Engl. trans. as *Critique of commodity aesthetics*. Polity Press, 1986).

Mumford, L. *Technics and Civilization*. Harcourt Brace, 1934.

3. Designing small-scale objects: chemistry

Author: Joachim Schummer

3.1 Introduction

Chemistry is the study of material substances, their properties and, particularly, their chemical transformations into each other. The focus on chemical transformations explains chemistry's rather undefined position according to standard distinctions between science and technology [Schummer, 1997a]. On the one hand, chemical transformations constitute chemical properties, for instance the capacity to react under certain conditions with another substance to form a third substance, which are characteristic properties for each chemical substance. On the other, such chemical knowledge about substances enables one to actually perform these transformations in order to create new substances. Since the mid-19th century, theoretical developments, most notably molecular structure theory, have allowed chemists to design and synthesize new substances on a regular basis at a tremendous speed, such that there are in 2006 about 90 million known substances [CAS, 2007]. The synthetic activity, which dominates chemistry overall, establishes a clear similarity to the activity of engineers. However, only a small, but increasing, fraction of chemical synthesis is performed with the goal of providing useful applications outside of chemistry. Indeed most new substances are produced in the course of research to further improve the synthetic capacity of chemistry both on the experimental and theoretical level [Schummer, 1997b; 1997c].

The unclear status of synthetic chemistry, between being a science and being a technology in the received sense, which has recently been called technoscience, has opened a space for values other than scientific truth and technological performance. The task of this section is to investigate the role of aesthetic values in that space and if and how they have influenced research decisions and directions both in a positive and negative way from epistemic and utilitarian perspectives. Unlike many previous studies of aesthetics in science, I do not start with the a priori assumption that the impact of aesthetics is always positive with regard to other values. If there is an impact at all, it seems more likely that this results in a conflict of values. However, because of the unclear status, it is sometimes difficult to determine the exact impact of aesthetic values on classical epistemic and engineering values in chemistry. Moreover, because synthetic chemistry is embedded in the wider context of general chemistry, it is useful to consider also the role of aesthetic values in non-synthetic fields of chemistry.

Aesthetic studies of chemistry are still in a rudimentary state (for a first collection of essays, see Spector and Schummer [2003]). That is in contrast to the frequent references to aesthetics by many chemists. Indeed, since the mid-19th century chemists have frequently compared their synthetic work to that of artists, because like artists and unlike other natural scientists, they create their own objects of study on a regular basis or are creative inventors in a similar sense as artists are [Jacobs, 2006, ch. III.4-5]. However, such references sometimes make use of the ambiguity of the term 'art', which comprises the fine arts as well as engineering and crafts. Thus, not every reference to 'art' entails an unambiguous reference to aesthetic values. Moreover, since the 1960s, when the public justification of high energy physics for weapon research lost considerable ground, physicists have tried to rehabilitate their public image by pointing to the alleged beauty of their theories [Stevens, 2003]. The reference to beauty along with the comparison to the work of fine artists thus became standard rhetoric in the popularization of physics and other disciplines including chemistry. For an analysis of the role of aesthetic values in the actual research process, it is therefore necessary to exclude such popularizations efforts via beautification as long as they are, despite their popularity, just a façade.

The following analysis focuses on four aspects of chemical research in which aesthetic values have played a discernible role: microscopic structures with a particular focus on symmetry (4.2), molecular representations (4.3), chemical experimentation (4.4), and mathematical modeling in chemical engineering and physical chemistry (4.5). Because knowledge of chemistry is frequently not common among philosophically minded readers, I will draw only on very prominent research examples that were mostly awarded by Nobel Prizes. The underlying concept of aesthetic values, and of aesthetics more generally, is intentionally broad. As a guiding principle, I identify aesthetic values through appreciations by chemists that are clearly not based on epistemic, instrumental, or consequentialist-ethical values. The identification by exclusion has the advantage of clearly distinguishing aesthetic values from other value fields, which enables determining their mutual impact.[9]

3.2 The quest for symmetry as guiding and misguiding research principle

From ancient Greece to the early 19th century, symmetry was a purely aesthetic concept to describe the balanced proportions, which were taken from the model of the perfect human figure, both between the parts of an artwork and between each part and the whole. In contrast the modern concept of symmetry, which was developed only in mid-19th-century crystallography [Schummer, 2006a], is a mathematical description of forms according to the invariance with regard to certain transformations, such as reflection on a mirror plane, rotation around an axis at a certain angle, or lateral translation by a certain length. In this approach, the higher the symmetry, the simpler is the form, which makes symmetry a measure of mathematical simplicity. Because of the influence of Plato, who considered mathematical simplicity a measure of natural beauty, and because of the double meaning of the term "symmetry", mathematical symmetry has become an aesthetic criterion in science, unlike in art and aesthetics. Following Kant (*Critique of Judgement*, §22) one could argue that scientists value symmetry/simplicity because it pleases their epistemic rather than their aesthetic sense. However, in as much as symmetry/simplicity is not an accepted epistemic criterion in the experimental sciences, it describes an extra-epistemic value and an important heuristic research principle, and only as such it may be called aesthetic.

