AESTHETIC VALUES IN TECHNOLOGY AND ENGINEERING DESIGN

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1 INTRODUCTION

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

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

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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.

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.

2 DESIGNING LARGE-SCALE OBJECTS: URBAN LANDSCAPE PLANNING AND ARCHITECTURE

2.1 Introduction

The concern of this section is to identify and discuss the main aesthetic values that inform the process of contemporary urban landscape planning and architecture. Although the distinction is a fine one, it is worth emphasising that our primary focus will be on the aesthetic values that have informed the *process* of urban landscape planning and architecture rather than planning and architectural *outcomes*, and it follows from this that our primary focus will be on the main aesthetic *ideas and values* that have informed contemporary planning and architecture. Below, I begin by clarifying what, for the purposes of this section, we are refering to when we speak of contemporary urban and landscape planning, and architecture, and what, for the purposes of this review, I take *aesthetic* values to be. The aesthetic values that underpin contemporary architecture and planning have themselves been largely shaped by the ideas and values that came to dominate the Modern movement in architecture and planning during the late 19^{th} and early 20^{th} centuries.[2] Accordingly, following the clarification of basic terms, I shall provide a brief historical overview of the attitudes to aesthetic considerations that prevailed in the Modern movement in architecture and planning before I come to describe the main aesthetic ideas and values that inform contemporary planning and architecture. I shall conclude with some more general reflections on the status and political significance of aesthetics in contemporary planning and architecture.

First, our terms of reference. "Urban and rural/landscape planning"[3] is often run together with "architecture", as if these were two aspects of a single — or at least an integrated — discipline and practice. And in fact, this used to be the case, in that "town" planning (as it used to be called) was once widely viewed as an extension of architecture, in the sense that it was concerned with the physical planning and *design* of whole towns, cities, and even regions (see e.g. Keeble [1952] and Taylor [1998, Ch. 1]). However, since at least the 1960s this "physical design" conception of town and country (or urban and rural/landscape) planning has undergone radical questioning and transformation, so that today urban and landscape planning is viewed as a much more complex process of managing the social and economic functioning of urban settlements and regions, as well as just their physical design. Further, the process of making decisions about urban and rural development (and hence the process of urban and rural planning) is now viewed as a highly political process, since different interest groups and "stakeholders" will often hold differing and sometimes conflicting views and values about the nature and location of new developments such as new roads, airports, major shopping or other commercial developments, and so on. Consequently, the contemporary urban planner is no longer someone who plans towns and cities in the same way that architects design individual buildings, but rather someone who seeks to manage a complex process of arriving at plans and decisions about future urban develop-

[2]Throughout this paper I shall employ the upper case "M" to distinguish the Modern movement in architecture and planning from what is modern in the everyday sense of being recent.

[3]For shortness sake, I shall often just write "planning", instead of the full formulation "urban and rural/landscape" planning. It also needs to be noted that what is termed "urban and rural" planning is sometimes also referred to as "town and country" planning, "city and regional" planning, "environmental" planning, "spatial" planning, etc. In this review I treat all of these as synonymous.

ment in ways that reflect a range of different interests and values.[4] In short, urban planners are typically not themselves the authors and designers of urban plans in the same way that architects are of their buildings, and this has a bearing on our subject since, in architecture, individual architects may come to express their aesthetic values and visions in the buildings they design whereas, in contemporary urban and rural planning, individual planners have far less creative autonomy in the making of urban plans and so are less able to stamp their particular aesthetic visions on large-scale plans for urban and rural development.

2.2 Aesthetic values in modern architecture and urban planning

The aesthetic values of contemporary urban planning and architecture have been greatly influenced by attitudes to the aesthetic aspects of urban form and buildings that developed during rise of the Modern movement that came to dominate architecture and planning for most of the 20th century, and so a brief overview of the main tenets of Modernism is needed as a foundation to this account. Two points, in particular, emerge from Modernist planning and architecture, each of which stands in some tension to each other.

2.2.1 The Modernists' concern with functional design independent of aesthetic style

During the latter years of the 19th century and the early part of the 20th century, the pioneers of Modern architecture and planning found inspiration in the great, and seemingly purely utilitarian or functional forms of 19th century civil engineering, such as the iron bridges of Telford and Brunel, Paxton's Crystal Palace, Eiffel's famous tower for the Paris exhibition of 1889 (see e.g. [Giedion, 1941]). This fascination with the great works of 19th century engineering combined with an equally powerful disdain for the "revivalist" architecture that had dominated the 19th century, and the matching architectural theory that claimed that the quality which distinguished *architecture* from merely utilitarian *building* was "style". For most architects (and architectural theorists) of the 19th century, the distinguishing mark of architecture was a self-conscious concern with the aesthetics of built form *independent* of utilitarian or functional considerations. Such a view was articulated by the influential 19th-century critic John Ruskin who, in his book *The Seven Lamps of Architecture*, defined architecture in terms of the aesthetic aspect of building. And since the aesthetic content of a building was not strictly necessary to its utilitarian purpose, it followed for Ruskin that architecture concerned that aspect of building design that was, literally, "unnecessary". As he put it: "Let us [...] confine the name (of architecture) to that art which, taking up and admitting [...] the necessities and common uses of the building, impresses on its form certain characters venerable and beautiful, but otherwise unnecessary.

[4]For an account of the evolution of changing conceptions of urban planning over the last century see [Taylor, 1998; 1999].

