
The Ever-Changing Nature of Materiality and the Meaning of Materials in Architecture and Construction

2

2.1 Introduction

It seems hard to believe that there can be found among things anything of solid body. For the thunderbolt of heaven passes through walled houses, as do shouts and cries; iron grows white hot in the flame, and stones seethe in fierce fire and leap asunder; then too the hardness of gold is relaxed and softened by heat, and the ice of brass yields beneath the flame and melts; warmth and piercing cold ooze through silver, since when we have held cups duly in our hands we have felt both alike, when the dewy moisture of water was poured in from above. So true is it that in things there is seen to be nothing solid.

Titus Lucretius Carus, *On the Nature of Things*, 59 BC, p. 43

For the Roman philosopher, Lucretius everything in the world is comprised of either matter or void. All that is tangible, that can be perceived with human senses has to exist and is therefore of material character. Since “nothing can be created out of nothing,” as he blasphemously observes in his *De Rerum Natura* (*On the Nature of Things*), all matter has to be made up from elementary bodies, too small to be observed by the human eye. Albeit these bodies are in themselves solid and indivisible, the matter they form is in constant flux, a permanent cycle of becoming and decay. Matter to Lucretius is thus a dynamic entity that continuously changes and behaves throughout space and time, dissolving and reemerging from the fundamental particles it emerges from (Carus and Bailey 1921, pp. 32, 45).

While Lucretius’ theory in respect to our contemporary scientific knowledge might appear a bit banal it does highlight a number of aspects, which we nowadays seem to try avoiding by all means. Lucretius addresses decay, ephemerality, and time as elementary and natural properties of all that is. To him nothing that we can perceive is eternal and solid, but will change its properties eventually, either through direct influences, like force or temperature, or indirect environmental impact. In today’s highly technologized environment we however tend to treat such aspects like atrocities. We identify good and healthy with clean and spotless and not only want our devices to remain immaculate but also our bodies, environment, and social appearance. Especially in architecture the introduction of biomimicry, bioinspiration, or even living biology, often argued for as a return to nature, a redemption for our egocentric ecological barbarism, tends to become a strange contradiction when considering our repulsion to just the slightest sign of life on our buildings, like the stains of patina or the growth of moss and mold.

This observation, whose further exploration in its cultural and social complexity would go beyond the scope and context of this chapter, gets however even more interesting when dealing with materials of which time and transformation are inherent properties: *Information materials*, as defined in the previous chapter. Professor at MIT Architecture and founding Principal of Kennedy

& Violich Architecture Ltd., Sheila Kennedy suggests that the notion of such a vibrant materiality implies a shift in architectural theory from “static material properties to dynamic material behaviors” (Kennedy 2011, p. 118).

But obviously the ideological concept of dynamic matter, constantly behaving and transforming, goes far beyond functional and technological aspects and actually questions the very core of architecture, its stasis. Considering the application and purpose of *information materials* in the context of adaptive architecture thus has to reach further than understanding the practical aspects of materials but has to delve into the meaning of substance and materiality in a much more abstract and theoretical sense.

To Lucretius, who was not an architect but a poet and philosopher, this is quite clear: without materials nothing would exist, especially no architecture, or as Jonathan Hill puts it in his book *Immaterial Architecture*: “Bound to each other, the architectural and the material are considered inseparable” (Hill 2006, p. 2). The role and importance of materiality thus includes much more than structural properties but equally informs a person’s experience of a building through its aesthetic, visual, and haptic qualities as well as its associated social, cultural, and historical meaning. Both constructive and ornamental elements represent fundamental parts of a larger assembly, whether obviously appealing or on a more subliminal level. Applying the right materials therefore represents a truly demanding task and requires not only knowledge and experience on the various material properties, but also sensitivity and intuition in anticipating their meaning and value over time; a combination, which paired with a clear understanding and interpretation of the term *appropriate*, might essentially distinguish *good* from *bad* architecture.

The Swiss architect Peter Zumthor describes good architectural design as sensuous (Zumthor et al. 2006, p. 2). “Sense emerges,” he writes, “when I succeed in bringing out the specific meanings of certain materials in my buildings, meanings that can only be perceived in just this way in this one building.” Despite his realization that materiality is infinite, not only in the amount

of available materials but also in the fact that “there are thousand different possibilities in one material alone,” he believes that materials can “assume a poetic quality in the context of an architectural object, although only if the architect is able to generate a meaningful situation for them.” Zumthor’s ultimate goal is the creation of emotional space, free from symbolism and premature meaning (Fig. 2.1). He considers form as secondary and instead focuses for as long as possible on use, structure, and materials, which to him are essential for the creation of atmosphere, the sublime quality of architecture to move, touch, and affect (Zumthor 2006, pp. 11, 25).

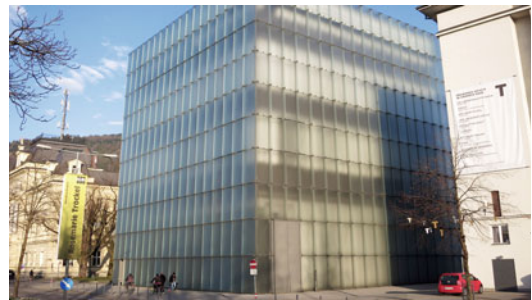


Fig. 2.1 The facade of Peter Zumthor’s Kunsthau Bregenz consists of etched glass panels diffusing the incident light and redirecting it to the ceilings in the exhibition areas (Kretzer 2015)

Zumthor’s approach reminds strongly of Louis Kahn’s philosophy, which describes “architecture [as] the thoughtful making of spaces, [...] the creating of spaces that evoke a feeling of appropriate use.” Kahn believes that architecture should express spirituality, which he feels was missing in many of the modernist buildings of his time. In order to accentuate building from pursuing purely formal or utilitarian aspects toward the creation of meaningful spaces he urges to reveal its construction and materiality through a careful consideration of their interdependence in relation to the respective task and location. By defining materials as ‘spent light’ he highlights the importance of a material’s inherent visual and tactile qualities, which, if understood appropriately, will then reveal the suitable construction and form:

If you think of Brick, you say to Brick, ‘What do you want, Brick?’ And Brick says to you, ‘I like an Arch.’ And if you say to Brick, ‘Look, arches are expensive, and I can use a concrete lintel over you. What do you think of that, Brick?’ Brick says, ‘I like an Arch.’ And it’s important, you see, that you honor the material that you use (Kahn 2003, p. 270).

Just as Kahn feels a lack of spirituality, Frank Lloyd Wright (Fig. 2.2) misses the necessary respect toward materiality. Referring to the ‘nature of materials’ he demands their proper use and contends that every material has its own significance, potential, and limitations:

Each different material required a different handling, and each different handling as well as the material itself had new possibilities of use peculiar to the nature of each. Appropriate designs for one material would not be at all appropriate for any other material (Wright 1936, p. 184).



Fig. 2.2 The curved exterior of Frank Lloyd Wright’s Guggenheim Museum was built using gun-placed concrete, which is sprayed into formwork instead of being poured (Kretzer 2009)

While the above positions bear obvious similarities they also make clear that just as the definition of architecture varies from architect to architect, the attitude toward materiality does, too. What a material is and what it means is thus tightly tied to subjectivity and personality and cannot satisfyingly be described in an objective or rational manner. Since architectural history is vast and rich, providing countless examples and solutions, Peter Zumthor asserts that much can be learned from the ways materials have been used in the past, both ideologically and practically (Zumthor 2006, p. 22). Following his advice, the present chapter depicts a brief,

largely chronological cross section throughout the evolution of architecture with a particular focus on theoretical treatises and the way materials are approached and perceived within the respective contexts. The work tries not to classify, simplify, or value certain materials but instead wants to reveal possibilities and positions. It does not aim for completeness nor does it try to propose or oppress a certain genealogy through its sequential order.¹

2.1.1 Structure of the Present Chapter

The present chapter is divided into two main parts as graphically displayed in Fig. 2.3. The first treats the topics *Natural Materials*, *Industrial Materials*, and *Synthetic Materials*, while the second addresses the areas *Digital Materials* and *Information Materials*.

The topic *Natural Materials* commences from an analysis of the writings of the Roman architect Vitruvius, the first architect to have left written records of his field. It is followed by the Gothic period, which is described through the drawings and sketches published in the early thirteenth century by Villard de Honnecourt. This evaluation is superseded by the Renaissance writings of Leon Battista Alberti and Giorgio Vasari. Addressing the founder of the Baroque style Gian Lorenzo Bernini, the section leaps into the era of Enlightenment, with a particular focus on Claude Perrault, Marc-Antoine Laugier, and Jacques-Francois Blondel. It is concluded with a look at the designs of Nicholas Ledoux, one of the earliest advocates of French Neoclassical architecture.

Part two, *Industrial Materials*, focuses mostly on the effects of the Industrial Revolution on

¹Ákos Moravánszky argues in his anthology *Architekturtheorie im 20. Jahrhundert* that a chronological “history of architectural theory” impedes a critical and vivid discussion between varying positions, which are not only spatially but also timewise distinct. Hanno-Walter Kruft on the other hand contends that a sequential order allows for the maintenance of a historical continuum, which has narrative advantages and provides stability and ease of orientation.

NATURAL MATERIALS	INDUSTRIAL MATERIALS	SYNTHETIC MATERIALS
Vitruvius De Architectura Libri Decem (27BC) Villard de Honnecourt (1230) Leon Battista Alberti De re Aedificatoria (1452) Claude Perrault Ordonnance des Cinq Espèces de Colonnes selon la Méthode des Anciens (1683) Marc-Antoine Laugier Essay sur l'Architecture (1755) Jacques-Francois Blondel Essay sur l'Architecture (1771) Claude Nicolas Ledoux L'Architecture Considérée sous le Rapport de l'Art, des Moeurs et de la Législation (1804)	Jean-Nicolas-Louis Durand Précis des Leçons d'Architecture données à l'École Royale Polytechnique (1805) Gottfried Semper Die Vier Elemente der Baukunst (1850) Der Stil in den Technischen und Tektonischen Künsten (1878) Joseph Paxton Crystal Palace (1851) Le Corbusier Vers une Architecture (1923) Five Points Towards a New Architecture (1926) Quand les Cathedrales étaient Blanches (1937)	Richard Buckminster-Fuller Nine Chains to the Moon (1938) Operating Manual for Spaceship Earth (1968) Frederick Kiesler Vitalbau-Raumstadt-Funktionelle Architektur (1925) Victor Yarsley and Edward Couzens Plastics (1945) Monsanto Chemical Company Monsanto House of the Future (1956) Yona Friedman Groupe d'Études d'Architecture Mobile (1956)
DIGITAL MATERIALS	INFORMATION MATERIALS	
Greg Lynn Folding in Architecture (1993) Bernard Cache Earth Moves: The Furnishing of Territories (1995) Branko Kolarevic Architecture in the Digital Age: Design and Manufacturing (2005) Fabio Gramazio, Matthias Kohler Digital Materiality in Architecture (2008) Ludger Hovestadt Beyond the Grid: Architecture and Information Technology (2009) Neil Gershenfeld How to Make Almost Anything: The Digital Fabrication Revolution (2012)	Tommaso Toffoli and Norman Margolus Programmable Matter: Concepts and Realization (1990) Seth C. Goldstein and Todd C. Mowry Claytronics: An Instance of Programmable Matter (2004) U. S. Army Research Office Workshop Smart Materials, Structures and Mathematical Issues (1988) Foresight, Institute of Materials, Minerals and Mining Smart Materials for the 21st Century (2003) Michelle Addington and Daniel Schodek Smart Materials and new Technologies: For Architecture and Design Professions (2005) Vera Bühlmann and Ludger Hovestadt Printed Physics: Metalithikum I (2013)	

Fig. 2.3 Overview of literature that has been reviewed, separated into the five parts natural materials, industrial materials, synthetic materials, digital materials, and

information materials, which can be sorted according to two main areas (Kretzer 2015)

both architectural building and thinking. Highlighting a number of outstanding material developments, such as steel, glass, and reinforced concrete it unfolds the works of Jean-Nicolas-Louis Durand, Gottfried Semper, and Joseph Paxton and their effects on the profession of the architect and the structures that were designed accordingly. It is concluded with the writings of Le Corbusier who marks the transition to the next episode.

The following section, *Synthetic Materials*, explores advancements in organic chemistry, which during the mid-twentieth century lead to

the introduction of new types of polymers that promised to define a new domestic lifestyle. The works of Buckminster Fuller and Frederick Kiesler are explained and the Monsanto House of the Future is described as one of the most publicly promoted experiments into a new type of plastic dwelling. The part is concluded with a number of positions emerging during the 1960s and 1970s and a shift in social thinking that marked the end of the plastic euphoria.

The part *Digital Materials* begins with the writings of Greg Lynn, Michael Speaks, and Bernard Cache on computer-aided design and

manufacturing at the turn of the twenty-first century. It continues with an investigation into the meaning of digital materiality, referring to the writings of Fabio Gramazio and Matthias Kohler. Building upon Ludger Hovestadt's discussion on the relationship between advancements in architectural production and the history of biology the section carries on with the development of computer-aided manufacturing technologies and is concluded with Neil Gershenfeld's take on the future of digital fabrication. After highlighting a few path breaking projects that employed digital fabrication technologies at a building scale it concludes with different positions on the benefits and downsides of digital design, digital fabrication, and essentially digital materials.