Mathematical symmetry plays a fundamental role in chemistry to describe crystal structures and molecules, to identify forms of molecular isomerism, to develop quantum-chemical models, to analyze spectroscopic results, and so on. There are even quantum-chemical rules, the Woodward-Hoffman rules for which Roald Hoffmann received the 1981 Nobel Prize in Chemistry, that predict the products of certain reactions from the symmetry of molecular orbitals. Apart from such routine uses, however, symmetry is also a guiding principle of research by suggesting certain explanations about the natural order of substances or certain synthetic strategies for the design of new products. In these extra-epistemic contexts, symmetry functions as an aesthetic principle that can guide or misguide research from an epistemic point of view. Three examples may illustrate that.

One of the most flourishing fields of chemistry since the 20th century is the synthesis and study of transition metal complexes. These compounds, which were long neglected because they belonged neither to organic nor to inorganic chemistry, have received particularly

[9] The disadvantage of this approach is that some sophisticated relationships between aesthetic and non-aesthetic values might be overlooked, such when aesthetic values and epistemic values tend to coincide or mutually contribute to each other or when aesthetic values are articulated in epistemic terms. However, as in any applied field, there is a limit to conceptual sophistication in applied aesthetics, because the concepts need to be useful to distinguish clearly between real cases based on the available evidence, whereas overly conceptual fine-tuning might only result in confusion.

attention because of their potential use as catalysts in petrochemical processes and polymer production. In liquid solution their structure is rather instable, so that they are complexes rather than molecules, which made their structural analysis very difficult. Synthesizing and studying hundreds of such compounds in the 1890s, Alfred Werner (1866-1919) brought order to the matter and thus established the entire field, for which he eventually received the Chemistry Nobel Prize in 1913. Since he found that other atoms combine with transition metals only at the numbers of 3, 4, 6, and 8, he suggested that these atoms are coordinated around the transition metals in a regular way. And because Werner, like Plato, believed that "nature" prefers simple and symmetrical structures, he suggested that complexes form regular polyhedra, for instance, that coordination number 6 corresponds to a regular octahedron. Werner's aesthetic intuition proved largely successful in later x-ray diffraction studies, but exceptions began to grow. In a theoretical study of 1937, Hermann A. Jahn and Edward Teller showed that in certain cases regular polyhedra are instable, such that the actual structures are distorted polyhedra. The result was a blow to all Platonist, because it suggested that "nature" sometimes prefers distortion to regularity. However, Werner's aesthetically driven choice has survived as a first-order approach to structural classification that distinguishes between regular structures as the norm and the distorted ones as exceptions.

While these distortions cannot be corrected by chemical means, there are many other examples where chemists have worked hard to produce the ideal, aesthetically preferred form. The most prominent one is the ideal crystal, which requires tremendous efforts at purification and recrystallization, without being ever achieved in practice because of remaining impurities and entropy effects. The ideal crystal has perfect translational symmetry such that a small unit represents the whole crystal, which allows for theoretical representation. In addition to these theoretical advantages, approximately ideal crystals sometimes have distinguished properties of practical importance. For instance, the perfect metal crystal has maximum electric conductivity and the perfect diamond has maximum transparency and stability. However, there is no general rule or law according to which only ideal crystals have properties optimized to material needs. In contrast, artisans such as smiths and steel-makers have long benefited from impurities and crystal defects in their products. Chemists, on the other hand, when synthesizing new materials for technical applications, have virtually always worked towards pure and ideal crystals and then checked for their suitable properties. The engineering approach by chemists thus follows the aesthetic preference of the pure and ideal form. While that has proved successful in some cases, it completely ignores, and despises, the entire field of impure, disordered, and defect crystals for aesthetic reasons. However, since the 1970s, that field has been explored by the newly emerging discipline of materials science and engineering. In particular, nanostructured materials, with crystal defects and disorders in the nanometer range, are the most flourishing and promising field, because tailoring the defects has become a means of tailoring unprecedented properties. The example illustrates that aesthetic values can be deeply misleading to the extent that they make you blind for rich opportunities, which, in this case, were harvested by others who either ignored or embraced the opposite of the aesthetic values.