[...] *that* is Architecture" [Ruskin, 1849, Ch. 1, pp. 14-15]. For Ruskin, then, considerations of style and aesthetics in their own right were what distinguished architecture from building. And this also distinguished architecture from engineering, for whereas the prime concern of architecture was with the aesthetics of built form (and hence style), the prime concern of engineering and construction was with structures that were functional to their purpose; indeed, this is what, for Ruskin, made architecture, but not engineering, an "art".[5]

Now, it was just this distinction between "aesthetic architecture" and "functional building and engineering" that the early Modernists contested. Thus they challenged, on the one hand, the view that purely functional buildings and forms could not also be works of architectural art, and, on the other hand, the view that architecture required ornamentation and "style" to *be* architecture. Indeed, some of the pioneers of Modernism went so far as to assert that a truly modern architecture — that is, an architecture consonant with the contemporary age of industry, science and engineering — should be an architecture whose forms were primarily, if not solely, governed by functional considerations, and hence an architecture that would be free of independent stylistic or aesthetic considerations. Thus the early Modern American architect Louis Sullivan suggested that the "form" of buildings should "follow" their function, and, as regards the use of "unnecessary" ornament on buildings, he wrote: "I should say that it would be greatly for our aesthetic good if we should refrain entirely from the use of ornament for a period of years, in order that our thought might concentrate upon the production of buildings well formed and comely in the nude" [Sullivan, 1892]. It was in this way that early Modernist architects downplayed aesthetic considerations, even to the extent regarding them as irrelevant to the design of (a genuinely modern) architecture.[6]

2.2.2 The aesthetics of geometrical "purism" in modern architecture and planning

In spite of the rhetoric of functionalism that played such a central role in early Modernist architecture and planning, we find that most of the leading figures of the Modern movement of architecture and planning were actually very particular about the aesthetics of the new Modern architecture, so much so that, by the 1930s, a distinguishable style — the so-called "International Style" — had come to dominate Modern architecture, so that henceforth Modern architecture became instantly recognisable because of its *style*. In particular, the kind of architectural forms preferred by the pioneers of Modern architecture were "pure" geometrical

[5]Ruskin also defined architecture as "the art which [...] disposes and adorns the edifices raised by man, for whatsoever uses, that the sight of them may contribute to his mental health, power, and pleasure" [Ruskin, 1849, Ch. 1, p. 13]. What Ruskin failed to acknowledge was that the great 19^{th}-century engineers also sought to create aesthetically beautiful forms whilst solving functional problems, as the writings of David Billington have made clear (see e.g. [Billington, 1979; 1983].

[6]As we shall see, not all Modernists adhered to this purely functionalist view of architectural design, but one who did was Hannes Meyer, the second director of the Bauhaus School of Art and Design (see e.g. [St John Wilson, 1995]).

forms — forms that were "pure" in two senses. First, the actual forms out of which the new architecture was composed were themselves *pure geometrical forms*, such as cubes, rectangles, cylinders, and cones, and second, these forms were pure in the sense that they were left *plain and undecorated*. Thus Le Corbusier, in one of the seminal texts of architectural Modernism, advocated an architecture of "primary" forms:

> Primary forms are beautiful forms because they can be clearly appreciated. [...] Architecture is the masterly, correct and magnificent play of masses brought together in light. [...] cubes, cones, cylinders or pyramids are the great primary forms which light reveals to advantage. [...] it is for this reason that these are *beautiful forms, the most beautiful forms*. [Le Corbusier, 1927, pp. 26, 31]

In fact, Le Corbusier was once held to be responsible for characterising Modern architecture as "functional" architecture because, in a letter he wrote to the Italian Alberto Sartoris about a book the latter was writing about the new architecture titled *Architettura Razionale* (*Rational Architecture*), Le Corbusier commented that: "The title of your book is limited: it is a real fault to be constrained to put the word *Rational* on one side of the barricade, and leave only the word *Academic* to be put on the other. Instead of Rational say *Functional* [...]" (quoted in Banham [1960, Ch. 22, p. 320]).[7] In spite of this, Le Corbusier was one of the leading advocates of the purist aesthetics of Modern architecture (see St John Wilson [1995]), and in his *Towards a New Architecture*, he drew essentially the same distinction between architecture and engineering as Ruskin had earlier drawn:

> it will be a delight to talk of ARCHITECTURE after so many grain stores, workshops, machines and skyscrapers. ARCHITECTURE is a thing of art, a phenomenon of the emotions, lying outside questions of construction and beyond them. [...] You employ stone, wood and concrete, and with these materials you build houses and palaces; that is construction. Ingenuity is at work. But suddenly you touch my heart, you do me good, I am happy and I say: 'This is beautiful'. That is Architecture. Art enters in. My house is practical. I thank you, as I might thank railway engineers or the telephone service. You have not touched my heart. But suppose that walls rise towards heaven in such a way that I am moved. [...] The relationships between them have not necessarily any reference to what is practical or descriptive. They are a mathematical creation of your mind. They are the language of Architecture. By the use of inert materials and starting from conditions more or less utilitarian, you have established certain relationships

[7]Sartoris quoted Le Corbusier's letter approvingly in the preface to his book, which was published in 1932 with the revised title *Gli Elementi dell'Architecttura Funzionale* (*The Elements of Functional Architecture*).

> which have aroused my emotions. This is Architecture. [Le Corbusier, 1927, pp. 23, 187]

In short, in spite of the rhetoric about functional design in the Modern movement, there emerged a distinct "purist" aesthetic style that governed Modern architecture, and indeed, this often prevailed at the expense of genuine functional design (see again [St John Wilson, 1995]). And it was the very ubiquity of the aesthetic values of pure geometrical form, plain undecorated surfaces, and harmonious geometric proportions that, by the 1930s, led Modern architecture to be instantly recognisable as a distinctive style. And it was because this style was adopted by Modernists right across Europe and North America that the style was later dubbed the "International Style".

Three points are worth adding to this account of the aesthetic values that underpinned Modern architecture. First, whilst the early Modern architects praised, and in many ways sought to imitate, the purist aesthetics of the functional forms designed by the civil engineers of the 19th and 20th centuries, it is misleading to presume that, for their part, the great engineers were only preoccupied with functional considerations in their designs. To be sure, bridges and grain stores had, of necessity, to be fit for their purposes of spanning rivers and storing grain. But as David Billington has pointed out in a succession of writings (e.g. [Billington, 1979; 1983]), the great engineers of the 19th and 20th centuries sought also to create beautiful forms and, in so doing, most of them also sought to create forms of geometrical purity and harmonious proportions. In this respect, Billington [1979] is correct to describe the memorable works of 19th and 20th century civil engineering — such as Robert Maillart's bridges — as works of "structural art".

Second, the aesthetic values — of both the great engineers and the early Modernist architects — which emphasised purity of plain geometrical forms and harmonious proportion were values that had been emphasised before in Western architectural and engineering design, namely, in the great tradition of classicism. For this reason, in spite of its seemingly radical new forms, Modern architecture has sometimes been viewed as a revival of *classical* aesthetic values (see e.g. [Gelernter, 1995, Ch. 8, pp. 225-229; Ch. 9, pp. 252-254]).