The last section, *Information Materials*, commences from different scientific approaches toward the creation of programmable matter, in the form of fine-grained particles that can in unison assemble into larger functional elements. The part then turns toward the area of smart materials, describing their history, evolution, and varying terminologies in detail based on a number of related reports and surveys. It highlights their theoretical and practical usage in the area of architecture and construction and describes a number of realized architectural works. The section is concluded with more abstract and theoretical views on the abilities of *information materials* and their related production techniques.

2.2 Natural Materials

Although it would next be in order to explain the proper proportions and symmetry of temples and public buildings, as well as of private houses, I thought best to postpone this until after I had treated the practical merits of the materials out of which, when they are brought together, buildings are constructed with due regard to the proper kind of material for each part, and until I had shown of what natural elements those materials are composed. But before beginning to explain their natural properties, I will prefix the motives which originally gave rise to buildings and the development of inventions in this field.

Vitruvius Pollio (1486) On Architecture, pp. 35–36

Vitruvius' treatise *De Architectura Libri Decem* (The Ten Books on Architecture), which marks the to date oldest architectural discourse and only surviving record on classical architecture was most likely written between 27 and 23 BC (Kruft, p. 447). The comprehensive work is divided into ten consecutive volumes, each dealing with a certain aspect of Roman building and construction. While the first volume introduces "the functions of architecture and the scope of the art" as well as an architect's ideal training and "what the qualities of an architect should be," the second volume is solely dedicated to "the use of the building materials which nature provides," which are brick, sand, lime, pozzolana, stone, and timber. In order to explain why these are the only relevant materials for Roman building and to convey how to apply them successfully, Vitruvius elaborates on "the origin of the building art, how it was fostered, and how it made progress, step by step, until it reached its present perfection" (Vitruvius Pollio 1914, pp. 35, 41).

De Architectura begins with the assumption that it "was the discovery of fire that gave rise to the coming together of men," an accidental intervention of nature, which lead to earliest social systems, collaborative exchange, and essentially the requirement for shelter. Vitruvius describes the ability of humans to converse and teach one another, which distinguishes them from the rest of living creatures, as the essential key toward improving and progressing structures and methods. He argues further that the earliest human dwellings were either entirely of natural origin, such as caves or holes, or based on the imitation of procedures found in the animal and plant kingdom, such as copying the nest building techniques of swallows.

Disregarding the role of man in the creation of shelter he describes two basic models as the archetypes of human construction, both emerging as logical consequences from the direct use of the respective materials. The first one, as depicted in the French translation of Vitruvius by Claude Perrault from 1673 (Fig. 2.4 Left), is explained as a kind of tower, constructed by placing wooden beams, alternatingly and perpendicular on

top of each other. It has a pyramidal roof and “the interstices, which are left on account of the thickness of the building material, are stopped up with chips and mud.” The second model, which originated in areas where timber was scarce, is pictured in Fig. 2.4 Right as “a pyramidal roof of logs fastened together, and [covered] with reeds and brushwood.”

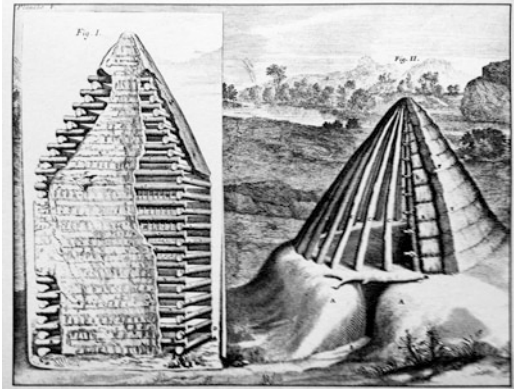


Fig. 2.4 *Left* Graphical depiction of the primitive house of the Colchians; *Right* Drawing of the primitive house of the Phrygians (both from *Les Dix livres d'architecture de Vitruve*, Claude Perrault, 2nd ed., Paris 1684)

Vitruvius' descriptions are less funded in real archaeological findings than in personal observations he made among the building techniques of various foreign tribes of his time. From these studies he concludes that the evolution of architecture is a logical consequence from the resources that are available in nature as well as the progress man made “by becoming daily more expert in building.” Describing the advent of the craft of carpentry as the turning point, when humans “passed from a rude and barbarous mode of life to civilization and refinement,” he explains that together with “the multiplication of the arts they gave up huts and began to build houses with foundations, having brick or stone walls, and roofs of timber and tiles.” Further intellectual development leads to the understanding and use of symmetry, a focus on style and luxury, and finally culminated in the Greek temple (Fig. 2.5), which to Vitruvius marks the unsurpassed archetype of architectural proficiency (Vitruvius Pollio 1914, pp. 38–40).



Fig. 2.5 The Greek Temple of Segesta, Sicily is thought to have been built in the 420s BC. It follows a Doric order and has six by fourteen columns on a base measuring 21 by 56 m, on a platform three steps high (Kretzer 2015)

2.2.1 The Influence of Vitruvian Thought on Current New Materialism Positions

Vitruvius is however not only impressed by the clarity and elegance of Greek building but also deeply moved by their thinking and philosophy. Referring to Thales, Heraclitus, Democritus, and the school of Pythagoras he asserts, similar to his contemporary Lucretius, that “there is no kind of material, no body, and no thing that can be produced or conceived of, which is not made up of elementary particles,” which are water, fire, earth, and air. Since these elements cannot be dissolved, cut, or harmed, they must be eternal and retain infinite solidity. From this he assumes that every material has some inherent natural characteristics that determine the possible structures it allows for and thus the forms that are possible to realize. The Greek temple hence is to him not only the peak of architectural evolution but also presents a logical incarnation of naturalness and material usage and thus must be seen as a direct descendant of the earliest human form of shelter (Vitruvius Pollio 1914, pp. 41, 109).

Similar theories and conclusion have resurfaced multiple times throughout history and gain considerable attention among current ‘New Materialism’ positions. The philosopher Manuel De Landa describes New Materialism as “based on the idea that matter has morphogenetic capacities of its own and does not need to be commanded into generating form” (Dolphijn and van der Tuin 2012, p. 43).

We may now be in a position to think about the origin of form and structure [...] as something that may come from within the materials, a form that we tease out of those materials as we allow them to have their say in the structures we create (DeLanda 2004, p. 21).

Rather than considering form or design as pure thought, imposed upon homogenized materiality he suggests the opposite, to treat materials as “active participants in the genesis of form,” indicating the existence of a heterogeneous materiality with variable properties (DeLanda 2001, p. 132). Relating this concept to certain principles that can be observed in nature he contends that architectural form finding could benefit strongly from considering the “combinatorial productivity of natural forms” such as, for example, the interplay of “bones bearing loads in compression and muscles bearing them in tension” (Braham et al. 2007, p. 391). Neri Oxman, who heads the Mediated Matter Group at MIT’s Media Lab, builds her research upon a similar argumentation:

As in Nature, when creation begins with matter, morphogenesis, or the generation of form, is a process engendered by the physical forces of Nature. [...] Material behavior in Nature appears to be a prerequisite for the emergence of form, and yet in design, shape eternally comes first (Oxman 2010a, b, pp. 70–71).

As an alternative she proposes “material based design computation,” emphasizing a “nonhierarchical association between form, structure, and material” (Oxman 2010a, b, p. 72). Oxman believes that natural forms, “which [are] directly informed by the materials from which they are made,” are more efficient and less wasteful than any of mankind’s own material strategies and are thus inherently sustainable (Oxman 2010a, b, pp. 80–81). She adds that even though novel design and fabrication techniques allow for increased variety and complexity, they only support the usage of materials with homogeneous properties, an approach that she considers as outdated in respect to the extremely diverse context of our time. In accordance to biological principles she alternatively aims to “facilitate the variation of material properties through a

heterogeneous materiality as a function of environmental performance which thus becomes an integral part of the form-generation process.”

In a similar but more structurally determined way demands Achim Menges an interrelated understanding of form, material, and structure based on computational techniques to analyze material capacities, geometrical restrictions, manufacturing processes, and assembly logic:

In contrast to the integral processes of material formation in nature, architecture as a material practice is still predominantly based on design approaches that struggle to fully explore the materials’ richness of performative capacity and resourcefulness for design (Menges 2012, p. 17).

Criticizing contemporary CAD tools that foster a hierarchical relationship between form and material, basically treating materiality as a passive entity to manifest geometry, he proposes a design in which a material’s inherent characteristics are utilized as ‘morphogenetic drivers’ for form generation. Through understanding a material’s microstructure in relation to its external appearance as a continuously transforming entity and by applying computation to navigate within this environment he recommends an “exploratory design process of unfolding material-specific gestalt and related performative capacity” (Menges 2012, p. 36).

Both Menges and Oxman share strong affinities in proposing computational form-finding concepts paired with an understanding of materials as heterogeneous entities to oppose the predominant preference of form over materiality in current architectural design. Menges analyzes natural phenomena, such as the tissue of bones or insect shells, as well as the microstructures of existing materials, and then adapts the observed biological principles in junction with material-specific criteria for the creation of experimental pavilions. Oxman argues to follow natural growth principles and in many of her projects utilizes 3D printing or other additive fabrication techniques to build up ‘new’ materials based on such observations.

Returning to Vitruvius it is interesting to observe that his elucidation, which originates from an anthropogenic technological point of

view, by explaining the primordial substances that make up all materials, is commenced with a chapter on brick—the first man-made composite, while retaining the notion that it is a natural material. To him naturalness thus refers to a shared quality inherent in all things in existence, including artificially produced materials and structures. Taking this notion as point of departure he arrives at yet another synthetic material to which he dedicates even more attention, pozzolana concrete:

There is also a kind of powder from natural causes produces astonishing results. [...] This substance, when mixed with lime and rubble, not only lends strength to buildings of other kinds, but even when piers of it are constructed in the sea, they set hard under water (Vitruvius Pollio, pp. 46–47).

The powder Vitruvius addresses is basically sandy volcanic ash, originally discovered at Pozzuoli, a region around Mount Vesuvius in Italy. Mixed with lime it results in hydraulic cement that can be used to create a strong mortar that even solidifies under water. The discovery of concrete enabled arches, domes, and vaults to be erected without the constraints of masonry and allowed Roman architecture to achieve a substantial leap in construction. The Pantheon, which was built from 118 to 126 AD, holds a hemispherical concrete dome that spans the circular interior of over 44 m. Its building technique and material were so advanced that it remained the largest single building span until the nineteenth century.

2.2.2 The Growing Detachment of Form from Materiality

With the fall of the Roman Empire, Western European architecture experienced a serious regression and a return to mostly wooden materials that lasted for several hundred years. Between the sixth and tenth century Romanesque architecture appeared, which aimed for a reproduction of Roman vaulted styles. The buildings, which had clearly defined, often symmetrical, forms were meant to express wealth and power and were thus made from heavy materials,

mostly stone and brick. In comparison to Gothic architecture, which followed in the twelfth century, Romanesque buildings were simplistic and reduced. Gothic architecture originated in France and spread with surprising speed across most of Europe. The term Gothic was however only introduced much later by the Italian painter and architect Giorgio Vasari in his book *Le Vite de' più eccellenti pittori, scultori, e architettori da Cimabue insino a' tempi nostri* (Lives of the Most Excellent Painters, Sculptors, and Architects, from Cimabue to Our Times), published in 1550, as a clear distinction from Renaissance architecture. Vasari describes the period as being “monstrous and barbarous, and lacking everything that can be called order” associating it with the Gothic tribes who fought the Roman Empire from the fifth to eighth century and destroyed the purity of the Roman style (Vasari et al. 1960, p. 83). Quite the contrary the Gothic style was based on sophisticated structural systems and came from the invention of a much lighter and defined type of masonry vault, which in comparison to the massive Roman vaults, consisted of an intricate network of arches, or ribs, that span the space. Little information on Gothic building and design has survived to date, partly because paper was not yet invented and the expensive parchment was only used in exceptional cases (Ackerman 1997, p. 42). Of particular importance is thus a set of architectural drawings and sketches published in the early thirteenth century by the French artist Villard de Honnecourt (Fig. 2.6). To Honnecourt the stylistic core of Gothic architecture are the linear articulating members, both animating the surface and describing the structure (Kidson et al. 1990, p. 136). While the plan of Gothic churches is similar to the Romanesque plan, the interior is much higher and completely surrounded with colored windows allowing light to triumph over substance. But especially on the outside the difference to the earlier periods can be felt, with Gothic exteriors being extremely complex, detailed, and ornamented, including carved figures, mystical rainspouts, called gargoyles, and often a huge round rose window above the large entrance.