Another chemical field in which the aesthetics of symmetrical forms has played a dominant role is the synthesis of molecules in which carbon atoms bind to form regular polyhedra or Platonic bodies. Since carbon atoms usually bind with bond angles of 109°, such molecules require increasingly distorted bonds if one goes from octahedron to cube to tetrahedron. Therefore, such molecules are extremely unstable and difficult to make, which requires sophisticated synthetic strategies. Indeed many research groups worked for years, if not for decades, on the synthesis of regular carbon polyhedra since the 1970s. It was rather like a sports competition, in which the goal was aesthetically attractive but extremely difficult to achieve [Grahn, 1981; de Meijere, 1982; Hoffmann, 1990; Hargittai, 2000, pp. 419f.]. Apart from the aesthetic attraction, it is questionable if there were at the beginning any aims involved other than that achieving the goal would require major improvements in the synthetic toolbox for the benefit of synthetic chemistry. Only later they discussed possible spin-offs, such as the use of these extremely unstable compounds as explosives or as cages for the inclusion of ions. The aesthetic fascination with regular carbon polyhedra even involved a broader public in 1985 when Harold Kroto, Robert Curl, and Richard Smalley incidentally made and discovered a soccer-ball-like stable carbon structure, which they called Buckminster fullerene and for which they received the 1996 Nobel Prize in Chemistry. Although that opened up the field of fullerenes as a new class of carbon compounds, for which technological applications were soon desperately sought for, the original fascination was a purely aesthetic one.

Taken together, the three examples discussed above prove that the classical aesthetic preference of symmetry and pure forms can play mixed roles with regard to expistemic and functional research values. It can provide a useful (first-order) guide, as with Werner's structural classification of transition metal complexes; it can be deeply misleading, as with the chemists' neglect of impure and defect crystals; and it can provide arbitrary orientation for research whose usefulness needs to be established only afterwards.

3.3 Aesthetics of molecular representations

Like in other fields of science and engineering, colorful images are nowadays omnipresent in chemistry both in research publications and in public presentations. Enabled by recently improved print and display technologies, these images help make a field more attractive to colleagues, students, and a general public and as such are tools of popularization. However, visual representations of molecules have also been very important in chemical research at least since the mid-19th century. Indeed chemists have developed their own sign languages which they use not only for presentations but also for their own research planning and contemplation. They have built their own molecular model sets or used stereo images for three-dimensional representations and eagerly embraced the latest innovations, including interactive Internet images and virtual reality sets for the visual understanding of molecular structures.

These visualizations are necessary tools in the research process, as they help formulate questions and find solutions. Thus, it is more than likely that the graphic styles and aesthetic elements have an important impact on chemical research directions, that research is frequently stimulated by aesthetic experiences. While case studies are rare is this area, chemists have frequently expressed ideas in that regard. There is at least one example illustrating that such aesthetic experiences can stimulate the development of an entirely new research field, here the fields of supramolecular chemistry and molecular nanotechnology [Schummer, 2006b].

In addition to their fascination with symmetrical molecules (see above), chemists have been particularly enthralled since the early 1980s by molecules that "look" like ordinary objects. Because molecules are invisible, indeed the result of a model approach that reasonably applies only to certain substance classes, it is rather a set of molecular images that have raised their fascination. These images are captivating because of their ambiguity. On the one hand they refer to entities in the molecular world, on the other hand they refer to objects of the ordinary world, like a basket with a handle, a wheel on an axis, or a two interlocked links of a chain. From a classical chemical point of view, these two worlds are quite disparate and disconnected from each other, because all the molecular properties that chemists are interested in are just missing in ordinary objects and vice versa. However, owing to their ambiguity, the images connected these two worlds in a productive manner that stimulated the imagination of combining both worlds into one. One way to combine both worlds appeared in cartoons of little humans walking through and playing with molecules like ordinary objects. Another way was to reproduce by chemical means the ordinary world in miniature. Indeed, since the 1980s, chemists have imitated all kinds of ordinary world objects on the molecular level, from funny things like dogs and pigs to technological artifacts like gears, turnstiles, and elevators. They have developed a whole battery of molecular systems and devices with various mechanical and electrical functions, like molecular machines and circuits. The field thus inspired by the aesthetic phenomenon of ambiguous images came to be known as supramolecular chemistry and, more recently, as molecular nanotechnology.