Third, the purist aesthetics of Modern architecture also found expression in Modernist urban planning which, in the era of the rise of Modernism, was dominated by Modern architects' visions of the "city of the future" (see e.g. [Taylor, 1998, Ch. 2]). Le Corbusier was again an important figure here, arguing for the modern city to be more clearly organised than its historical counterpart, with the major urban land uses distinguished from each other and allocated to distinct "zones", and also advocating a radically new urban morphology in which urban activities such as housing and commerce would be accommodated in large tower and slab blocks standing in open parkland and connected by urban expressways (see [Le Corbusier, 1924; 1933]). Such a vision represented a new conception of urban space in which buildings would stand out as individual forms punctuating a sea of free-flowing space, rather than being viewed in combination with other buildings that together bounded and defined distinct urban spaces such as streets and squares. This open-ended conception of space was also a central aesthetic value in the new architecture, where great sheets of glass curtain walls broke down the visual barrier between the outside and inside of buildings, thus allowing space seemingly to flow freely through buildings.

2.3 The critique of Modernist architecture and urban planning, and aesthetic values in architecture and planning in the contemporary "post-modern" era

According to some accounts, the Modernist architectural ideas and values described in the previous section had all been worked through by the end of the 1920s, so that this excursion into early Modernist aesthetic values might not seem so relevant to an examination of aesthetic values in architecture and urban planning today. But such a response would be superficial. For the Modernist ideas and values that developed at the beginning of the 20th century cast a spell over the remainder of that century and, in many respects, continue to hold sway today. Thus the design and form of many contemporary large-scale works of architecture and engineering continue to be informed and shaped by the purist geometrical aesthetics that were the mark of Modernism, so much so that some architects and critics continue to refer to this work as stylistically (if not ideologically) "Modernist" or, perhaps, as "Late Modernist" (see e.g. [Jencks, 1980]). What has complicated the picture over the last forty years since the 1960s has been the emergence of a vigorous critique of Modernism in architecture and planning, and the consequent assertion of alternative aesthetic values.

The reaction against Modernism came first in urban planning in the early 1960s. The heyday of Modernism in architecture and planning was, in fact, in the quarter century following the Second World War, when the Modernist ideas that had emerged in the first half of the 20th century were enthusiastically adopted for large-scale schemes of "post-war" urban planning, most famously and notoriously in the great schemes of "slum clearance", "comprehensive redevelopment", and social housing that took place in most of the old industrial cities of Europe and North America, but also in the planning and building of completely new cities, such as the new capital cities of Brasilia and Chandigarh. And very quickly most of these schemes of Modernist urban surgery came to be regarded as having failed, abysmally, to create either the functionally efficient or the aesthetically beautiful utopias that the pioneers of Modernism had dreamed of. Indeed, so quick was the revulsion against what Alison Ravetz described as the Modernist "clean sweep" approach to planning that, in 1972, the award-winning Pruitt-Igoe social housing scheme in St Louis, Missouri, was itself largely swept away by being dynamited. And paradoxically (given the functionalist rhetoric that had attended the rise of Modern architecture), it was precisely the lack of an adequate analysis and understanding of how successful cities (and the human beings within them) functioned that was at the heart of the trenchant criticisms of Modernist urban planning of the 1960s. Thus Jane Jacobs [1961] and Christopher Alexander [1965] pointed out that the Modernist urban utopias of architects such as Le Corbusier showed no real understanding of the subtle and complex inter-relationships between people and activities in real cities. Here, again, lay that conflict between the requirements of genuine functional planning and design, and the "purist" aesthetic values that, under the influence of such figures as Le Corbusier, had come to dominate Modern urban planning as well as Modern architecture. But the new post-war architecture and planning was also criticised simply in aesthetic terms. For the repetition of the same (or similar) bare blocks across large tracts of towns was seen as visually monotonous and alienating. As Charles Jencks put it, in reflecting with relief on the passing of the aesthetics of mass-produced Modern architecture, " the era of stupid and inarticulate slabs is over, the age of the repetitive cliché is finished" [Jencks, 2002, p. 2].

It was the lack of aesthetic richness and variety in Modern architecture that was the focus of Robert Venturi's criticism of "International Style" Modernism in his seminal publication *Complexity and Contradiction in Architecture* of 1966. At the outset, Venturi parodied the accepted aesthetic norms of "International Style" Modernism in opening his book by countering these with their opposites and implying that the choice between the two was not, as some Modernists had claimed, a rational one, but rather one of personal aesthetic taste and preference:

> I like complexity and contradiction in architecture. [...] Everywhere, except in architecture, complexity and contradiction have been acknowledged [...]. Architects can no longer afford to be intimidated by the puritanically moral language of orthodox Modern architecture. I like elements that are hybrid rather than 'pure', compromising rather than 'clean', distorted rather than 'straightforward', ambiguous rather than 'articulated' [...]. I am for messy vitality over obvious unity [...]. I am for richness of meaning rather than clarity of meaning. [Venturi, 1966/1977, Ch. 1, p. 16]

In place of the aesthetic purism and minimalism of Modern architecture, Venturi advocated an architecture that is aesthetically diverse and complex, even ambiguous and contradictory, and which is also unafraid to re-introduce ornament and decoration into its forms and surfaces. It was thus that Venturi's *Complexity and Contradiction* became the inspiration for "Post-Modern" architecture that overtly challenged the aesthetic values of Modernism, even to the extent of reviving historical architectural styles and motifs (see e.g. [Jencks, 1977]). Indeed, just as some past periods of architecture have witnessed a "battle of styles" (e.g. between neo-classical and neo-gothic styles in the 19th century), so the last forty years have witnessed a similar battle between those architects and designers who have wished to perpetuate whilst further developing the project of Modernism, and those Post-Modernists and others who have sought to challenge and go beyond Modernism.