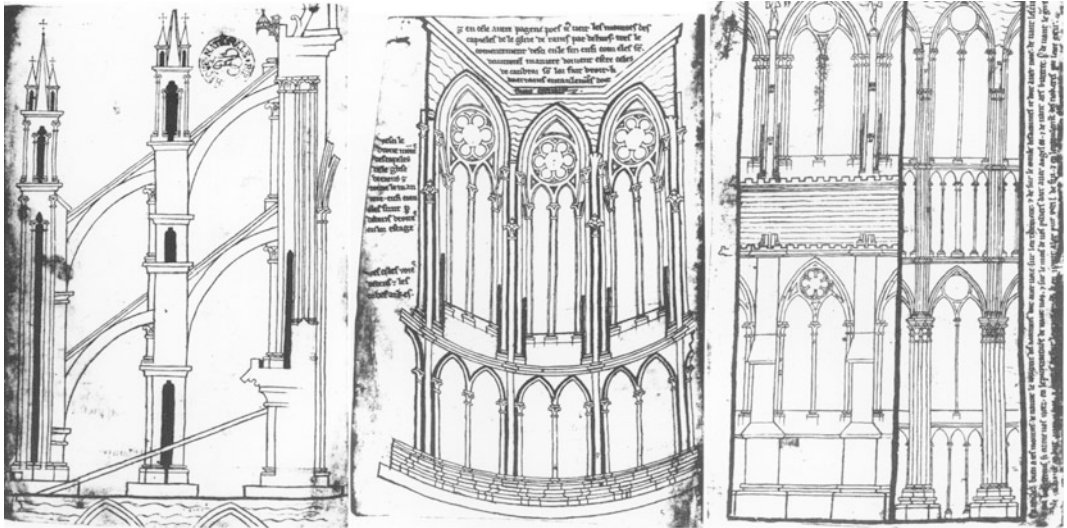


Fig. 2.6 *Left* Reims Cathedral, buttress elevation and nave section; *Middle* Reims Cathedral, interior of choir; *Right* Reims Cathedral, exterior and interior elevation

(both from *Sketchbook of Villard de Honnecourt*, Villard de Honnecourt 1220–35)

The Gothic style dominated much of European building, especially cathedrals and churches, until the sixteenth century, except for Italy. Italian architects, such as Vasari, rejected the structural basis of Gothic building and instead sought to revive the spatial magnificence of the Roman era. While Gothic builders created light-filled interior space through complex vaulting, Renaissance architects aimed for symmetry through mathematical proportions. Blaming the ‘Goths’ for ruining the ancient style and culture Vasari demands to “protect every country from such ideas and style of buildings” which “are such deformities in comparison with the beauty of our buildings” (Vasari et al., p. 83).

A similar, yet not as polemic, position can be found in Leon Battista Alberti’s *De re Aedificatoria* (On the Art of Building), published in 1452 during the beginning of the Italian Renaissance. Alberti’s work is the first book on architecture since Vitruvius’ and just as *De Architectura Libri Decem* is split into ten volumes addressing the various aspects of architectural building.

Appearing to be both a tribute and a challenge to the preceding masterpiece the major difference lies in the fact that while Vitruvius mainly describes how things are built in the past and present, Alberti sets out to propose how architecture should be done in the future. Alberti agrees upon Vitruvius’ claim that in order to construct a successful building one “should [...] copy the ingenuity of nature,” yet his notion of imitation is fundamentally different from the ancient understanding. Whereas Vitruvius believes in some kind of underlying God-given order, to Alberti copying nature means to discover and understand natural principles and then, through a certain intellectual abstraction, apply these rules to works of artistic production. This means that materials, despite their varying qualities, each suited differently well for particular purposes, become subordinate to design and take the role of transforming abstract ideas into physical artifacts.

To Alberti architecture is hence purely intellectual work, performed by the architect and preceding the actual construction of the building,

which is possible “without any recourse to the material” (Alberti 1988, pp. x, 7, 86). In the prologue of *De re Aedificatoria* Alberti writes:

Before I go any farther, however, I should explain exactly whom I mean by an architect; for it is no carpenter that I would have you compare to the greatest exponents of other disciplines: the carpenter is but an instrument in the hands of the architect. Him I consider the architect, who by sure and wonderful reason and method, knows both how to devise through his own mind and energy, and to realize by construction, whatever can be most beautifully fitted out for the noble needs of man, by the movement of weights and the joining and massing of bodies. To do this he must have an understanding of knowledge of all the highest and most noble disciplines. This then is the architect (Alberti 1988, p. 3).

In terms of building materials Alberti is basically content with Vitruvius, describing “lime, sand, stone, timber; and likewise iron, bronze, lead, glass, and so on” (Alberti 1988, p. 38). What is surprising however is the fact that neither Alberti, Palladio, Vasari, nor any other Renaissance writer dedicates any particular significance to pozzolana concrete, the material which Vitruvius describes so extensively.² Siegfried Giedion suggests that “concrete disappeared as Gothic architecture continued to pare down the size of its structural members to achieve pure skeletal forms, for concrete had been associated with the massive Roman wall” (Giedion 1971, p. 260). Yet the reason why the material did not reemerge during the Renaissance period, which aimed to both demarcate itself from the Gothic style and return to classical Roman building, remains unclear.

2.2.3 The Domination of Human Intellect Over Natural Materiality

The Renaissance period was superseded by the Baroque era, which began in the late sixteenth century. Strongly promoted by the Catholic

Church the new style was based on earlier Roman and Renaissance forms but differed in an unprecedented intensity in terms of mass, color, shadow, and light. Often credited for creating the Baroque style and also being the last Renaissance architect, in terms of having equal abilities in painting, sculpture, and architecture, is Gian Lorenzo Bernini (Boucher 1998, pp. 134–142). Bernini was in 1665 invited by Louis XIV of France, le Roi-Soleil, to finish work on the Louvre in Paris. However, due to growing misunderstanding and disagreement between the artist and the royal court, he returned to Rome only 4 months later and Claude Perrault was instead commissioned for the execution of the work. Perrault’s design had only little that could be called Baroque but was an expression of his own understanding of beauty and proportion, which he concluded from a careful analysis of classical architectural treatises.

In the *Ordonnance des Cinq Espèces de Colonnes selon la Méthode des Anciens* (Ordonnance for the Five Kinds of Columns after the Method of the Ancients), written in 1683 Perrault argues:

All those who have written about architecture contradict one another, with the result that in the ruins of ancient buildings and among the great number of architects who have dealt with the proportions of the orders, one can find agreement neither between any two buildings nor between any two authors, since none has followed the same rules (Perrault 1993, p. 48).

From this variance he reasons that beauty is less attached to proportions and thus an objective quality of buildings, as has been assumed earlier, but more related to subjective interpretation of the viewer and as such dependent on custom, time, taste, and fashion. As society evolves this perception changes, which explains why the proportions and styles of columns have changed accordingly. Perrault neglects that architecture should be an imitation of nature, since he finds no connection in neither the proportions of the human body to the column, nor in its resemblance to a tree trunk. In that sense he is the first to break the classical understanding that the Greek temple is a direct descendant from the primitive hut. Yet

²Vitruvius’ chapter on pozzolana concrete counts 840 words while his descriptions of brick (650 words), sand (350 words), lime (430 words), and stone (680 words) are much briefer.

Perrault believes that while certain aspects of beauty arise in the eye of the beholder and are thus constructed reality, other, more general, qualities can be measured empirically and evaluated scientifically. The beauty of the Pantheon, for example, is to him not a result of “the proportion of that temple’s wall thickness to its interior void,” as “most architects claim,” since these are unperceivable qualities. Rather it is based on beauty, which he calls of “convincing reasons [...] whose presence in works is bound to please everyone.” Perrault’s lucid position made him one of the early proponents of the Enlightenment, an intellectual movement, which aimed to break out of tradition and instead follow reason and scientific thought (Perrault 1993, pp. 49–50).

Another highly popular writer of the Enlightenment was Marc-Antoine Laugier who in 1753 published his *Essay sur l’Architecture* (An Essay on Architecture), arguing for a reform of architecture built upon the notion of the primitive hut, a vivid idealization of Vitruvius’ theory. The frontispiece (Fig. 2.7) of the second edition depicts a female personification of

architecture, directing the attention of a young child toward a simplistic structure consisting of four trees that are holding a triangular roof. In contrast to the earlier Perrault, the naturally grown temple becomes in Laugier’s view not only the genesis but also the embodiment of all architecture, representing an immediate imitation of natural processes:

The little rustic cabin that I have just described, is the model upon which all the magnificences of architecture have been imagined, it is in coming near in the execution of the simplicity of this first model, that we avoid all essential defects, that we lay hold on true perfection (Laugier 1977, pp. 11–12).

Obviously Laugier’s model is, even less than Vitruvius’ description, not based on archaeological facts but rather a deliberate theoretical position elevating the Greek temple as the true and only origin of building and the model after which new work should be created. Through this highly polemic demand he criticizes the formal excesses of the earlier Baroque and Rococo era and proclaims the return to the fundamental principles of architecture. While Laugier’s hut is strongly built upon the idea of natural and divine proportion, found in Vitruvius’ writings, it differs in the relationship of man and nature and the role materials play in connecting the two. With Vitruvius not attributing much credit to man as the creator of form but rather arguing that form and structure emerge from immanent material qualities, Laugier’s position is that, albeit form should be based on natural principles, it is man who induces the transformation and thus marks the dominant force (Braham 1980, pp. 48–49).

Laugier’s Essay had vast and immediate influence on many thinkers of his time and also informed the writing of Jacques-Francois Blondel, who in a very didactic manner proposes in his *Cours d’Architecture ou Traité de la Decoration, Distribution & Construction des Bâtimens* (Course of Architecture), published in 1771, a rational approach toward architecture and building. Just as Perrault, Blondel believes that good architecture is simply a manner of taste, something that cannot be determined, yet there are rules, which can lead to harmony between a building’s function, appearance, and structure



Fig. 2.7 An idealized version of the ‘primitive hut,’ envisioned by Laugier as the epitome and model for architecture (Frontispiece of Marc-Antoine Laugier: *Essai sur l’Architecture* 2nd ed., Charles Eisen 1755)

(Evers and Thoenes 2003, p. 296). Blondel's work is a demand for order and the development of a 'true style,' which "marks the entry of the modern concept of style into architectural theory," as Hanno-Walter Kruft observes (Kruft 1994, pp. 148–149).

One of Blondel's students was Claude-Nicolas Ledoux who became one of the earliest advocates of French Neoclassical architecture, a style in which classical forms, derived from Vitruvian principles and especially the work of Palladio, were assembled more for their dramatic effect than to create orderly arrangements. Strongly demarcating himself from other architects of his time, Ledoux thinks that architecture needs to propose a better future for society and has to emerge from the imagination of the architect and not rationality and consent (Pérez-Gómez 2005, p. 46).

His *Treatise L'Architecture Considérée sous le Rapport de l'Art, des Moeurs et de la Legislation* (Architecture in its Relations to Art, Customs and Legislation) was published in 1804 and aims to establish a generalized architectural system, including all the various tasks of an architect, thus reinterpreting his role within a visionary social structure. In this system of social coexistence, the architect becomes an educator, with equal political, moral, and religious responsibilities. Similarly radical are his architectural designs, which are massive symbolic monuments, like cubes, spheres, and cylinders, representing strong simplifications of classical building types. In his project for the salt-producing town of Chaux in the French Jura, of which the major part was built between 1774 and 1779, he realized not only some very modern ideas about industrial production, but also designed a series of geometrical monuments that visually express the activities its' tenants are involved in. The hoop makers were thus to live in houses shaped like wheels, the 'Pacifère,' the peacemaker, in a building shielded by fasces that symbolize unity, and the house of the river inspector should have the river running right through it (Evers and Thoenes, p. 320). The most popular of his designs, albeit never realized,

is the house of the forestry guard (Fig. 2.8), a spherical building without windows, completely deprived from any functionality or materiality, and only focusing on its pure form and symbolic character.

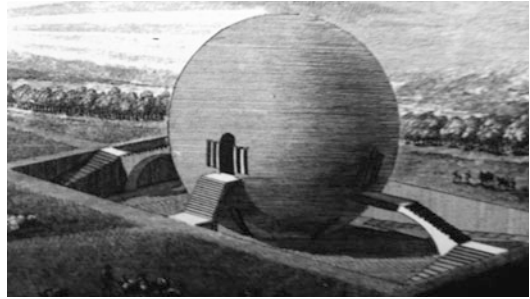


Fig. 2.8 Ledoux's spherical and windowless 'House of the forestry guard in château de Mauperthuis' was a deliberately geometrical concept to contrast architecture of the time (Claude-Nicolas Ledoux 1789)

2.3 Industrial Materials

Forms and proportions may be divided into three categories: those that spring from the nature of materials, and from the uses of the things they serve to build; those that custom in a sense made necessary to us, such as the forms and proportions of the buildings of antiquity; and finally, those simpler and more definite forms and proportions that earn our preference through the ease with which we apprehend them. Of these, only those in the first category are essential; but they are not so firmly defined by the nature of things that we cannot add to them or subtract from them, so that there is no reason not to combine them with those of the second class, derived from ancient buildings. Since these vary considerably [...] one is at liberty to select the simplest, [...] the best suited to satisfy both the eye and the mind.

Durand (1831a, b, *Précis des Leçons d'Architecture*, pp. 108–109)

A major turning point, not only in architecture but essentially every aspect of life, occurred during the second half of the eighteenth century, with the emergence of the Industrial Revolution, first in Great Britain and then, within a few decades, in Western Europe and the United States.