Umberto Eco's semiotic theory of aesthetics [Eco, 1962/1989] is a useful approach to understand the aesthetic inspiration that has triggered the historical development [Schummer, 2006b]. Faced with ambiguous signs, the interpreter is prompted to lower the tension of ambiguity by developing new, potentially reconciling interpretations and by contemplating and revising the form of the signs. Indeed supramolecular chemist have not only tried to solve the ambiguity by reproducing the ordinary world on the molecular level, they have also developed a new chemical language of technomorph signs which they frequently use in combination with classical structural formulas. In accordance with Eco's aesthetic theory, this creates a new productive tension that calls for reinterpretation and semiotic revision as a reiterative process, which chemists perform by exploring further parts of the ordinary world on the molecular level and adjusting their sign language. In Eco's theory, the process eventually reveals more about the interpreters and their imagination than about the original signs. Estimated from the specific areas of the ordinary world that chemists have selected to imitate on the molecular level, chemists revealed a deep fascination with mechanical and electrical engineering.

The aesthetic experiences that stimulated the emergence of supramolecular chemistry and molecular nanotechnology are difficult to grasp by the classical aesthetics of beauty. Moreover, it is hard to identify the aesthetic values underlying the chemists' aesthetic fascination with certain molecular representations. The example thus illustrates that the field of aesthetics in science is much richer than a simple product-oriented aesthetics of beauty would suggest, that intermediate representations and their symbolic references play an important role, and that more sophisticated aesthetic theories, like Eco's, are able to explain important research dynamics, which would otherwise remain miraculous.

3.4 Aesthetic virtues of chemical experimentation

Scientists frequently use aesthetic categories like beauty to denote the importance, historical significance, or model character of certain experiments, as in top ten lists of "the most beautiful experiments" [Freemantle, 2003]. In so doing, they make some kind of value judgments without expressing the specific kind of value they mean. In order to identify the aesthetic kernel of such statements it is useful to exclude first the non-aesthetic values that are frequently confused with beauty. If an experiment is valued only because it produced new knowledge or confirmed or refuted a theory, the underlying value is not of aesthetic but of epistemic nature. Likewise, historical significance or importance is clearly not an aesthetic but an instrumental value, because it values something only because it enabled something else, for instance the subsequent development or the present state of the art, which here alone is considered valuable in its own right. More generally, if an experiment is valued only because of its result, for instance the synthesis of an important substance or some economic improvement, it is not the experiment but the result that matters. This also includes all cases in which the experiment is ethically valued in a consequentialist sense, for instance if it helps avoid harm by providing useful insights or by replacing harmful procedures like animal experiments. If we thus exclude all epistemic, instrumental, and ethical values and focus on the experiment itself, any further evaluation is likely to be guided by aesthetic values.

It might be recalled that in the experimental sciences like chemistry, an experiment is not just a test for hypotheses as in mathematical physics, but also an explorative approach under controlled conditions that might be related to improving theoretical knowledge but is more frequently aimed at discovering new effects or phenomena, including new substances as in synthetic chemistry. In a recent book, Philip Ball has scrutinized historical experiments in chemistry for their aesthetic appreciation by the chemical community [Ball, 2005] (see also Schummer [2006c]). He found ten aesthetic traits that apply both to particular experiments and to the particular attitude of the experimenters in performing these experiments. By analogy with virtue ethics, one can speak of experimental virtues that are valued for aesthetic rather than epistemological reasons. Ball's ten virtues and the experimenters who exemplified them are: exact quantification (Johan Baptista van Helmont); attention to details (Henry Cavendish); patience in the conduct of the experiment (Marie Curie); elegance in the design of the experiment (Ernest Rutherford); miniaturization and acceleration of the experiment (various nuclear chemistry groups); conceptual simplicity (Louis Pasteur); imagination that transcends common views (Stanley Miller); simple-minded and straightforward reasoning (Neil Bartlett); economy and avoidance of deviations (Robert B. Woodward, see also Woodward [1989]); and conceptually straightforward design (Leo Paquette).