To be sure, the on-going protagonists of Modernism have not simply persisted with reproductions of the "International Style". As Modernists, they have insisted that a genuinely Modern architecture must be modern in the everyday sense of designing buildings that use the materials and possibilities generated by the latest technology; hence the coining of the terms “Late Modern” and “Hi-Tech” to describe the varieties of architecture that have been spawned by this late efflorescence of Modernism. Nonetheless — and at the risk of some crudeness of generalisation — what makes this Late Modern architecture still *aesthetically* Modern is the persistence of a preference for pure form and plain, undecorated surfaces. We see this, for example, in contemporary glass architecture, which, in its pristine elegance and light transparency, is the inheritor of that formally minimalist tradition pioneered by Mies van der Rohe. In contrast to this contemporary Modernist architecture, “Post-Modern” architecture is characterised by an eclectic mix of building styles — some “progressive” in the sense that its authors are unafraid to adopt recognisably Modern forms and yet equally unafraid to mix these with more traditional echoes and decorative motifs, some conservative to the extent of reviving — lock, stock and barrel — the architectural styles of a past age. The architecture of (for example) Michael Graves illustrates the former tendency, while the replica Georgian terraces and mansions of Quinlan Terry are an example of the latter.

This account has come to focus on the contemporary scene in *architecture*, and a brief word needs to be added about the aesthetic values of contemporary engineering and urban planning to provide a more balanced picture. In the case of those large-scale objects in townscapes and landscapes that are chiefly the products of contemporary civil engineering, such as new bridges and power stations, the aesthetic form of these has continued to be — perhaps for necessary functional as well as aesthetic reasons — to reflect those aesthetic values of pure geometrical form and harmonious proportions that became the hall-mark of Modern design (see again [Billington, 1983]). By contrast, the state of affairs in urban planning following the disasters of large-scale modernist development of the 1960s is altogether more complex. But two generalisations can be made. First, the general failing of modernist architect-planners to understand and plan sensitively for the greater complexity of cities and human settlements led to a radical change of view about the nature of urban planning as a profession and the most appropriate qualifications for its practice. In particular, the view emerged that — at least at the larger scales of the planning of the land uses and development of whole cities and regions — planners with a prior training in geography and/or the social sciences were better equipped properly to undertake the necessary analysis for this kind of urban planning. This refocusing of the profession of urban planning away from architecture and design led in turn to a greater emphasis being placed on “social and economic” (and also political) considerations in urban planning, and a corresponding downplaying of aesthetic considerations (see e.g. [Taylor, 1998, pt. II]). Secondly, in so far as aesthetic considerations did continue to play a part in urban planning and decision-making about large-scale development, there emerged a renewed emphasis on the “rehabilitation” of old buildings, rather than their comprehensive redevelopment, and more generally a concern for urban conservation and environmental protection. This more conservative aesthetic has arisen partly in reaction against the large-scale comprehensive planning of the 1960s that had so insensitively swept away large tracts of cities to which many citizens were emotionally attached, and partly as a result of the emergence of ecological thinking and the "green" movement after the 1960s, (see e.g. [Bishop and Phillips, 2004; Larkham, 1996]). It can also be seen to be a result of the greater politicisation of urban planning as a result of the protests of communities against the insensitive planning of the 1950s and 60s; as noted in the introduction, to a much greater extent than architecture, what now happens in the name of urban planning is often the result of many voices and interests, rather than a single creative designer.

2.4 Conclusion: the importance of aesthetic values in contemporary urban development and planning

I shall conclude this brief resume of the aesthetic values that have informed contemporary architecture and urban planning by commenting more explicitly on the importance attributed to aesthetic considerations in the process of design and planning. I offer three general reflections.

First, although the Modern movement in architecture and planning was heavily infused with the rhetoric of "functionalism" and, connectedly, with the notion of "rational design", as we have seen, its chief protagonists advanced some clear aesthetic values, namely, those that emphasised the "classical" virtues of pure geometry and proportion, combined with a utilitarian cleansing away of "unnecessary" ornamentation and decoration. Nonetheless, the rhetoric of functionalism and rationality did have an important impact in undermining the importance attributed to aesthetic considerations in the training of architects and planners, and — by extension — in the process of architectural design and decision-making in urban planning. Thus still today many university programmes in architecture and planning do not contain any separate courses on, or provide any systematic education in, aesthetics. In this respect, the process of design in contemporary architecture and urban planning remains what Hearn [2003, Ch. 4, p. 81] has termed an "inside-out" approach in which the design, and hence the exterior form of built structures is determined primarily by the prior demands of how best to accommodate the internal functions, rather than by some preconceived idea of what the exterior form should look like. In this respect, Le Corbusier's observation that "The plan is the generator" has indeed come to pass [Le Corbusier, 1927, pt. III, pp 44-45].

Second, this relegation of aesthetic values to (at best) a subsidiary role in the process of contemporary architectural design and planning mirrors the relatively minor importance attributed to environmental aesthetic considerations in political decision-making, and in contemporary developed societies more generally. Thus in considering proposals to build new power stations or shopping centres, roads or port facilities, the primary focus of debate in contemporary societies tends to be on current or projected demands for energy, consumer products, travel and transhipment, rather than on the aesthetic impact that the large-scale structures associated with these activities will necessarily have on the landscape. To be sure, since (roughly) the 1980s, the wider "environmental" impact of planned large-scale developments has become an ever increasingly important consideration. But these wider environmental considerations focus mostly on the degree to which new development is "environmentally sustainable", and here the prime considerations are ecological, not aesthetic. But the marginalisation of aesthetic considerations in contemporary developed societies is also associated with more deeply ingrained attitudes, values, and philosophical assumptions. Thus, even when it is acknowledged that the aesthetic quality of our surroundings is important, the objection is frequently made that qualitative aesthetic judgements are a matter of "subjective" personal taste, from which it is typically inferred that there can be no generally accepted norms or principles to govern the aesthetic form or "style" of major new developments. Then again, and perhaps because of its association with "the arts", the aesthetics of architecture and planning are widely assumed to be just a "luxury" in comparison with allegedly more fundamental "social and economic" matters, and even, because of this, only of importance to privileged elites or the "middle-class".[8]