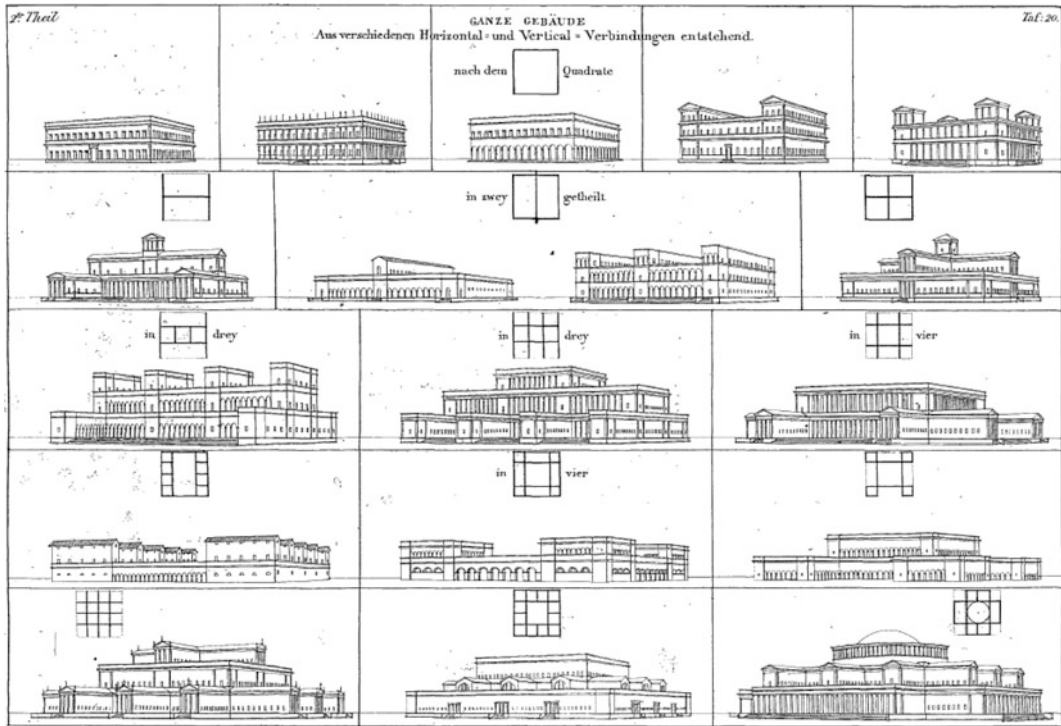


Fig. 2.9 Proposal for buildings based on simple *rectangular* shapes, divided vertically and horizontally (Durand 1831a, b)

One notable architect, who was born into the vast technological transition of automated manufacturing and the mass production of new materials, was the French, Jean-Nicolas-Louis Durand. In 1831 a collection of his lectures at the École Polytechnique in Paris was published, the *Précis des Leçons d'Architecture données à l'École Royale Polytechnique* (Precis of the Lectures on Architecture). The comprehensive work was initially intended as a primer or construction manual for his students but soon became one of the most influential textbooks of his time: a new grammar for architecture. Strongly motivated by the unprecedented possibilities that emerged from the growing Industrialization, Durand was one of the first architects to clearly define function, in terms of human value, technical performance, and economy, as the key aspect of architectural design. He argues that since building is the most expensive of all arts, yet the sole that is in constant use and thus provides the greatest benefits, it

should, in a very Vitruvian manner, be durable, neat, and comfortable, and, in order to keep costs down, symmetrical, regular, and simple (Durand 1831a, b, pp. v, 3). According to Durand, materials appropriate for building are split into three categories: Materials that are hard, difficult to process, and thus expensive, suitable only for buildings of great importance whose public status justifies their usage. Materials that are softer and easier to treat, good for private houses with a smaller budget. And materials whose main purpose is to connect the ones from the previous classes, like iron, copper, lead, but also gypsum, cement, or sand.

Durand distances himself from both the classical assumption that order and proportion are derived from the human body, and the belief in a primitive hut as the archetype for building. As such he neglects the imitation of nature as a design guide and reasons that decoration and ornamentation are temporal matters of taste and,

since utterly expensive and not increasing the functionality of a structure, unnecessary and useless. He believes that architecture can be described by certain fundamental principles that are found in any building, regardless of its epoch or style. These elements, once identified, can then be reassembled according to generic methods to create new architecture independent from stylistic considerations, efficient both economically and in terms of design and functionality. By graphically portraying various building types and abstracting their form into simple geometric shapes, he develops a codified scientific method and explicit didactic system that is intended to be applicable without knowing or considering the works of the past (Fig. 2.9).

2.3.1 Durand's Grammars in Relation to Schumacher's Parametricism

Durand's objective of creating a systematic approach for architectural design bears striking similarities to contemporary advocates of computational methods. Patrik Schumacher, Director at Zaha Hadid Architects, describes Durand as "the first to introduce a diagrammatic process within architecture." Durand's simple system of combining basic, standardized elements like walls and columns according to certain rules of alignment, regularity, and symmetry lead to an unprecedented variety of possible results, from which "the rest of the design (including all the familiar classical detail) followed automatically." Schumacher compares Durand's programmatic approach with the compositional processes emerging during Modernism, which became "the true moment of the ordinary diagram." Reasoning further, as an evolution from the ordinary, metric diagram he proposes the extraordinary, parametric diagram, which according to him first appears during the mid-nineties in the use of animation software. Schumacher asserts that parametric modeling allows "to link any parameter/property of any object with arbitrary parameters/properties of any or all other objects within the model." To him the possibilities that

arise from setting up dynamic, infinite chains of interdependencies go beyond architectural relevance but are useful "for the organization and articulation of social complexity" (Schumacher 2011, pp. 349, 354).

Concluding from this assumption and reassured in the observation that parametric principles are becoming omnipresent in contemporary architectural design, he proposes a new label for the current period: Parametricism, which according to him could become the first epochal style after Modernism.

The contemporary style - Parametricism - takes off with the concept that every form in architecture is susceptible to the formulation in terms of continuously varying parameters. [...] Each urban or architectural system is continuously differentiated and functions are scripted that correlate the different differentiations. In this way, deep resonances are established within the overall composition, and the sense of overall organic integration is intensified (Schumacher 2011, pp. 295–297).

The architecture critic Peter Buchanan admits that Parametricism might produce novel and temporarily interesting forms but diminishes its importance to become a successor to Modernism:

The style can neither adequately frame nor address public space, with facades whose composition and elements allow us to identify and relate to them. Nor do parametric buildings relate to each other (beyond establishing superficial formal contiguities), nor to other architecture (Buchanan 2011).

To Buchanan the potential of parametric modeling is less than the generation of sculptural form but to "bring a wide range of increased efficiencies, in terms of structure, energy, constructional assembly, shaping of flows of people, air, and so on." Buchanan describes Parametricism as a form of 'hypermodernity,' pushing the limits of modernity but not overcoming them. Instead he demands a 'transmodern theory,' which should address global challenges while utilizing a shift toward a sustainable society.

Whether or not the value of both Durand's method of composition as well as current approaches in parametric design is in their ability to create new formal explorations or rather in their use for functional applications, it is interesting to observe that we are currently

experiencing a similar frustration with the status quo as did the thinkers of the nineteenth century.

2.3.2 The Intellectual Emancipation of Form from Materiality

Just as Durand, Gottfried Semper shares the opinion that their era is lacking architectural style and like many of his contemporaries he is interested in discovering fundamental architectural principles to formulate new ideas. Yet Semper criticizes Durand's schematic pragmatism and also does not believe that an answer can be found by demanding a return to the origins of architecture, especially not in a Vitruvian sense. To Semper the similarities between the Greek temple, as the paragon of style, and early wood constructions are purely formal and not enough to claim a certain genealogy. In return he develops his own theory on the origins, published in his 1850 book *Die Vier Elemente der Baukunst* (The Four Elements of Architecture), which describes four basic human motifs or necessities. To him the first and 'moral' element of architecture is the fireplace, the hearth, which comes from a necessity for warmth and the heating up of nutrition. Around the central fire the other three elements are formed, the roof, the enclosure, and the terrace, in order to protect it from the remaining and hostile natural elements, wind, water, and earth. Semper claims that all technical proficiencies of humanity can be derived and they originate from these basic elements. Thus the hearth lead to ceramic and metallic manufactures, carpentry origins from the roof, masonry from the terrace, and weaving and textile work through the enclosure (Semper 1851, pp. 55–56). Semper's elements are hence not materially or formally graspable but must be understood as desires or ideas forming from basic needs out of which architecture emerges, in contrast to the Vitruvian notion of imitation. While the elements might be found in nature, the architect creates artificial works; hence he does not imitate but rather translates. In the prolegomena to his in 1878 published work *Der Stil in*

den Technischen und Tektonischen Künsten (Style in the Technical and Tectonic Arts, Or, Practical Aesthetics), he explains his theory of style as searching for the components of form, which are not formal in themselves but rather idea, force, means, and matter (Semper 1878, p. viii). From these components he believes that form and architecture will be able to create meaning, transferring purpose through one material to the other, a transformation that he calls 'Stoffwechsel.' Semper, who is quite aware of the scientific progress of his time in other disciplines, borrows the term from biology, where it means metabolism, describing the life-sustaining chemical transformations and exchange of matter within the cells of living organisms. But it can also be understood as 'phase change,' referring to the transitions between solid, liquid, and gaseous states of matter. What Semper means to emphasize however is that primordial human requirements will always remain the same and so will the functionality and purpose of their physical manifestations, even though their form and materiality evolves and changes over time. This emancipation of form from a particular material allows Semper to highlight that the symbolic function of architecture, transferring purpose through one material to another, is as imperative as its material structure since it creates stability on a cultural level (Muecke 2005, p. 30).

Semper's theory marks a decisive moment in architectural thinking. In the past architectural form had often been justified by tracing its evolution back to primitive archetypes that were based on natural principles, representing proportion and order. Similarly, materials were described as having inherent properties, which if discovered determine their correct usage. Others however argued that architecture is largely a formal practice, beauty and proportion a matter of individual taste, and that materials can be categorized and simply applied to fulfill particular demands. Semper does not take any of these positions. He asserts that materiality and spirituality are closely linked, but does not value one over the other since to him the creative idea is at

the core of architectural design. Form is thus not a fixed entity but rather a continuously changing and becoming configuration (Semper 1878, pp. viii, xv).

2.3.3 Technological and Material Advancement During the Industrial Revolution

While Semper's *Stoffwechseltheorie* resulted in a certain dematerialization in architectural thinking, untying form, function, and materiality, actual progress in construction and the development of new fabrication and material processes lead to a dematerialization of architecture in its physicality.

In 1851 the Great Exhibition took place in London's Hyde Park, showcasing the latest technological developments of the Industrial Revolution. The structure to house the exposition was the Crystal Palace (Fig. 2.10), a groundbreaking, modular, glass and iron building, designed by the English gardener, Joseph Paxton. The Crystal Palace can be regarded as the first physical outcome of Durand's systematical thinking, even though he did not see iron as an architectural material but solely to connect or decorate others. The glazed structure, which was 564 m long, 124 m wide, and 39 m high, was completely build from standardized parts, which enabled an extremely efficient erection within a very short span of time. But despite the structure being revolutionary in its promotion of homogeneous elements for ease of construction, and its application of new industrial materials like sheet glass in combination with wrought and cast iron, its direct impact on architecture and architects of the time was comparably little.

Even Gottfried Semper, who just after the exhibition ended, wrote a short but essential review on its potential effects for architecture remained fairly reserved. To him the structure was little more than a very versatile "glass-covered vacuum that suits everything one would like to bring into it" (Semper 1852, p. 71). While praising its importance for the technical advancement of glazed open spaces he did not



Fig. 2.10 Joseph Paxton's Crystal Palace in London was entirely covered in transparent glass plates (Queen Victoria opening the 1851 Universal Exhibition, at the Crystal Palace in London, Thomas Abel Prior 1851)

treat it as a work of real architecture and, a bit sarcastically, argued that, since the qualities of iron are its thinness, its ideal would be an 'invisible architecture' (Semper 1878, p. 251).

Only a few years after the Great Exhibition, in 1855, Henry Bessemer patented a process to purify liquid pig iron, enabling the mass production of steel, and by this solved various technical issues that so far weakened the material and prevented it from becoming architecturally relevant.

Based on the development of Portland cement in 1824, whose thermal expansion properties are almost identical to those of iron and steel, reinforced concrete emerged in 1867, when the French gardener Joseph Monier experimented with adding iron mesh into concrete flowerpots. Monier quickly improved his artisan process and used it to create water tanks, bridges, and even beams and columns. During the 1870s Thaddeus Hyatt performed numerous empirical tests on reinforced concrete beams and developed the basic groundwork for its further usage (Ballard Bell and Rand 2006, p. 53). However, it was not until 1887 that Mathias Koenen demonstrated how to calculate the necessary reinforcement and provide a scientific basis for the placing of the steel bars (Forty 2012, p. 18).