One might object that these experimental virtues are also valued for epistemological and instrumental reasons because they would enable experimental success. However, even if they enabled experimental success in the particular historical cases, on which later chemists might place their hopes, these virtues do not guarantee success. There is no logical relation between the virtues and experimental success. Even worse, some virtues seem to contradict each other, for instance, imagination that transcends common views and simple-minded and straightforward reasoning. Ball's analysis rather provides categories to describe different *styles* of experimentation that have been valued at different times by different communities or research groups. Such styles include, beyond the standard methodology of the discipline, particular ways to approach a problem, particular foci and care on certain aspects of experimentation, and particular ways of reasoning or designing. Beyond epistemic and instrumental values, experimental styles meet aesthetic preferences that might resonate with general aesthetic preferences of the corresponding socio-historical context.

Aesthetic values thus perform an intermediate function in chemical experimentation. On the one hand, they are believed to enable experimental success, which qualifies them for provisional instrumental or epistemic rather than for aesthetic values proper. On the other hand, because these beliefs have no methodological basis but rather refer to general aesthetic preferences, they provide aesthetic guidance of research. If such guidance is successful in the long run, the aesthetic values can be incorporated into the standard methodology of the discipline and thus become epistemic or instrumental values.

3.5 Aesthetic values in mathematical modeling of chemical engineering and physical chemistry

There is a long Platonic tradition in mathematics that considers mathematical simplicity an aesthetic value in its own right. Based on the metaphysical belief that nature has a simple mathematical structure, mathematical physicists have tried to combine aesthetics with epistemology in order to derive mathematical simplicity as an epistemological criterion in science. For instance, the Cambridge professor of mathematics Paul Dirac [1963] famously claimed that for a physical theory the mathematical beauty of its equations, here its algebraic symmetry, is more important than its accordance with experiments. Dirac's controversial claim reflects the particular epistemological tension between experimental and theoretical physics. His allusion to beauty helped him downplay the epistemological standards of the experimental sciences in favor of the epistemological standards of his own field. However, apart from such epistemological struggles, there is also an aesthetic appreciation of certain mathematical structures in fields that use mathematical models in a more instrumentalist way, particularly in chemical engineering and physical chemistry.

A major issue in chemical engineering is to develop mathematical models of industrial processes where standard physical approaches of analysis do not work for complexity reasons, for instance the fluid flow or heat transfer through a complicated system that cannot fully be described in simple geometrical and physical terms or that require too many parameters with too many functional dependencies. A standard modeling approach for such systems is dimensional analysis. The art of dimensional analysis consists in combining all possible parameters into a few terms such that all units cancel. In addition, these terms, which are called dimensionless numbers, must have a physical meaning and be accessible by the measurement of the system elements – for many standard engineering problems the data is even catalogued. If the analysis is successful, the modeling problem wondrously reduces from sheer overcomplexity to a simple equation with few retrievable parameters. This sudden mathematical simplicity frequently arises an aesthetic appreciation among engineers (see, for instance, Aris [1997]), which is above the suspicion of Platonist epistemology because the model must be feasible in industrial processes. However, as with all appreciations of mathematical simplicity, it would be wrong to say that the solution of the modeling problem is guided by aesthetic values, because reducing the mathematical complexity is actually the proper engineering goal. Instead, the aesthetic feeling arises only in addition to the satisfaction from solving the problem.

Apart from simplicity, there are other mathematical features that are aesthetically valued by chemists. In particular, formal analogies are prominent candidates. If the mathematical structure of one equation is analogous to the mathematical structure of another, this suggests that the two systems described by these equations are somehow related to each other. For instance, studying the phenomenon of osmosis of liquid solutions Jacobus Henricus van 't Hoff (1852-1911) derived in 1887 an equation that was formally analogous to the ideal gas law and for which he eventually received the first Chemistry Nobel Prize in 1901. The formal analogy made a deep aesthetic impression on many chemists and does so still today (see, for instance, Root-Bernstein [2003, p. 36]), because it connected two formerly disparate fields. It suggested that solutions and gases behave in similar ways and thereby eventually opened up the entire field of thermodynamics of solutions. Besides being scientifically productive, such analogies seem to be aesthetically satisfying because they suggest an underlying holistic structure of nature in which, despite the analytical approach of science, everything is related to each other.