And yet, in spite of these prevailing attitudes and values, almost every day numerous cases surface where it is apparent that ordinary people do care enormously about the aesthetic quality of their surroundings and the large-scale objects that threaten to alter the character of places. Recent controversies over the siting of wind turbines in open landscapes (in spite of their otherwise beneficial environmental effects) are a vivid illustration of this concern, as are the numerous other campaigns that have been fought throughout the developed world, often with great passion, against new development proposals for roads, airports, etc, that bring about the destruction of cherished landscapes and townscapes. We touch here on a paradox concerning this subject. This is that, on the one hand, it often appears that aesthetic considerations in relation to the built environment are not highly valued. And yet, on the other hand, there is also plenty of evidence — for example, from people's choices about where to live and take their leisure — that suggests that the aesthetic quality of places is of central importance to the quality of people's lives. Certainly, the latter has been revealed in some studies. Thus, in a very thorough investigation into people's attitudes to green urban open spaces (urban parks) in London, Jacqueline Burgess and her fellow researchers showed that ordinary working class people, including ethnic minorities, valued very highly the sensory, aesthetic pleasures of having access to green urban spaces, so that this was very far from being an unimportant, or simply a "middle class", issue (see [Burgess *et al.*, 1988]). Whilst, then, aesthetic values rarely figure prominently in everyday public and political debate, and so might seem to be an unimportant political issue, in people's everyday lives, and in numerous local campaigns and forms

[8] One of the characters in Milan Kundera's novel *The Unbearable Lightness of Being* — Sabina, a painter — considers that, for all our material wealth, our age is an age of ugliness, or at least an age where a concern with the beauty of our surroundings is not widely thought to be a central factor in the quality of life [Kundera 1984, p 93].

of "community action", the aesthetic quality of the built environment emerges as a most important, and often highly charged political matter.

3 DESIGNING SMALL-SCALE OBJECTS: CHEMISTRY

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 (3.2), molecular representations (3.3), chemical experimentation (3.4), and mathematical modeling in chemical engineering and physical chemistry (3.5). 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

[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.

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 late 19$^{\text{th}}$ century has been 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 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 or proven statistical 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, or 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.

4 DESIGNING VIRTUAL OBJECTS: SOFTWARE ENGINEERING

4.1 Introduction

Software engineering is a historically new activity, so it does not have a long aesthetic tradition as do the other arts and engineering disciplines. Therefore it is helpful to begin our aesthetic inquiry with analogies to longer-established disciplines, always keeping in mind the distinctive characteristics of software. In this article I will draw analogies principally from two sources. First, because software systems are large and complex, often constructed by teams, intended to serve a useful function, and capable of causing injury and economic loss if they fail, I will draw analogies from the structural engineering of towers and bridges (e.g., [Billington, 1983]), which shares these characteristics. This will lead to an exploration of the practical importance of elegance for both the designers and users of software systems. Second, because of the abstract and formal character of software I will draw analogies with aesthetics in the exact sciences, including mathematics (e.g., [Heisenberg, 1975]). Here we find that beauty depends on a harmonious interrelationship among the parts of an organic whole. Next I will discuss means for making abstract aesthetic qualities perceptible, including visual programming languages and models grounded in human embodiment. Finally, I will consider how we may advance the aesthetic dimension of software engineering.

4.2 Importance of aesthetics in software engineering

4.2.1 Designer's perspective

Following Billington [1983] we may identify three dimensions along which designs may be evaluated: *efficiency*, *economy*, and *elegance* — "the Three E's." These correspond to three aspects of any artifact, the *scientific*, *social*, and *symbolic* ("the Three S's"). *Efficiency* deals with the physical resources used by the system, which in the case of software artifacts is primarily computer time and memory. Typically there are tradeoffs involved, with efficiency weighed against factors such as functionality, reliability, and maintainability. These are *scientific* issues because they concern the physical resource utilization of the system's design.

Economy refers to all aspects of the cost of the system, including hardware and human costs, in all phases, including development, use, and maintenance. These are *social* issues because costs depend on market forces, social processes, governmental policies, etc. Due to the uncertainties in these factors, the economy of a design is more difficult to evaluate than its efficiency, and it is subject to change and local context. Furthermore, it cannot be assumed that all costs can be reduced to a common denominator, such as money, as is often the case with human suffering.

This brings us to the explicitly aesthetic dimension of a design, its *elegance*, which depends on the aspects that Billington calls *symbolic*. Although we may take for granted that aesthetically appealing designs should be preferred, other things being equal, there are other compelling reasons for preferring elegant designs, but to understand them we need to review some of the characteristics of software systems. (See also [MacLennan, 1999, pp. 156–60].)

Modern software systems can be enormously complex, often comprising millions of lines of instructions. Even a text editor, generally considered a basic software tool, can be hundreds of thousands of lines in length (e.g., the open source "vim 7.0" editor has approximately 300 000 lines of source code). The steady increase in software complexity has resulted from a number of factors (both scientific and social), including the increasing capacity and speed of computer systems, users' demands for new features and richer interfaces, and competing systems with more features.

Software systems with such large numbers of instructions are among the most complex systems ever constructed, and analytic tools for understanding them (such as program verifiers and test generators) are still quite limited. The complexity results in part from the fact that these millions of components interact with each other (and with other software and hardware systems) in real time, and that the number of interactions to be considered increases with at least the square of the number of components. Furthermore, the components (e.g., computer instructions) are far removed from physical objects and interactions for which we have an intuitive basis for understanding (e.g., the physical components and interactions of a mechanical system). Therefore, our intuition is set adrift, and our analytical tools do little to anchor it.

Every analysis makes idealizing simplifications, and generally, the more complex the system, the greater will be the simplifications in its analysis. In the case of physical systems, for example, we may assume that the dynamics is linear, because that simplifies the mathematical analysis (or makes it feasible), even though we know that it is nonlinear. In the case of a software system, we may assume that any two numbers can be added and that the result will be correct, although we know that computer arithmetic is limited in range and precision. Similarly we may assume that input-output processes and other system services will operate correctly and be completed within real-time constraints.

It is important to realize that simplification is an inherent limitation in the analysis of complex systems, since an analysis is supposed to separate out the relevant features of the system, so that we can understand them better (with our limited cognitive capacities), from the irrelevant features (which we intend to ignore). Therefore the validity and usefulness of an analysis depends on decisions (sometimes tacit) as to what the analysis should include or omit, which derive from assumptions (often unconscious) as to what is relevant or irrelevant. Furthermore, since human cognitive capacities are limited, the more complex a system is, the more must be omitted from its analysis so that the analysis itself will not exceed our understanding. Thus there are inherent limitations to the analysis of very complex systems, such as modern software systems.