The superior strength of steel essentially enabled the steel frame structure toward the end of the nineteenth century. Together with the introduction of another technological breakthrough, the Otis safety elevator, the first high-rise buildings appeared. The ten-story

Home Insurance Building in Chicago, build in 1885, was the first tall building that utilized the basic principles of skeleton steel frame construction and its load-bearing opportunities (Leslie 2013, p. 46). In 1931, the 102-story-high Empire State Building in New York was finished as a steel frame structure and remained the tallest building for nearly 40 years. Almost as impressive as the immense height of the building was the speed and execution of its construction, which Rem Koolhaas describes as “a form of automatic architecture”. Rising almost a story per day, the building seemed “to generate itself, feeding on the never-ending stream of materials that arrive with split-second regularity” (Koolhaas 1994, pp. 139–141).

2.3.4 Functionality Takes Precedence Over Aesthetics and Form

Notwithstanding the mechanic automation of processes and timely execution of tasks, Le Corbusier, who visited New York for the first time in 1935, was not very affected, by neither the Empire State Building nor the American skyscraper in general, which he provocatively deemed as being ‘too small.’ To him the American skyscraper was purely decorative, “a plume rising from the face of the city.” Instead he proposed the so-called Cartesian skyscraper, a modern and rationally designed tower based on a biaxial cruciform plan.

The Cartesian skyscraper is a miracle in the urbanization of the cities of machine civilization. It makes possible extraordinary concentrations [...] while taking up only 8 to 12 per cent of the ground, 92 to 88 per cent being restored, usable, available for the circulation of pedestrians and cars! These immense free areas, this whole ward in the business section, will become a park. The glass skyscrapers will rise up like crystals, clean and transparent in the midst of the foliage of the trees (Corbusier 1964, p. 83).

Representing a “function of capacity” the monolithic building should be made from a steel skeleton structure, without walls and enclosed in a

facade of glass (Corbusier 1964, pp. 53, 81). Laying these towers in a dense but generous grid he made radical proposals for vast urban redevelopments, such as his *Ville Voisin*, a concept city for Paris with low residential blocks divided by large areas of greenery and parks. Both in its function and form, Le Corbusier’s Cartesian skyscraper stands exemplary for his thinking of the house as “a machine for living in” (Corbusier 1986, p. 95).

This blunt but crucial analogy is intended to highlight the necessity for more efficient, modern, and human-focused environments, and suggests adapting processes from engineering and industrial design to overcome formal ideals. By this architects, he believes, will be able to create novel forms that respond to specific needs, without having to claim a relation to earlier architectural styles, since to Le Corbusier style is unnecessary, and although sometimes pleasing, solely decorative (Corbusier 1986, p. 25).

The core of Le Corbusier’s ideals are summed up in his manifesto *Five Points Towards a New Architecture* and can be found in many of his buildings (Fig. 2.11). First, the structure should be lifted from the ground, resting upon slender reinforced concrete columns, “the supports.” Second, the building should contain a “roof garden,” which protects the concrete roof against changing temperatures, creates a luxury outdoor space, and makes up for the green area consumed by the structure. The support system, providing the structural foundation of the building, allows the “free design of the ground plan,” meaning that the space can be configured into rooms without the need for supporting walls. The fourth point concerns the “horizontal window,” which provides unrestricted views of the surrounding and lights the rooms more efficiently than with vertical windows of the same surface area. The fifth point addresses the “free design of the facade,” independent from the location or arrangement of interior rooms. Le Corbusier’s five points meant a radical departure from the past and can as such be considered a direct and critical response to Vitruvius’ *Ten Books on Architecture* (Corbusier 1970, pp. 99–101).



Fig. 2.11 The roof level of Le Corbusier's Cité Radieuse in Marseille (1947–1952), with the children's paddling pool, atelier, and ventilation stack, exhibits a number of his five points toward a new architecture (Kretzer 2014)

2.4 Synthetic Materials

The business of Architecture is to establish emotional relationships by means of raw materials.
 Architecture goes beyond utilitarian needs.
 Architecture is a plastic thing.
 The spirit of order, a unity of intention.
 The sense of relationships; architecture deals with quantities.
 Passion can create drama out of inert stone.
 Corbusier (1986, *Towards a New Architecture*, p. 151)

Le Corbusier's use of the term plastic in the above quote is meant to highlight crucial poetic and sensual qualities of architecture as opposing to solely focusing on utility and construction. Instead of trying to find inspiration in classical and natural forms, he suggests looking forward, to learn from adjacent disciplines and draw from the qualities of machines (Banham 1980, p. 223). Condemning architecture as the only profession "in which progress is not considered necessary" he promotes the use of composite and synthetic compounds and demands an architecture that reaches beyond purely utilitarian needs but instead embraces technological evolution and new materials (Corbusier, pp. 109, 215, 229).

The first entirely artificial material Bakelite plastic was invented in 1907 by Leo Baekeland. Its astounding properties quickly lead to its intense use by the United States military as an

alternative to steel for the production of lightweight weaponry. During the 1920s, in the post WWI era, the North American economy expanded massively and boosted further industrial research which led to the invention of new types of plastics at a regular basis, including Nylon, Teflon, PVC, or Vinyl. In 1933 Eric Fawcett and Reginald Gibson accidentally discovered polyethylene (PE), which continues to be the most produced and highest selling plastic in the world today (Ballard Bell and Rand, p. 220).

Richard Buckminster Fuller was one of the first to propose plastics in his mobile and eco-friendly scenarios, like the Dymaxion House (1927), the Wichita House (1945), or the iconic Montreal Biosphere for the Expo 1967 (Fig. 2.12).

In respect to physical resources, until recently man had assumed that he could produce his buildings, machinery, and other products only out of the known materials. [...] But now in the aerospace technology man has developed his metaphysical capabilities to so advanced a degree that he is evolving utterly unique materials "on order." Those new materials satisfy the prespecified physical behavior characteristics which transcend those of any substance previously known to exist anywhere in the universe. Here we witness mind over matter and humanity's escape from the limitations of his exclusive identity only with some sovereignized circumscribed geographical locality (Buckminster-Fuller 1969, p. 32).



Fig. 2.12 Buckminster Fuller's Montreal Biosphere was originally enclosed with acrylic cells and incorporated a dynamic shading system to control its internal temperature (Kretzer 2009)

Another remarkable pioneer during these times was the Austrian-American architect, Frederick Kiesler, who already in 1925 formulated a series of

architectural demands as an opposition to the mostly functionalist architecture of his time. He demanded:

1. Transformation of the surrounding area of space into cities.
2. Liberation from the ground, abolition of the static axis.
3. No walls, no foundations.
4. A system of spans (tension) in free space.
5. Creation of new kinds of living, and, through them, the demands which will remould society (Kiesler 1925, pp. 141ff).

Kiesler's five points became the theoretical foundation for his Endless House project, a speculative study that aimed to create a spatial symbiosis between man, nature, and technology (Bogner and Noever 2001, p. 11). To him space and time were continuous and elastic and should thus be interwoven and mutually dependent. Moreover, architecture should be capable to provide ideal solutions to the varying social demands and uses of its occupants. As a physical manifestation of his ideas he designed the Space House in 1933 for the New Yorker Company Modernage Furniture, which was supposed to be cast entirely in plastics to create a fluid transition between floors, walls, columns, and ceilings.

Kiesler believed that his ideas were very influential on architects of his time, like Le Corbusier or Mies van der Rohe, yet his projects were received rather dismissively (Borden and Rendell 2000, p. 62). This however only strengthened his desire to break out of the ordinariness, especially the International Style, and propose ever more radical and futuristic visions. But even though he continued to develop his ideas in constant response to technological and social trends, the Space House remains the only building he ever realized, a fact which in 1960 lead Philip Johnson to call him "the greatest nonbuilding architect of our time" (Johnson 1960, p. 70).

2.4.1 The Age of Plastics

After the Second World War, due to a lack of conventional building materials and a shortage in

housing, research into petroleum chemistry seriously caught fire, and various types of plastic were brought into commercial application. In the final chapter of their book *Plastics*, published in 1941, the British chemists Victor Yarsley and Edward Couzens, vividly anticipate an Utopian vision of the 'Plastic Age' that was to follow:

This 'Plastic Man' will come into a world of colour and bright shining surfaces, where childish hands find nothing to break, no sharp edges or corners to cut or graze, no crevices to harbour dirt or germs, because, being child, his parents will see to it that he is surrounded on every side by this tough, safe, clean material which human thought has created. The walls of his nursery, all the articles of his bath and certain other necessitates of his small life, all his toys, his cot [...] all will be plastic. [...] As he grows he cleans his teeth and brushes his hair with plastic brushes, clothes himself with in plastic clothes [...] The windows of his school [...], like those of his house are of moulded plastic, light and easy to open never requiring any paint (Yarsley and Couzens 1941, p. 149).

The first practical architectural experiments focused on the development of prefabricated elements to create mass-produced shelter. But it was not until the early 1950s, when a new generation of plastics appeared, that architects started to really develop ideas that did justice to the materials' various properties. At a 1954 conference on the use of plastics in building Robert K. Mueller from the Monsanto Chemical Company compares the impact of new technologies and materials on the reduction of costs in automobile construction and predicts dramatic advances in building methods and materials:

The trend towards prefabricated building structures and structural elements presents an unusual opportunity for plastic materials. Plastics are capable of revising the "architectural index" of our time. We predict that plastics engineering will play a significant role in a new American style of building architecture because of inherent features of plastic materials and their adaptability in any type of design (Mueller 1955, p. 127).

The visionary thinking of the company, back then a major global producer of plastics, was manifested in a collaborative project with Disney Imagineering and the MIT from 1953 to 1956, the Monsanto 'House of the Future.' The almost

5-m wide building, with its four square rooms cantilevering outward from a central core, was made entirely from glass fiber-reinforced plastic (GFRP) shells and showcased a vision of the year 1986. The center of the structure housed the kitchen and two bathrooms, while the living room, family room, master bedroom, and two small bedrooms occupied the wings. According to a press release from the Monsanto Chemical Company in 1960, the influence of the experiment on the building industry was remarkable:

All told, 23 per cent of the plastics made in this country now go into construction, compared with 15 per cent the year before Monsanto's experimental house was built. The pace being what it is, the "Plastics Home of the Future" may soon be just one of many plastics homes of the present (Weiss 2010).

Although Monsanto's vision of plastic homes did not quite come true as they imagined, the usage of polymers in building construction has continuously risen, making it the second largest consumer of plastics today, just after packaging (Fernandez 2006, p. 161). Ironically, it was precisely the house's futuristic and style-dependent use of technologies and materials that lead to its abolition only 10 years after its opening. While the high-tech interior simply became standard and out of fashion, the use of fiber-reinforced polyester for the shell structure failed as a building material because it conversely was too durable and resistant for a time that valued temporality and progress.

2.4.2 Utopian Visions for a Better Tomorrow

In 1958, motivated by the results of the 1956 CIAM congress held in Dubrovnik, which addressed issues of mobility, flexibility, growth, and communication, a group of young architects around Yona Friedman, founded the 'Groupe d'Études d'Architecture Mobile (GEAM).' Centered on the understanding that people should be actively engaged in the process of constant sociological and technological change, the group proposed the so-called 'architecture mobile,'

which was to consist of flexible room modules without specific functions that could be dynamically inserted into load-bearing infrastructures (Jeska 2008, p. 12). Friedman explains:

The two techniques I proposed were aimed to liberate the building from the groundwork. The elements were the 'span-over blocks,' supported by stair towers which were about 60 meters away from each other and the 'raft blocks,' boxes placed on the ground which rested on 'beams.' [...] I express this philosophy accepting the unpredictability of human behavior, of the inhabitants, also accepting the illusion of planning, the erratic character of each person's story. I assume that in every domain, the process is important and a final result which can be determined with absolute certainty does not exist (Friedman 2006, pp. 14–15).

The formation of the group and its visionary and radical philosophy were characteristic for the period of the early 1960s. Driven by a euphoric decision to abandon traditional practice, a fascination for space travel, and a strong belief in technological progress and the usage of uncommon materials, numerous artistic collectives like Archigram (1960), E.A.T. (1967), Haus Rucker Co. (1967), Coop Himmelb(l)au (1968), or AntFarm (1968) formed around the globe and developed architectural concepts based on mobility, individualism, and self-expression. For them architecture had to go beyond the creation of isolated structures and tend toward environmentally and organically funded design (Scott 2008, p. 62). They relied on a future of abundant resources and developed visionary urban scenarios and large spatial experiments that tried to escape from the limits of established norms but wanted to generate a more flexible and independent living (Sadler 2005, p. 95).

Plastic turned into a term that stood for far more than simply a material. It became eponymous for a complete era, a time and people that were elastic and dynamic but also slick and clean, just as Andy Warhol famously noted:

I love Los Angeles, and I love Hollywood. They're beautiful. Everybody's plastic, but I love plastic. I want to be plastic (Lavin 2014, p. 15).

The World Expo 1970 in Osaka with its theme 'Progress and Harmony for Mankind' marks to

date the climax of plastic architectural exploration and experimentation. Showcasing pneumatic structures, media pavilions, and stretched skin systems it represented a cheerful and optimistic vision of the material's outstanding properties and possible structural manifestations. Despite the public success of these case studies and experiments, the first real plastic buildings on the market however turned out to be the exact opposite, creating anonymous, inhuman, and impersonal environments, with no room for individuality and self-expression. In junction with the oil crisis in 1973 this sudden realization meant the abrupt end of the plastics euphoria demanding a return to natural and more human materials (Jeska 2008, p. 22).