One of the most impressive examples in this regard are the reciprocal relations by Lars Onsager (1903-1976), for which he received the Chemistry Nobel Prize in 1966. It was long known that a pressure difference causes matter flow, that a temperature difference causes heat flow, and so on for each pair of thermodynamic forces and flows. Yet, studying such forces and flows in more detail, Onsager found that a pressure difference can also cause heat flow and that a temperature difference can cause matter flow, and so on for each combination of thermodynamic forces and flows. Moreover, for each combination the flows are equal, which is mathematically expressed by the numerical equality of the reciprocal coefficients or by the symmetry of the coefficient matrix. Although Onsager's relations meet the need for mathematical simplicity, they clearly oppose the idea that nature is simple, because any flow is now related to any force, albeit in a regular way. Thus, the aesthetic satisfaction rather arises from the fact that, contrary to previous analytical approaches, the reciprocal relations reveal a deeply holistic structure of nature.

In general, there seem to be two different sources of aesthetic appreciation in mathematical modeling. One arises from unexpected or surprising mathematical simplicity, which equally applies to the modeling of natural and engineering systems. Other than an inclination to over-simplification, aesthetic values here cannot provide any extra-guidance of research, because what is aesthetically valued is at the same time the sought-after solution of the research problem. The other source of aesthetic appreciation seems to be rooted in metaphysical views of nature. Whether mathematical simplicity or the holistic constitution of nature, such metaphysical preconceptions are likely to have an impact on the personal choice of those research fields which promise aesthetic satisfaction to the individual researcher. In particular, the appreciation of analogous and holistic structures seems to be epistemologically productive because the exploration of analogies frequently opens up new insights and research directions.

3.6 Conclusion

In science as well as in everyday life, "beauty" is frequently used as a proxy for values that cannot be clearly defined. In this section I have tried to identify aesthetic appreciations of chemists by exclusion of appreciations that are based on epistemic, instrumental, and ethical values. Although the distinction is not always clear-cut, the results proof that there is ample space for aesthetic values in various areas of chemical research. Indeed aesthetic values have played important roles in selecting and designing synthetic targets, in designing and interpreting molecular representations, in designing and performing chemical experiments, and in developing mathematical models. The impact of aesthetic values has not always been productive with regard to epistemic and functional goals. Particularly the extreme fascination of chemists for symmetry and purity has led to a strong and persistent neglect of "dirty" and disordered materials, which the new discipline of materials science and engineering has systematically explored instead with many surprising results of economical importance. In other fields, however, particularly in supramolecular chemistry, the aesthetic fascination with molecules that "look" like ordinary objects has opened up an entire promising research field that is nowadays called nanotechnology. In chemical experimentation, where aesthetic values shape the particular styles of experimentation in the form of experimental virtues, aesthetics allows for an intermediate space for provisional and tentative methodological values. In all cases, whether productive or not, the aesthetic values of the individual researchers have been an important research motivation.

Because of its focus on epistemology and the justification of physical theories, philosophy of science has long neglected aesthetic values in science, unless they are treatable as quasi-epistemological criteria of mathematical equations in the Platonic tradition. However, scientific research is about the production of new knowledge rather than about the justification of old knowledge, and much scientific and all engineering knowledge is ultimately aimed at developing useful products. This makes science an arena for a multitude of different values, including aesthetic, ethical, economic, and epistemological, which may harmonize or be in conflict with each other. Understanding the role of aesthetic values in scientific research is therefore essential to the philosophical understanding of science. And because of its unclear position between science and technology in the received sense, chemistry is an excellent candidate to start with.

References

Aris, R. Reflections on Keats' equation. *Chemical Engineering Science*, 52 (15), 2447–2455, 1997 (reprinted in Aris, R. *Mathematical Modeling: A Chemical Engineer's Perspective*, pp. 400–414. Academic Press, 1999).

Ball, Ph. *Elegant Solutions: Ten Beautiful Experiments in Chemistry*. Royal Society of Chemistry, 2005.

Chemical Abstract Service (CAS). *Statistical Summary, 1907-2006*. Chemical Abstract Service, 2007.

de Meijere, A. Sport, Spiel, Spannung – die Chemie kleiner Ringe. *Chemie in unserer Zeit*, 16, 13–22, 1982.

Dirac, P. The evolution of the Physicist's Picture of Nature. *Scientific American*, 208 (May), 45–53, 1963.

Eco, U. *Opera aperta*, Bompiani 1962 (English trans. as *The Open Work*. Hutchinson, 1989).

Freemantle, M. Chemistry at its most beautiful. *Chemical and Engineering News*, 81(34), 27–30, 2003.

Grahn, W. Platonische Kohlenwasserstoffe. *Chemie in unserer Zeit*, 15, 52–61, 1981.

Hargittai, I. *Candid Science: Conversations with Famous Chemists*. Imperial College Press, 2000.