Similar problems arise in structural engineering, and Billington observes that the best structural engineers are guided by aesthetics as well as by mathematical analysis. In elegant designs the dispositions of masses and forces are manifest in the design, and therefore the designs that look good (look balanced, secure, stable, etc.) correspond to the designs that are safe, efficient, and economical. For example, although extensive mathematical analysis was used in the design of the Tacoma Narrows Bridge, it collapsed four months after it was completed because aerodynamic stability had not been included in the analysis (it was not considered relevant). In contrast earlier bridges, designed without the benefit of complex mathematical models but in accord with aesthetic principles, were aerodynamically stable. How is it possible that good aesthetics can lead to good engineering?

Billington observes that in structural engineering, designs are under-determined, that is, there are many designs that will solve a particular structural engineering problem, such as bridging a certain river (see also [Ferguson, 1992, p. 23]). Therefore, in contrast to Louis Sullivan's architectural maxim, *form follows function*, which suggests that the design is strongly determined by its function, Billington argues that the more appropriate structural engineering maxim is *function follows form*, because there are many structures that will accomplish a particular function. The same arguments are even more applicable in software engineering, in which typically many different software designs will satisfy the system requirements. Therefore in software engineering we have a great deal of freedom in the choice of solutions to a software problem.

In particular, software engineers (like structural engineers) can choose to work in a region of the design space in which experience has shown that designs that *look good* in fact *are good* (e.g., safe, efficient, and economical). In the case of towers and bridges, such designs make the interaction of forces manifest, so that designers (and, as we will see, users) can perceive them clearly. Since aesthetic judgment is a highly integrative cognitive process, combining perception of subtle relationships with conscious and unconscious intellectual and emotional interpretation, it can be used to guide the design process by forming an overall assessment of the myriad interactions in a complex software system.

The discussion thus far has focused on the cognitive aspects of aesthetics, for an elegant software system is easier to understand and can be designed more reliably than an inelegant one. Thus there are practical, engineering reasons for striving for elegance. However, aesthetics also plays a less tangible role, which may be called *ethical*, for a design also symbolizes a set of moral values. Specifically, if a designer is seeking an elegant design, then they are being guided by a set of aesthetic values (which imply engineering values in the chosen subset of the design space). A design may be robust or delicate, spare or rich in features, straight forward or subtle, ad hoc or general, and so forth, and the values exemplified in the design will call forth extensions and modifications consistent with those values. By keeping certain values, embodied in the design aesthetic, before the designers' eyes, these values will be kept in their attention and persist as conscious goals. Conversely, values incompatible with the aesthetic, or not exemplified by it, will tend to recede into the background of the designers' minds, and will be underrepresented in the design. Thus a software system may embody a coherent ethical-aesthetic character, which is difficult to state in words but can guide the aesthetically sensitive engineer.

Aesthetic appreciation can unite a software development organization through a common set of values embodied in a shared sense of elegance. We can see a similar role for aesthetics among mathematicians and theoretical scientists, who strive for proofs and theories that are elegant. For example, Heisenberg [1975, p. 176] says that science "also has an important social and ethical aspect; for many men can take an active part in it." Scientists, he says, are like the master masons who constructed the medieval cathedrals, for "[t]hey were imbued with the idea of beauty posited by the original forms, and were compelled by their task to carry out exact and meticulous work in accordance with these forms" (*ibid.*). Like cathedrals and scientific theories, large software projects are the result of the efforts of many people, and aesthetic standards provide criteria by which individual contributions can be objectively evaluated (*ibid.*).

Thus, in software engineering, as in mathematics and theoretical science, correctness is required, but among the correct solutions, the more elegant are preferred. (The education of mathematicians and theoretical scientists also provides models for how a shared sense of software elegance might be learned.) Therefore a shared aesthetic sense can unite a software engineering team in a common purpose.

4.2.2 User's perspective

Hitherto I have stressed the importance of aesthetics for the *designers* of software artifacts, but it is also important for the *users*. In the modern information economy many people spend much of their working lives interacting with one or a few software systems (e.g., a word processor, database system, or reservation system); further, in their recreational time, people may be engaged with the same or other software artifacts (e.g., a web browser or computer game). Therefore the external aesthetics of software systems can have a significant effect on the quality of many people's lives. Other things (such as functionality) being equal, most people would prefer to work with a beautiful tool than with an ugly one.

Furthermore, for many people the computer is not simply one tool in an otherwise uncomputerized occupation; rather, the computer and its software constitute, to a large degree, the *entire* occupation. In these cases the software system defines the work environment as fundamentally as the physical workspace does. Therefore, the aesthetics of the software systems deserves at least as much attention as that due the architecture, decor, etc. (From this perspective, many contemporary programs are the software equivalent of sweatshops: cluttered, dangerous, ugly, alienating, and dehumanizing.) As architecture deals with the functionality and aesthetics of physical space, organizing it for practicality and beauty, so software engineers organize cognitive (or virtual) space toward the same ends. Thus software aesthetics can have a major effect on quality of work and quality of life.

An elegant software design can also promote confident use of the system, for eventually users will acquire an aesthetic sense of the design space and will come to recognize that the designs that look good also are functionally good. As is well known, many people approach software fearfully, and part of this fear arises from the fact that software is unpredictable (for them, but often also for the designers!). In elegantly designed software, however, the dynamical interaction of the parts is manifest in the external form, and so aesthetic comprehension of the form can guide the user's understanding of the system's operation. Therefore, as in mathematics and theoretical science, the goal is that beauty coincide with intelligibility, for then users (as well as programmers) will experience pleasure through understanding. This is possible for both beauty and intelligibility are grounded in the interrelation of the parts (Section 4.3; cf. [Heisenberg, 1975, pp. 169–70]).