2.5 Intermediate Summary and Conclusion

Architecture is generally a rather slow and conservative discipline. New material innovations thus often take much longer until they lead to substantial changes and advancements. Steel, for example, was in the beginning only used in works of engineering, such as bridges or towers, before it turned architecturally relevant due to its amalgamation with concrete. Plastics on the other hand were treated as a highly imperative structural material but in the end had a much more subliminal influence and are today mostly found in technical appliances and infrastructures. The impact of a material on building is thus not only related to technological advancements but equally to various associative qualities, differing according to culture, society, fashion, and time (Ashby et al. 2009, p. 46). Obviously, none of the above-described periods can simply be reduced to the small number of positions that are portrayed, neither can these opinions be fully grasped in the brevity of the present discourse, yet there appear to be underlying, recurring patterns driving, and strengthening the various stages.

Architects of the Enlightenment, such as Perrault, Laugier, or Ledoux, for example, relate strongly to thinking during the Renaissance, in

particular the writings of Alberti, while expressively demarcating themselves from the previous Baroque and Rococo era. The Renaissance period in turn is clearly defined by a rediscovery of the work and philosophy of the Roman time, as is the Romanesque, and tries to express its difference to the earlier Gothic buildings. At the same time the intricate and decorative architecture of the Gothic era can be associated with the ornamental Baroque, Rococo, and the later Romanticism. When displaying this observation graphically it can be depicted as an ascending curve Fig. 2.13, divided into two distinctive sides. The left part of the diagram displays the styles that aim for structural forms and functional spaces, the right side is more playful in the addition of ornament and decoration. As styles progress they often try to demarcate themselves from the directly previous period while relating to the one before. The graph also displays that the time span of how long it takes for the respective styles to be superseded by a more modern approach gets continuously shorter. While Roman architecture lasted for almost 650 years, the Gothic style was deprecated after 350 years, Neoclassicism after 200 years, and Modernism already after 60 years.

Leibit this is clearly a hypothetical assumption, it can be exemplified further through one particular material: concrete. During Roman times concrete was used pragmatically as a structural material, but remained mostly hidden behind more appreciated materials, such as brick or marble. While concrete disappeared after 500 AD, sandstone took its place, which during the Gothic era was treated sculpturally and during the Renaissance rather reductive and restrained. The use of cement slowly returned in the mid seventeenth century, this time largely in the form of decorative stucco during the Baroque. With Industrialization reinforced concrete emerged and again its structural qualities prevailed. Le Corbusier emphasized the plasticity and malleability of concrete, yet used it in a very clear and formal manner. The same applies for the spatial explorations in plastics during the 1950s and 1960s.

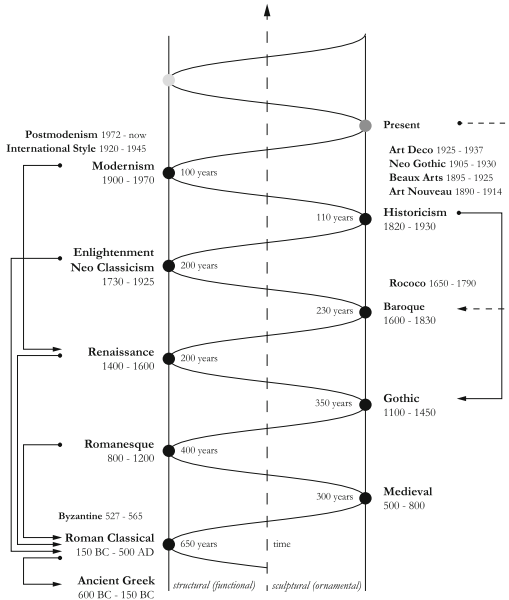


Fig. 2.13 Graphical depiction of alternating architectural styles in form of an ascending curve with arrows showing various relations (Kretzer 2015)

Very recently, we are experiencing a new sculptural approach toward the same material, enabled by novel manufacturing techniques and more sophisticated and powerful computer hardware and software. One very prominent example is the study *Digital Grotesque* (Fig. 2.14) by Michael Hansmeyer and Benjamin Dillenburger at the Chair for CAAD, ETH Zurich, where complex algorithmic processes in combination with cutting edge 3D sandstone



Fig. 2.14 The 3D printed space *Digital Grotesque* explores the current limits of computational design- and fabrication technologies (Hansmeyer and Dillenburger 2014)

printing are applied to create intricate, uncanny computational forms and geometries.

2.6 Digital Materials

Digital machines and productive technologies in general allow for the production of an industrial continuum. From the mold we move toward modulation. We no longer apply a preset form on inert matter, but layout the parameters of a surface of variable curvature. A milling machine that is commanded numerically does not regulate itself according to the build of the machine; it rather describes the variable curvature of a surface of possibility. The image-machine organization is reversed: the design of the object is no longer subordinated to mechanical geometry; it is the machine that is directly integrated into the technology of a synthesized image.

Cache (1995 *Earth Moves: the Furnishing of Territories*, pp. 96–97)

As described in the previous chapters, every new technological development has not only affected the creation and design of architecture but equally architectural thinking and theory. Around the turn of the twenty-first century the growing prominence of computer-aided design tools paired with influences from computer graphics and especially motion and cinematic animation lead to a number of critical investigations into their greater relevance in relation to future architectural explorations. In the *AD—Architectural Design* issue *Folding in Architecture*, edited by Greg Lynn and first published in 1993, Lynn argues that architects during the preceding two decades had been largely focusing on the creation of “heterogeneous, fragmented and conflicting formal systems” resulting “from a logic which tends to identify the potential contradictions between dissimilar elements.” Emerging as a reactionary response to this formal dispute he addresses a second tendency that aims at recovering unified architectural languages either through historical reference (Neoclassicism or Neomodernism) or by finding local consistencies (Regionalism). Yet Lynn contends:

Neither the reactionary call for unity nor the avant-garde dismantling of it through the identification of internal contradictions seems adequate as

a model for contemporary architecture and urbanism (Lynn 1993, p. 24).

As a more appropriate alternative he proposes a post-contradictory work based on smooth transformations that allow the incorporation of variety within an incessant but heterogeneous whole. Referring to Deleuze's understanding of smoothness as "continuous development of form" Lynn reasons that through smoothness and pliancy architecture can address complexity through flexibility, which will allow the integration of "unrelated elements within a new continuous mixture." Mentioning both the Gehry House (1991) and Peter Eisenman's Wexner Center (1989) he implies that despite their clear deconstructivist appearance they express a certain softening toward curvilinear deformations that foster "a more fluid logic of connectivity" rather than emphasizing contradiction and conflict. From this observation he argues for the development of an architecture that bends and folds locations, materials, and programs rather than breaking and disrupting them, to create fluid and dynamic systems that maintain both the individual characteristics of each element and remain open for future additions (Lynn 1993, pp. 24–28).

In Bernard Cache's *Earth Moves*, Michael Speaks builds upon Lynn's argumentation but wonders whether a shift from deconstructivist forms toward folded forms is enough in order to be called new and important or if it does "simply repeat what already exists." Contending that Deleuze's work is much more comprehensive than what Lynn emphasizes, Speaks bemoans that by simply picking certain theoretical or philosophical ideas and translating them into architectural shapes, "architecture becomes applied philosophy, and necessarily gives up all claims to singularity and creativity." To Speaks the real value of the Deleuzian concept of the fold lies in the "shaping of the form of practices (including techniques and logics), rather than the shaping of individual architectural forms." In that sense he demands a more abstract understanding and translation of the Deleuzian notion:

Thus new forms of architecture will not emerge as a result of the effects achieved by ever more pliant, fluid, complex, and heterogeneous shapes or architectural forms, but rather with the development of more pliant, complex, and heterogeneous forms of architectural practice—with architectural practices supple enough to be formed by what is outside or external to them, yet resilient enough to retain their coherence as architecture (Speaks 1995, pp. xv, xvi).

Bernard Cache has according to Speaks succeeded in developing a conversion from theory toward practice, by employing the fold as a method to reconsider the relationship of the interior with the exterior world through images. Cache has early on been strongly engaged in what he calls Computer-Assisted Conception and Fabrication (CFAO) systems. He identifies two main types of CFAO usage in the industry, mainly in the areas of mechanical engineering and automobile or aeronautical applications, which albeit they have "increased the productivity of the idea" they so far do not offer any fundamental "advances over the work done by hand." Growing from this he imagines second-generation systems where objects are not any more designed but calculated, allowing the creation of complex forms that would be difficult or impossible to draw in a traditional manner. More interestingly however he asserts that such systems might incept a "nonstandard mode of production" where objects from the same series can vary in size and shape by simply modifying certain fabrication parameters on the fly. Since neither the function of an object nor its materiality are any longer linked to a particular form but can vary continuously, the digital representation "takes precedence over the object." The primary depiction of an object is hence not anymore its image but a model of simulation, of numerical manipulation, resulting in a kind of digital materiality (Cache 1995, pp. 88–98).

The shape of this new objectivity prolongs surfaces of resonance, whether screens or membranes, that restore the materiality of the numerical processes. Data of this sort can then create an image on a cathodic screen, but it can also create a sound on an acoustic membrane or, better still, produce a surface of variable curvature (Cache 1995, p. 97).

Fabio Gramazio and Matthias Kohler at ETH Zurich build upon this notion and use the term digital materiality to describe materials that are increasingly being enhanced with information technological characteristics:

Digital materiality evolves through the interplay between digital and material processes in design and construction. The synthesis of two seemingly distinct worlds - the digital and the material - generates new, self-evident realities. Data and material, programming and construction are interwoven. This synthesis is enabled by the techniques of digital fabrication, which allows the architect to control the manufacturing process through design data. Material is thus enriched by information; material becomes 'informed' (Gramazio and Kohler 2008, p. 7).

In contrast to materials that only exist in digital or virtual form, such as textures for 3D renderings or computer software that simulates material properties for evaluation or visualization, the present meaning of *physical* digital materials is thus directly tied to the emergence and evolution of digital design and fabrication techniques.

In *Beyond the Grid*, Ludger Hovestadt compares the development of architectural manufacture to the history of biology: While during the seventeenth century nature was described in rather broad terms and with the help of patterns, the invention of the microscope allowed the study of individual cells and thus not only facilitated the decomposition of biological forms but also their schematic reconstruction. A similar leap happened in the architectural world during the eighteenth century when "production became a necessary condition for architecture" in contrast to the slow and laborious building techniques of the previous times. A little later, during Industrialization, the standardization of building elements paired with new technological processes made possible unprecedented architectural explorations as exemplified in the previous chapters.

In biology another crucial breakthrough occurred with the discovery of DNA in the 1950s. Since then the internal code of cells can be revealed and in a very moderate way be recombined and reassembled. Around almost the

exact same time lie the roots of computation and digital fabrication (Hovestadt 2009, p. 19).

2.6.1 The Emergence of Digital Design and Fabrication Techniques

In 1949 the United States Air Force assigned John Parsons to develop an economical, automated method for the manufacture of helicopter rotor blades. Parsons teamed up with the Servomechanisms Laboratory at MIT, who back then was on the global forefront of mechanical computing and feedback systems, and together they created the computer-controlled 'Card-a-Matic Milling Machine' for three-axis contour milling. Although the machine required relatively long in preparation and could only perform a limited set of operations that were fed from punch card tapes, it represented a revolution in automated manufacturing. The machine reduced workforce, downtime, and waste material while increasing productivity, precision, and especially versatility through the use of a single tool. However, the industry was hard to convince of the machine's potential and remained unwilling to provide the necessary funding for further industrial development (Caneparo 2013, p. 55).

During the 1960s computing became much more publicly prominent and a new generation of cyberneticists began actively speculating about architectural design and its similarities to cybernetic systems (Spiller 2008, p. 10). In 1963 Ivan Sutherland released Sketchpad (Fig. 2.15), a pioneering attempt for human-computer interaction, often credited as the very first computer-aided design (CAD) tool. Sutherland himself describes Sketchpad as a system that, "by eliminating statements (except for legends) in favor of line drawings, opens up a new area of man-machine communication," which in the past "has been slowed down by the need to reduce all communication to written statements that can be typed." The tool ran on a Lincoln TX-2 computer, a highly advanced machine at the time, and incorporated a light pen that was used to directly draw lines and other geometrical shapes onto a

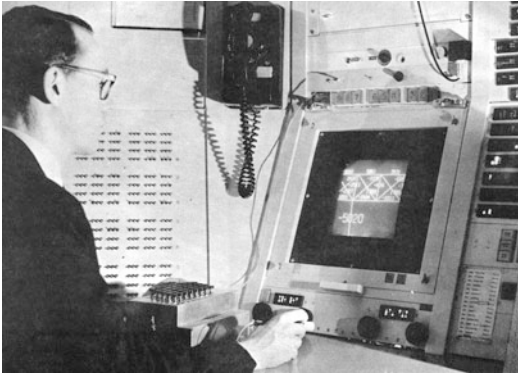


Fig. 2.15 Ivan Sutherland using Sketchpad with a light pen to directly draw geometrical shapes onto the computer (scanned by Kerry Rodden from original photograph by Ivan Sutherland 1963)

small connected cathode ray tube. Additional knobs and buttons allowed the further manipulation of the content in real time and an adjacent plotter was used to print the created diagrams.