Hoffmann, R. Molecular Beauty. *The Journal of Aesthetics an Art Criticism*, 48, 191–204, 1990.

Jakobs, S. *"Selbst wenn ich Schiller sein könnte, wäre ich lieber Einstein": Naturwissenschaftler und ihre Wahrnehmung der "zwei Kulturen"*. Campus, 2006.

Laszlo, P. Foundations of Chemical Aesthetics. *Hyle: International Journal for Philosophy of Chemistry*, 9, 11–32, 2003.

Root-Bernstein, R. Sensual Chemistry: Aesthetics as a Motivation for Research. *Hyle: International Journal for Philosophy of Chemistry*, 9, 33–50, 2003.

Schummer, J. Ist die Chemie eine schöne Kunst? Ein Beitrag zum Verhältnis von Kunst und Wissenschaft. *Zeitschrift für Ästhetik und Allgemeine Kunstwissenschaft*, 40, 145–178, 1995.

Schummer, J. Challenging Standard Distinctions between Science and Technology: The Case of Preparative Chemistry. *Hyle: International Journal for Philosophy of Chemistry*, 3, 81–94, 1997a.

Schummer, J. Scientometric Studies on Chemistry I: The Exponential Growth of Chemical Substances, 1800-1995. *Scientometrics*, 39, 107–123, 1997b.

Schummer, J. Scientometric Studies on Chemistry II: Aims and Methods of Producing New Chemical Substances. *Scientometrics*, 39, 125–140, 1997c.

Schummer, J. Aesthetics of Chemical Products: Materials, Molecules, and Molecular Models. *Hyle: International Journal for Philosophy of Chemistry*, 9, 73–104, 2003.

Schummer, J. Symmetrie und Schönheit in Kunst und Wissenschaft. In *Ästhetik in der Wissenschaft*, W. Krohn ed., pp. 59–78. Meiner, 2006a.

Schummer, J. Gestalt Switch in Molecular Image Perception: The Aesthetic Origin of Molecular Nanotechnology in Supramolecular Chemistry. *Foundations of Chemistry*, 8, 53–72, 2006b.

Schummer, J. The End of Silent Rites. Book Review of Philip Ball: Elegant Solutions: Ten Beautiful Experiments in Chemistry. *Hyle: International Journal for Philosophy of Chemistry*, 12, 157–159, 2006c.

Spector, T.I. and Schummer, J. (eds.). *Aesthetics and Visualization in Chemistry*, special issue of *Hyle: International Journal for Philosophy of Chemistry*, 9 (1 & 2), 2003.

Stevens, H. Fundamental physics and its justifications, 1945-1993. *Historical Studies in the Physical and Biological Sciences*, 34, 151–197, 2003.

Woodward, C.E. Art and elegance in the synthesis of organic compounds: Robert Burns Woodward. In *Creative people at work: twelve cognitive case studies*, D.B. Wallace and H.E. Gruber, eds., pp. 227–253. Oxford University Press, 1989.

5. Conclusion

Author: Joachim Schummer

As was mentioned in the Introduction, the three engineering fields have been selected to represent different modes regarding the size and visibility of their respective engineering products, from large-scale to small-scale to virtual objects. In conclusion we may asked how that affects the role of aesthetics in the design process, if aesthetic differences correspond to this order, and if there are common aesthetic features in all fields.

Because aesthetics of engineering is still in its infancy and far from being a canonized field, the authors of the previous sections have each discussed their engineering domain from a personal angle, such that one should be careful with premature generalizations. However, if we move from the engineering of large-scale to small-scale to virtual objects, there are four trends in the aesthetic emphasis, some of which are obvious and less surprising, with important exceptions though. The first trend is the decreasing importance that the anticipated aesthetic experience by consumers plays in the design process. Of course that is a trivial observation, because the less visible and comprehensible the product structure by consumers is, the less need engineers in their design process consider the aesthetic experience by consumers. As a consequence, aesthetic considerations are less connected to general aesthetic discourses, which allows engineers to develop their specific aesthetic preferences in either a reflected or unconscious manner. In chemistry that has occasionally led to unlucky popularization efforts in which chemists publicly praised the alleged beauty of their molecules, which, however, nobody else was able to comprehend. Instead, for much of the general public, chemical products, like plastics, have become a symbol of the synthetic, artificial, and anti-natural, if not of excessive Modernism, which for aesthetic reasons alone have been rejected, regardless of their molecular structure. Software engineering seems to be the exception to the rule, since, as Bruce MacLennan argues in Section 4.2.2, the software structure that is aesthetically preferred by engineers is at the same time the software that users aesthetically enjoy most because of their transparency and intelligibility.