It is well-known that people's ability to use technological devices with pleasure, confidence, and fluency depends on their ability to build a *cognitive* or *conceptual model* of the device's behavior [Norman, 1988, Ch. 7; 1998, Ch. 8; 2005, Ch. 3]. An effective cognitive model of a system is not required to reflect its actual internal structure or operation, but it must be accurate enough not to mislead the user (thus resulting in a loss of confidence and in frustration). By implying an intelligible dynamical structure, an elegant design can help the user to form an effective cognitive model. Therefore an elegant design aids users' understanding of a system in much the same way it aids that of the system's designers.

Similarly, just as for the designers the aesthetics of a design has an ethical dimension and exemplifies certain values to the exclusion of others, so also the design aesthetics has ethical implications for users. At very least, by making some practices easy and others awkward, and by bringing some concerns into the foreground while leaving others in the background, the external aspect of the system will influence users in its use. Indeed, such non-neutrality is an unavoidable characteristic of the phenomenology of all tools [Ihde, 1986, Chs. 5, 6; 1993; MacLennan, 1999, pp. 33–35]. In addition to this, however, is the symbolic dimension, for by exemplifying particular aesthetic norms, the system keeps these before the eyes of the users, and increases the likelihood that they will be guided by these norms in their own work.

Finally, there is a social aspect for the users of an elegant design just as there is for the designers. As users come to appreciate the beauty of an elegant design, they will develop an appreciation for its aesthetic principles and come to expect similar elegance in other software systems. Thus the users (and consumers) of software systems are included in a feedback loop that encourages the development of elegant software and discourages the inelegant. This will accelerate the development of software that is efficient, economical, reliable, and a pleasure to use. (Billington notes the role of an aesthetically educated public in improving bridge design in Europe.)

4.3 Intelligibility

All arts have their formal and material characteristics, but software engineering is exceptional in the degree to which formal considerations dominate material ones. All the issues that are most fundamental in software engineering (e.g., correctness, efficiency, understandability, maintainability) depend primarily on the formal characteristics of the program and only secondarily on its material embodiment (i.e., the effect of the hardware on the software). Clearly, the hardware cannot be ignored (especially in cases in which the engineering is pushed to its limits), but in general hardware considerations are secondary and often an afterthought.

Software engineering is a new discipline and so it does not have a well-established aesthetic tradition. We may look to other arts for suggestions and analogies, but software's lack of essential material embodiment implies that perceptual qualities will not have so great a role as they do in the other arts. Rather, aesthetic considerations in software engineering will be comparable to those in mathematics and theoretical science.

Indeed, discussions of the aesthetics of mathematics and theoretical science often focus on such qualities as correctness (either consistency or empirical adequacy), generality, simplicity, and (abstract) beauty, and the same qualities are central to the aesthetic evaluation of software. (See, for example, [Curtin, 1982; Farmelo, 2002, Pref.; King, 2006; Wechsler, 1988].)

Science attempts to comprehend a multiplicity of phenomena under a single principle, expressed as a simple, elegant mathematical relationship among abstract ideas. Most commonly the phenomena are dynamical relationships and processes evolving in time, and so, as Heisenberg explains (in the case of Newtonian mechanics), "The parts are individual mechanical processes ... And the whole is the unitary principle of form which all these processes comply with [and which is expressed] in a simple system of axioms" [Heisenberg, 1975, p. 174]. In science, then, as in art, "Beauty is the proper conformity of the parts to one another and to the whole" (*ibid.*).

The goals of the software engineer are similar to those of the scientist in that both are attempting to give a static abstract description of material processes and interactions taking place in time. One difference, of course, is that the scientist is trying to describe naturally occurring phenomena, whereas the engineer is attempting to design a static structure (program) that will generate the desired temporal interactions.

As mechanical processes are described by the axioms of Newtonian mechanics, so a program, contingent on external events, describes a set of possible execution sequences. Individual execution sequences are the parts with respect to the infinite set of all sequences, for which the program provides an *intensive* (finite) definition. Beauty, then, resides in the conformity of the execution sequences to each other and to the program. They should form a harmonious ensemble (*extension*) and have a simple relation to the program (*intension*). For elegant programs the dynamic possibilities (extension) will be easy to visualize from the generative form (intension). The engineers will have a reliable intuitive understanding of the consequences of their design.

Conversely, in designing a program, software engineers have certain desired execution sequences in mind, and they have to expand these in their minds into a coherent infinite set of possible sequences (conformity of the parts to one another). From this multiplicity of possible dynamics they need to derive a finite and unified static generative form (conformity of parts to the whole). Beauty resides in the simplicity, harmoniousness, orderliness, and symmetry of these relations, which elicit simultaneous intellectual and aesthetic appreciation.

4.4 Visual beauty

Sensuously perceivable beauty is a means toward apprehension of the intellectual beauty of abstract forms. Therefore I will consider briefly the role of *visual* beauty in software design.

Vision is our richest sensory modality, and thus it is not surprising that visual representations have played an essential role in the development of engineering, in engineering design, and in engineering education [Ferguson, 1992]. In particular, aesthetic evaluation of designs is aided by such "tools of visual analysis" as *characteristic curves*, which provide memorable and comprehensible visual representations of the relations of relevant variables, and *graphic statics*, which afford intuitive assessment of the relative forces in a structure [Ferguson, 1992, ch. 5]. Are there comparable means for visualizing the relevant abstract structures in software?

Visual programming languages (VPLs), in which programs are represented as two-dimensional figures rather than as text, have been investigated since the earliest days of electronic computing (e.g., AMBIT/G, SKETCHPAD), and VPLs continue to be developed (e.g., Alice, StarLogo TNG), especially for introductory programming instruction (e.g., [Eades and Zhang, 1996; Stasko, *et al.*, 1998]). In these languages formal relations between program parts are represented as spatial relations between visual forms. Early VPLs represented programs as flowcharts, in which connecting edges represented possible paths of control flow, but after the introduction of structured programming around 1970 it became more popular to represent visually the hierarchical structure of the program, which reflects both the logical and dynamical organization of a structured program.

Often visual representations of hierarchical program structure take the form of some kind of tree diagram. Sometimes these are graphs, in which leaves represent atomic program components (individual programming language statements), interior nodes represent composite program components, and edges connect composite components to their immediate constituents. A more recent style, facilitated by improved computer graphics capabilities, represents program components by two-dimensional shapes reminiscent of jigsaw puzzle pieces, which can be interlocked only in conformity with the programming language's syntax (e.g., Alice, StarLogo TNG).