Sutherland saw the advantages of his invention especially in the creation of drawings where motion, analysis, high accuracy, or repetition were essential, yet he conceded that “it is only worthwhile to make drawings on the computer if you get something more out of the drawing than just a drawing” (Sutherland 2003, pp. 17, 99, 110).

Graphical CAD systems were further improved in the 1970s and became suitable tools for designers and architects for the creation of geometric representations. Simultaneously, numerical control (NC) systems were enhanced to add visual descriptions of the work piece and process. The new software was called computer-aided manufacturing (CAM) and the immediate connection to CAD helped that it was quickly adopted by various industries for the creation of complex products like ships or automobiles. While in the beginning the technology remained only viable for projects with large turnovers and as such big companies, continuous increase in computing power and the concomitant reduction in costs eventually lead to the propagation of CAD/CAM technologies and CNC fabrication in the areas of industrial design and manufacturing (Corser 2010, p. 13). In parallel to the

development of subtractive fabrication processes such as milling or cutting, additive manufacturing, today best known as 3D printing, came on the market in the 1980s, and was rapidly promoted by the emergence of numerous companies that pushed its development (Gershenfeld 2012, p. 45). Around the same time industrial robots became more prominent and sophisticated in the range of movements and actions they could perform. Due to their great versatility since the “end effectors, attached and controlled by these arms, are as diverse as the materials they can process” much of today’s research into digital fabrication focuses on the potential of robotic arms (Beorkrem 2013, p. 10).

Neil Gershenfeld, head of MIT’s Center for Bits and Atoms, argues that the cumulative emergence and evolution of these fabrication technologies will inevitably result in a ‘new digital revolution,’ empowering people “to design and produce tangible objects on demand, wherever and whenever they need them.” Drawing analogies to the history of computing he predicts that through the continuous increase in performance and versatility of, for example, desktop 3D printers and the open access to their blueprints, tool owners can not only use but also reproduce and alter them, just as the early personal computer allowed people to create their own software. Encouraged by the success of **Fab Labs** he believes that the power of these technologies lies in their largely unregulated but well connected nature, thus their real strength “is not technical; it is social.” Gershenfeld suggests that the ultimate abilities of what he calls ‘assemblers,’ the future descendants of 3D printers, will be “to create complete functional systems in a single process” without the creation of any waste or trash (Gershenfeld 2012, pp. 43, 52, 57).

2.6.2 New Instruments for the Architectural Design Practice

Despite the obvious advantages of digital technologies for design and manufacture and despite the fact that code already represents the base and

framework for any kind of planning, communication, financing, infrastructure, and construction, as Hovestadt observes, the building industry has to date been fairly slow and repellent in adapting (Hovestadt 2009, p. 19). This is due certainly to the fact that it mostly deals with one-off projects and relatively small profit margins, however the reason might also be rooted in an outdated understanding of architectural design and production based on tradition and craftsmanship. Referring to William Mitchel, Branko Kolarevic, Professor at the University of Calgary, states that while in the past “architects drew what they could build, and built what they could draw” we have now reached a state where the constructibility of a design, enabled through digital production processes, becomes directly linked to the limits of computation. Due to this:

The question is no longer whether a particular form is buildable, but what new instruments of practice are needed to take advantage of the opportunities opened up by the digital models of production (Kolarevic 2003, pp. 31–33).

Fabio Gramazio and Mathias Kohler add that in order “to make the full spectrum of digital technologies in architecture accessible [...] they have to be considered conceptually in design from the very beginning.” Hence they argue for research and practice-based approaches that go beyond investigating the potential of technologies but focus on “integrating them in an early design phase in order to finally overcome the still prevalent separation of design and making and introduce new meaning and substance into the profession” (Sheil and Glynn 2011, pp. 2, 6).

An early pioneering application in using computer-aided design and engineering for architectural fabrication can be witnessed in the Sydney Opera House, designed by the Danish architect Jørn Utzon and realized from 1956 to 1973 (Fig. 2.16). Digital modeling was applied for both structural analyses as well as the detailed layout of building assemblies and inventory documentation. Additional computer-generated information was used for factory production and plotted templates were created for on-site cutting of large glass panels. While the majority of the



Fig. 2.16 Sydney Opera House by the Danish architect Jørn Utzon behind Harbour Bridge, Sydney, realized from 1956 to 1973 (Kretzer 2005)

work was still based on manual labor, the project would not have been realizable without the application of computers to solve and simplify the complex geometry. The Sydney Opera House thus marks a building utilizing and progressing technologies way ahead of its time.

One of the first architectural projects that was developed and also produced largely digital is the Great Fish Sculpture by Frank Ghery at the entrance to the Vila Olimpica in Barcelona, Spain, built in 1992 (Fig. 2.17). The structure, which is 55 m long and 35 m high, is made of interwoven steel strips that are connected to an open steel framework. Since back then no architectural computer software existed that would allow for both the design and the production of the intricate form, the architects leaned toward the aerospace industry and found a



Fig. 2.17 Frank Ghery’s Great Fish Sculpture at the entrance to Villa Olimpica, Barcelona, built in 1992 (Kretzer 2016)

solution in the program CATIA. In what Kolarevic calls “a radical departure from the normative practices of the profession,” the tool was used for the design, structural analysis, fabrication, and as on-site construction guide (Kolarevic 2003, p. 31).

The realization that complex surfaces and geometries consisting of multiple unique pieces can be manufactured in a digitally controlled way without significantly increasing the cost of fabrication in comparison to mass production motivated Ghery and Partners to establish Ghery Technologies in 2002. The company since then develops and promotes Digital Project, a version of CATIA, tailored to the specific demands of multifaceted architectural projects including the preparation of fabrication data. The work of Frank Ghery is thus not only revolutionary in its architectural complexity and appearance but according to Lisa Iwamoto, founding partner of Iwamoto Scott in San Francisco, also in expanding “the role of the architect to include oversight of the building and construction-management process, much as it was in the age of the master builder” (Iwamoto 2009, p. 6).

2.6.3 The Digital Chain: From Design to Production

Today, digital design and fabrication technologies have infiltrated almost every architectural school on various levels and many of the larger architectural offices have established their own specialized computation units and in-house fabrication and prototyping facilities, slowly arriving at what Kolarevic calls “a digital continuum from design to production” (Kolarevic 2003, p. 7). Bob Sheil, Director of The Bartlett School of Architecture, consents and describes a paradigm shift arising from the direct engagement with digital technologies, which empower the architect to become involved in areas that he has formerly been excluded from. Sheil reasons that in the past the making of buildings was inherently dependent on the successful communication between the various involved disciplines, often resulting in negotiated translation of the

original design intent, depending on the complexity of transfer from one area to the other. However through the integration of digital technologies “the exchange of information between design and fabrication is no longer a slow chain of vulnerable links, but a rapid flow of data, where design and making can be a simultaneous process,” redefining the role of architects into ‘hybrid disciplinarians’ (Sheil and Glynn 2011, p. 156). Hovestadt describes a similar phenomenon when referring to the digital chain:

The digital chain represents the general formulation of the building process, its reference process, including all of its abstract building blocks. Form and its design become a variable that - freed from the dependency on function - can now focus on their essence, that is, representation (Hovestadt 2009, p. 133).

Yet, while new algorithmically computed forms are continuously emerging and while digitally controlled tools become increasingly accessible, materials still have fairly little design influencing effects and are often shifted to the end of the process where they undergo solidification within production. As a result contemporary architects often think of materials as immaterial components, which can be chosen from a design palette and, similar to the use of textures in 3D renderings, applied as visual and compositional architectural elements. This trend of categorizing and sorting materials into sets of quantifiable qualities becomes evermore obvious in the large amount of material databases, libraries, and catalogs that appear in print, online, and physically in every larger city.

Criticizing the “impoverished notion of form generation, which refers to various digitally driven processes resulting in shapes that remain detached from material and construction logics,” Achim Menges and Michael Hensel demand a more holistic understanding of form, material, structure, and behavior (Hensel and Menges 2008, pp. 55–56). According to Mette Ramsgard Thomsen, head of CITA (Centre for Information Technology and Architecture) at the Royal Danish Academy of Fine Arts, this will strengthen the reemergence of ‘good building culture’ and help to overcome the loss of

uniqueness and shift toward the general and mass-produced, which came from the industrialization of construction processes (Ayres et al. 2012, p. 8).

However, there are two things that tend to be neglected. First, for computer-controlled machines to analyze and apprehend the particular materials they are treating they would need to be equipped with some sort of feedback and evaluation systems. Second, they would have to be able to learn and respond to observed material variances by improvising and adjusting their fabrication strategy. Until this is achieved they will always require super-standardized and homogeneous materials, since albeit the executed steps may differ the operational principle remains the same. So while the complexity of possible material handling increases with the versatility of the tool, the homogeneity of the material has to be raised accordingly, leading to a certain dematerialization of material-specific characteristics, especially when dealing with nonsynthetic substances. The decisive properties of wood, for example, like its fiber orientation, texture, varying density, strength, and color are hardly tolerable for automated manufacture and thus have largely been eliminated by the creation of various wood composite materials such as chipboard, medium-density fiberboard (MDF), or oriented strand board (OSB) (Schindler 2009, pp. 173–179, 207). What this all amounts to is that digital fabrication techniques may promote the departure from the *industrialization of construction processes* but at the same time require the increased *homogenization of material properties*.

2.7 Information Materials

The mechanical brain does not secrete thought “as the liver does bile,” as the earlier materialists claimed, nor does it put it out in the form of energy, as the muscle puts out its activity. Information is information, not matter or energy. No materialism which does not admit this can survive at the present day.

Wiener (1961, *Cybernetics*, p. 132)

The term *information materials* aims at describing a type of newly emerging materials which share certain commonalities that distinguish them from the traditional notion of materiality.

- First, *information materials* have the inherent capability to contain and harvest (digital) information and transform it into physical representation. Thus they are dynamic and can change their state over time in a controlled way and in response to external influences.
- Second, *information materials* are based on information technology. They are artificially created on a symbolic level by the combination of formerly distinct elements into functional assemblies using digital technologies. As such they are not built upon anything that can be found in nature but are sole products of human intellect (Bühlmann and Hovestadt 2013, p. 11).

The new term *information materials*, as a distinction from other names, such as programmable matter or smart materials, which will be discussed in the following, wants to establish a general awareness of these phenomena and develop a linguistic proficiency among the architecture and design community. The concept thus aims at proposing and mediating a new way of thinking, liberated from a materialistic and mechanistic point of view, and instead focusing on *materiality*, the empowering ability to create synthetic materials with performative abilities.

2.7.1 Programmable Matter

Programmable matter generally refers to matter or materials that are capable of changing their physical properties, such as shape, density, conductivity, opacity, etc., in a controlled and direct way. The term was introduced by Tommaso Toffoli and Norman Margolus, describing the concept of a three-dimensional network of fine-grained functional substrates. These minute

elements are able to interact with each other and through varying their formation, arrangement, or individual properties, produce a dynamic, new kind of synthetic material. More precisely, Toffoli and Margolus define four essential key aspects of what they understand as programmable matter:

- (i) It can be assembled into lumps of arbitrary size (the limits being given by economics rather than technology).
- (ii) It can be dynamically reconfigured into any uniform, polynomially interconnected, fine grained computing network.
- (iii) It can be interactively driven, in the sense that its dynamical evolution can be started, interrupted, and resumed at any moment in response to the occurrence of specified internal or external events.
- (iv) It is totally accessible to real-time observation, analysis, and modification (Toffoli and Margolus 1991, p. 266).

What they essentially aim for is the creation of individual artificial computing nodes at a scale small enough in order to accumulate and self-assemble into any kind of materiality. Building upon this work, Seth Goldstein and Todd Mowry initiated the Claytronics project at Carnegie Mellon University, researching the production of nanoscale computers and robots, referred to as claytronic atoms, or catoms that can form tangible three-dimensional objects that users can interact with. Each catom is in its preliminary design “a unit with a CPU, a network device, a single-pixel display, one or more sensors, a means of locomotion, and a mechanism for adhering to other catoms” (Goldstein et al. 2005, p. 99).

Once the work succeeds in overcoming some crucial aspects, such as shrinking the elements, which are still in the centimeter range, to millimeter or even micrometer sized particles, providing the individual nodes with sufficient energy while maintaining their lightness and versatility, and developing stable software and hardware configurations that function in ensembles of millions of catoms, Goldstein and Mowry imagine:

Programmable matter will allow us to take a (big) step beyond virtual reality, to synthetic reality, an environment in which all the objects in a user’s environment (including the ones inserted by the computer) are physically realized (Goldstein and Mowry 2004).

The possibilities that such an environment would open up are nearly infinite, and even though the concept still sounds more like something from a science fiction movie, researchers in the domain are convinced that it is only a question of time and persistence until it becomes physical reality (Guin 2012).

While both Goldstein and Mowry as well as Toffoli and Margolus imagine to build up some sort of universal material from a multitude of minute controllable elements another approach toward *information materials* involves the creation of multifunctional materials with specific dynamic properties, also referred to as smart materials. Although these materials certainly lack the versatility of the former approach, they offer various advantages including the departure from mechanics and engineering toward the areas of materials science, chemistry, and biology and as such a much softer domain of research.