The second, equally less surprising, trend is that, if one moves from the engineering of large visible objects to that of virtual objects, the aesthetic role of primary sensual experience decreases. The second trend is compensated for, however, by the third trend of the increasing importance and increasingly deliberate use of representational tools and media, which become the primary objects of sensual experience for engineers in the design process and at the same time move the impact of aesthetic values to the early research state. The creation and selection of representational tools and media imply aesthetic choices and preferences that guide and shape the research and design process and its final products. In architecture the effect might be observable in slight design changes because of the recent shift from drawing boards to computer-aided design programs. In chemistry the creation and use of molecular models is so influential that it can inspire entirely new research fields (Section 3.3). Software engineers have even moved one step further by deliberately employing the latest psychological understanding of our sensorimotor capacities to build various metaphorical models, like physical spaces, for the representation of software in the design process (Section 4.6). What appears aesthetically preferable in the metaphorical model is thus translated into decisions about the preferred abstract structure of the software.

The forth trend concerns the relationship between aesthetic and epistemological values. In architecture and urban planning, the connection is less present, partly because architecture has been more removed from the epistemological mainstream discourse. However, from ancient architecture, as exemplified by Vitruvius, to Renaissance and Modernist architecture, particularly in the works of Le Corbusier, there were much stronger ties, since mathematical proportions figured prominently not only as aesthetic ideals but also as epistemic guidelines for adjusting constructions to human nature. In chemistry aesthetic values frequently assume the role of proto-epistemological criteria, i.e. they guide epistemological decisions in case of epistemological indetermination and, if they turn out to be successful in the long run, might be incorporated in the methodological standard canon (Section 3.4). Finally, in software engineering, at least in the aesthetics suggested by Bruce MacLennan (Section 4), aesthetic and epistemological values merge to form a common basis for assessing the quality of software.

A common feature in all three areas of engineering discussed in this article is the prominent, albeit slightly different, role that classical aesthetics, with its emphasis on mathematical purity and conceptual clarity, still plays today. This is perhaps less obvious in architecture and urban landscape planning; but, as Nigel Taylor argues in Section 2, contemporary aesthetic debates in architecture are still deeply influenced by early 20th-century Modernism and its aesthetic preference of pure geometrical form and the clear expression of function, which post-modernist approaches have tried to overcome. As guidelines for identifying and designing the "ideal" human environment, these classical aesthetic values have certainly failed in the excessive Modernists projects of post-WWII urban landscape planning. While classical aesthetics has been debated, and periodically embraced and rejected, in architecture for more than two thousand years, chemists discovered these aesthetic values only recently. As with the excesses of architectural Modernism, the chemists' obsession with geometrical symmetry and purity has led to many misconceptions and the almost complete neglect of "impure" materials, which others have very successfully harvested instead (Section 3.2). In the design of virtual objects, software engineering has inherited much from mathematics to the extent that the classical ideal of "beauty coinciding with intelligibility" becomes meaningful in as much as the criteria for beauty are related to mathematical features of abstract structures.

Another common feature in all three engineering field is the neglect of explicit treatments and serious investigations of aesthetics, although for different reasons. In architecture and urban landscape planning, which one would expect to make use of their long aesthetic tradition, the neglect is largely a heritage of the "anti-aesthetic" attitude of early 20th-century functionalism. In addition, as Nigel Taylor points out (Section 2.4), the more recent move of urban planning into the political sphere has led to the paradox that aesthetic aspects, although highly valued by citizens, are difficult to articulate in the political decision process. In chemistry the lack of serious aesthetic investigations is in accordance with a general neglect of chemistry, if not chemophobia, by most humanists, which chemists, on the other hand, are likely to increase rather than to overcome by popularization efforts that refer to beauty. In software engineering the neglect seems to be largely because of the youth of the discipline, because, as Bruce MacLennan emphasizes (Section 4.2.1), the use of aesthetic criteria is increasingly required because of the increasing complexity and functional underdetermination of software products.

The neglect of explicit considerations of aesthetics in engineering thus coincides with the richness of aesthetic values and their strong impact on the engineering design process at various stages, whether consciously or not. Since the aesthetic impact can be both productive and counter-productive with regard to purely functional values, as many examples in this chapter have illustrated, even the most functionalist-minded engineer or philosopher might become easily convinced of the need of further serious investigations of aesthetics in engineering.