Visual representations of hierarchical program structure would seem to be ideal as a medium for elegant program design, and they are certainly superior in this regard to flowcharts. By representing abstract relations spatially, they create a correspondence between the domains of abstract forms and of spatial forms, and facilitate the visual perception (and aesthetic appreciation) of well-organized, symmetric, and balanced structures; that is, beauty coincides with intelligibility. Unfortunately, in practice these visual representations have limitations, for even small program modules can be quite deeply nested (and it can be argued that for *very small* modules visual representation is not important). As a consequence, the visual representations can be quite large in whatever dimension represents nesting depth. Due to the limitations of human visual perception and practical computer screen size, we are faced with the undesirable alternatives of displaying the entire structure, but with many tiny components, which are difficult to discern, or of displaying only a portion of the structure at one time and having to use devices such as panning and zooming to explore the structure sequentially. Neither is conducive to Gestalt recognition of the program's structure, or to an intuitive intellectual comprehension and aesthetic appreciation of it. Perhaps the problem is that VPLs result in a too literal representation of program structure in perceptible form, and that an aesthetically satisfying *expression* of the design will require a less literal representation.

4.5 Embodiment

Fishwick and his colleagues have explored a more metaphorical approach to programming aesthetics (e.g., [Fishwick, 2002]). Noting that graphs are "largely devoid of texture, sound, and aesthetic content," he seeks to make software "more useful, interesting, and comprehensive" by an approach that begins with a model; this is the "craft-worthy, artistic step." The model is intended to be the usual representation of the software design, the textual program being relegated to a secondary, marginalized status comparable to assembly language. However, since most software concepts are abstract and do not have real-world correspondents, they are represented *metaphorically*. Therefore, once the model is determined, an aesthetic must be chosen as a foundation for the metaphors. For example, if architecture were chosen, then abstract control-flow relations in the program could be represented by corridors in a building through which avatars move. Notice that such a metaphorical representation recruits our embodied understanding of physical space and motion to improve our understanding of the program (see below). Similarly, our aesthetic understanding of architectural space guides the design of the program and our aesthetic and intellectual appreciation of it. The metaphorical model is the principal representation of the software, which becomes an object of aesthetic expression and appreciation, thereby enriching the experience of software. Fishwick notes that even three-dimensional visual programming languages tend to use simple iconography rather than sensuously rich objects: "One is aesthetically-challenged and Platonic whereas the other promotes familiar sensory appeal". [Fishwick, 2006] contains recent contributions to *aesthetic computing* ("the impact and effects of aesthetics on the *field of computing*," p. 3).

Recent developments in psychology have illuminated the essential role played in cognition by embodiment, thus confirming insights from phenomenological philosophy and psychology (e.g., [Gibbs, 2006]). Much of our understanding of the world is rooted in our sensorimotor capacities, both those that are part of our genetic inheritance, and those that are acquired, especially in early childhood. Indeed, Lakoff and Núñez [2000] have argued that our understanding even in such abstract domains as mathematics is built on a network of interrelated metaphors grounded in sensorimotor skills. For example, at an intuitive level abstract sets are understood as physical containers, abstract trajectories as paths through physical space, and so forth.

All human beings have an enormous repertoire of sensorimotor skills, and it is normal to feel pleasure when acting skillfully, competently, and fluently, and to be dissatisfied otherwise; this is part of the feedback mechanism that increases the range and depth of our skills. Therefore to the extent that users' interactions with a system, such as a program, are accomplished through an existing repertoire of sensorimotor skills, they will feel competent and satisfied when they use it. In this way, aesthetic appreciation arises from the correspondence between people's embodied skills and the sensorimotor interface and abstract structure of the system, which is a different sort of resonance or congruence between the system and human cognitive structures.

Therefore aesthetic appreciation and satisfaction will be improved if a system and its parts, including the interface, behave similarly to the physical world, including the objects and processes that are familiar to most people. For example, if when we pull on or drag an object on a computer screen it behaves similarly to a physical object (e.g., in terms of stretching or inertia), then our sensorimotor skills will be engaged, and our skillful manipulation will be pleasurable [Karlsson and Djabri, 2001].

4.6 Applying aesthetic principles in software engineering

The foregoing remarks have merely sketched an approach to an aesthetic theory appropriate to software engineering, and so it will be worthwhile to say a little about how such a theory might be further developed. We can progress by four simultaneous activities, which we may call *experiment*, *criticism*, *theory*, and *practice*.

Experiment refers to learning by means of the self-conscious practice of the *art* of program design and the empirical evaluation of the results. For this to be effective, software engineers must be aware of aesthetic issues during the design, and they must evaluate the aesthetics of the resulting designs as experienced by themselves and others (evaluated phenomenologically and statistically). This entire activity presupposes greater aesthetic awareness in programmers.

Criticism plays an important role in all of the arts, most obviously to provide the general public with aesthetic evaluations, but more importantly to make various aesthetic issues salient, which influences the aesthetic sensibilities of both the producers and consumers of art. Even when artists disagree with criticism, they are encouraged to defend their aesthetic choices in word or deed. Thus criticism provides an important feedback loop that can improve artistic quality. To accomplish this we need more published *aesthetic* criticism of software, both of its external appearance and behavior, and of its internal structure and design, focusing on aesthetics in both cases.

Theory refers to the use of research results from cognitive neuropsychology and allied fields, which will continue to provide insights into the qualities that make something simultaneously intellectually comprehensible and aesthetically pleasing (that is to say, *elegant*). Theoretical understanding contributes by explaining the results of previous aesthetic experiments, and by suggesting new ones.

In spite of all the foregoing, the art of program design is neither a body of theory nor a set of design rules; rather, it is a *practice*. Both the long history of aesthetic debate and the analogy of aesthetic considerations in mathematics and the exact sciences suggest that beauty is an illusive concept. Therefore, in programming as in the other arts, while many aesthetic principles can be stated explicitly, others must remain implicit and essentially embodied in the practices of skilled artisans.

5 CONCLUSION

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 20^{th} 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 20^{th} 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.

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