2.7.2 The Soft Kinetics of Smart Materials

The director of MIT’s Self-Assembly Lab, Skylar Tibbits, investigates in what he calls 4D printing, which “entails multimaterial prints with the capability to transform over time, or a customized material system that can change from one shape to another, directly off the print bed.” The material that is being used for the active parts of his transformable assemblies is a hydrophilic polymer, which is able to expand 150 % upon immersion in water. In combination with a rigid polymer that provides the required stability the printed systems can then self-change from one state to another when put in contact with water. While Tibbits’ method in 3D printing smart materials undoubtedly offers various exciting opportunities, which he finds mostly

“for the future of the products, and the shipping and manufacturing sectors,” the creation and application of shape changing smart materials is not new (Tibbitts 2014, pp. 119–121). Among the best-known and widest-used materials are so-called bimetals, which due to the differential expansion of two tightly bonded metals are able to flex reversibly in response to a change in temperature. This property has among others been extensively used for the actuation of on/off switches within early thermostats and is depicted in the following graphic (Fig. 2.18).

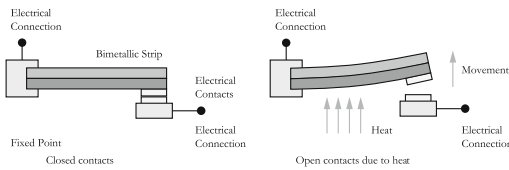


Fig. 2.18 Schematic diagram of the working principle of a bimetallic strip as used in early thermostats (Kretzer 2015)

The English scientist Gordon Pask was one of the earliest to describe the puzzling effect of the self-activated material in 1972:

It seems to me that the notion of machine that was current in the course of the Industrial Revolution - and which we might have inherited - is a notion, essentially, of a machine without goal, it had no goal ‘of’, it had a goal ‘for’. And this gradually developed into the notion of machines with goals ‘of’, like thermostats, which I might begin to object to because they might compete with me. Now we’ve got the notion of a machine with an underspecified goal, the system that evolves. This is a new notion, nothing like the notion of machines that was current in the Industrial Revolution, absolutely nothing like it. It is, if you like, a much more biological notion, maybe I’m wrong to call such a thing a machine; I gave that label to it because I like to realise things as artifacts, but you might not call the system a machine, you might call it something else (Haque 2007, p. 54).

Pask was a convinced advocate of cybernetics, a term coined by Norbert Wiener in 1948, describing systems that are able to assess feedback on their state and progress and alter their course accordingly. To Pask the thermostat represents a very basic cybernetic system that, when the temperature of a space goes beyond a certain

threshold, will automatically either induce a heating or cooling process in order to retain the previously set target temperature. It is interesting to observe Pask’s trouble in properly describing and defining the phenomenon of both the cybernetic system as well as the dynamic material. He clearly distinguishes it from the mechanical notion of machines and refers toward more biological and organic associations. By this Pask already anticipated some of the difficulties we are still facing today when dealing and working with *information materials*.

2.7.3 Definitions of Smart Materials

The term smart materials is a relatively young invention and generally refers to materials that can change their properties in response to environmental conditions, such as changes in temperature, humidity, pressure, stress, pH level, magnetic or electrical field, light radiation, and many more. The degree of smartness or behavioral response of a certain material is often measured by comparing the amount of transformation to the duration it takes to complete a full cycle. Smart materials are generally classified according to their basic physical or chemical effects. Table 2.1 shows an overview of several smart materials displaying both the stimulus applied and the actual response of the material.

The history of smart materials differs according to the respective type of material and the first recorded occurrences of certain effects can in cases date back centuries, like, for example, the discovery of Luminescence by Vincenzo Casciarolo in 1602. Their commercial emergence as a new class of materials is however often traced to the research of S. Donald Stookey at Corning Glass, who in the early 1960s aimed to develop a glass that turns opaque automatically when exposed to light and vice versa increase its transparency when the light source is withdrawn. By adding silver and copper halides into the glass formula Stookey succeeded in creating a photochromic glass, which to date still forms the basis for light-sensitive glass with self-adjusting transparencies (Geiser 2001, p. 249).

Table 2.1 Stimulus response matrix for a selection of smart materials

Response → ↓ Stimulus	Electrical	Magnetic	Optical	Thermal	Mechanical	Chemical
Electrical		Magnetoelectronics Spinelectronics Spintronics	Electrochromic Electroluminescent Electrooptic Piezochromic Kerr Effect Pockel Effect	Thermoelectric (Peltier)	Piezoelectric Electrostrictive Electrorheological Electrokinetic	Electrolysis Electrochemical Bioelectric Electromigration
Magnetic	Magnetoelectronics Spinelectronics Spintronics, Hall Effect		Magneto optic Piezochromic	Magnetothermal	Magnetostrictive Magnetorheological	Nuclear magnetic resonance Magnetochemical
Optical	Photoconductive	Optomagnetic	Optical stability	Photothermic	Optomechanical Photoacoustic	Photochemical Photosynthesis Photocatalyst
Thermal	Thermoelectric Superconductivity Radiometer Effect Pyroelectric	Curie point	Thermochromic Thermoluminescent		Shape-memory	
Mechanical	Piezoelectric Electrostrictive	Magnetostrictive	Mechanochromic, Rheochromic		Rheopexic Auxetic Shear-thinning Dilatants Non-Newtonian Pseudo Plastic	
Chemical		Magnetochemical	Color change Litmus Luminescence	Exothermic Endothermic		Catalysis

Adapted from Darrell Mann: Smart Materials Solve Contradictions: paper first presented at ETRIA TRIZ Future Conference, November 2008

Other innovations followed rapidly with one of the most notable being the shape-memory effect found in Nickel-Titanium alloys in 1962 at the now disestablished Naval Ordnance Laboratory (NOL) in White Oak, Maryland, creating a material that is accordingly called Nitinol. The shape-memory effect has since then been discovered in a few other alloys, Nitinol however remains the most popular. Shape-memory alloys (SMA) have the ability to remember the shape in which they were annealed and upon heating try to remake that shape, creating relatively large forces in the process. Starting in the 1980s and early 1990s, several companies are now producing and distributing Nitinol materials and components including connectors, heat engines, and various types of actuators (Cai 2003, p. 9).

Due to the continuous emergence of further types of smart materials the United States army organized a workshop on *Smart Materials, Structures, and Mathematical Issues*, in September 1988 aiming to “identify recent significant developments and breakthroughs in science and technology.” Its main focus was to develop a general agreement on the definition and characteristics of a “smart/intelligent material or structure,” since the use of different, often complementary terms, such as smart, intelligent, active, multifunctional, or adaptive lead to growing confusion among the scientific community. Dr. Iqbal Ahmad, director of the Materials Science Division of the United States Army Research Office and chairman of the workshop, proposes to stick to the term smart and define it technically as:

A system or a material which has built-in or intrinsic sensor(s), actuator(s) and control mechanism(s) whereby it is capable of sensing a stimulus, responding to it in a predetermined manner and extent, in a short/appropriate time and reverting to its original state as soon as the stimulus is removed (Ahmad 1988, pp. 1, 4).

The Defense Advanced Research Projects Agency (DARPA) in the United States is highly convinced that smart materials will change the capabilities of military systems and commercial applications in the near future. Since the early 1990s they have put serious efforts in the

development of advanced actuator designs to move developing concepts of smart materials into practical applications. To them the term smart materials has thus always been used to describe a materials system “constructed of actuation materials, structural materials, structure design, sensing, and control” (Wax et al. 2003, pp. 17–23).

A similar definition is the base of a Foresight study performed by the Institute of Materials, Minerals and Mining, London entitled *Smart Materials for the twenty first century*, which highlights the “development of products with increasing levels of functionality” as a “key to twenty-first century competitive advantage.”

Here, we define ‘Smart Materials’ as materials that form part of a smart structural system that has the capability to sense its environment and the effects thereof and, if truly smart, to respond to that external stimulus via an active control mechanism (Institute of Materials, Minerals and Mining 2003, p. 9).

To disperse misunderstanding in relation to different terminologies and meanings they continue:

The terms ‘smart’, ‘functional’, ‘multifunctional’ and ‘intelligent’ are often used interchangeably. This is reasonable, if confusing, for the first three terms but the last almost certainly suggests a degree of consciousness that does not exist in any non-biological system. There is arguably no such thing as a ‘smart material’ per se - there are only materials that exhibit interesting intrinsic characteristics which can be exploited within systems, or structures that, in turn, can exhibit ‘smart’ behavior (Institute of Materials, Minerals and Mining 2003, pp. 5, 11).

2.7.4 Concepts for Information Materials Usage in Architecture

Building upon this notion of “materials which can alter their properties or transmit information merely due to electronic or molecular proceedings,” the British architect Mike Davis presented in 1981 the concept of his polyvalent wall, a wall that controls the flow of energy from the exterior to the interior via thin, multifunctional layers. Proposing that this would become the future

envelope of a building, removing “the distinction between solid and transparent” he proclaims the shift from “the mechanical age to a ‘solid state’ era” (Davis 1981, pp. 55–57).

With no lesser conviction emphasizes John Orton in his book *Semiconductors and the Information Revolution: Magic Crystals that made IT Happen*, the utter importance and ubiquitous presence of semiconductor technologies in our current time and grants that they should “rank alongside the Beethoven Symphonies, Concord, Impressionism, medieval cathedrals, and Burgundy wines and we should be equally proud of it” (Orton 2009, p. vi). Similarly claims the Physicist, Karl Wolfgang Böer that:

Semiconductors have sparked the beginning of a new material epoch. Technology has evolved from the stone age through the bronze and iron ages into the age of semiconductors, materials that are influencing culture and civilization to an unprecedented degree (Böer 2002, p. 2).

While it is a bit simple to reason from the influence of stone and iron on architecture that semiconductors and as such *information materials* will equally and as importantly find their way into the (built) environment they do undoubtedly offer an immensely broad scope of potential applications. These range from the (imaginative) creation of fully transformable immersive environments (something that Winy Maas explored in his ‘Barbapapa’ and ‘Transformer’ studios held at ETH Zurich and TU Delft) over climate responsive facade systems and building envelopes, like Decker Yeadon’s homeostatic facade system (Decker 2014, p. 78), to novel forms of interaction with and through a dynamic materiality, like Stefan Ulrich’s Funktionide, a shape-shifting, soft, and amorphous robot (Dezeen 2009). A more practical and applied suggestion is Manuel DeLanda’s reference to the self-monitoring and self-healing capacities of biological structures when emphasizing the potential of such materials to respond to the occurrence of cracks in load-bearing components. He proposes to enhance concrete columns with optical fibers or piezoelectric crystals to analyze incipient fissures, which could

consequently be closed by activating embedded shape-memory alloys (DeLanda 2006, pp. 122–123). The earlier mentioned Foresight study provides similar suggestions, emphasizing the advance of ‘smart’ buildings and infrastructure:

The report specifically identifies as exemplars the use of embedded sensors to remotely monitor building performance, the use of smart technologies for identity, data collection and management, and decorating paint that electronically changes colour and warns of stress points (Institute of Materials, Minerals and Mining 2003, p. 23).

Although the number of such practical, yet still mostly theoretical, ideas is relatively large they have so far only seldom gone beyond a prototypical state toward more applied and spatial scales. Thus the amount of realized architectural projects challenging the usage of *information materials* and proposing alternatives to existing structures is rather limited. This is due to certainly the low-cost culture in respect to building materials but probably also because of a general lack of knowledge as well as limited access to architectural *information material* products. Michelle Addington and Daniel Schodek add that “materials continue to be chosen not so much for how they perform, but what they connote.” In that respect *information materials*, whose fundamental properties are of behavioral nature, are largely overlooked since they possess only little connotative qualities. Departing from this they demand to “move beyond fetishization of the gadgets, and get over our preoccupation with showing off the advanced materials in a purely provocative manner” (Addington and Schodek, pp. 201–203).

Most of the early works employing *information materials* in a spatial context originate however exactly from such an intention, displaying smart materials for their artistic, surprising effects. One of the earliest examples is Sigmar Polke’s Thermowand installation at the Musée d’Art Moderne de la Ville de Paris from 1988. Using three different types of thermochromic liquid crystal substances the German artist covered a convex-curved wall with a large area of temperature-sensitive paint, which visualized the daily path of the sun by changing its

color in response to the sunlight shining upon it (Ritter 2007, p. 86).

In 1999 the Dutch architecture firm OMA was commissioned by Prada to design a number of flagship stores around the globe. The New York 'Epicenter' opened in 2001 and on top of its avant-garde design it features a number of experimental technologies and new materials. The doors of the changing rooms, for example, are made of Privalite glass, a liquid crystal composite that switches from transparent to translucent when customers enter (Vegesack and Eisenbrand 2006, p. 152).

Another innovative concept is SmartWrap, a proposal of a multifunctional building skin developed by Kieran Timberlake Associates, which bears striking similarities to Mike Davis' polyvalent wall described earlier. The two-layer facade skin is made of transparent, elastic PET foil. Organic photovoltaic cells are printed onto the outer surface to harvest energy, which is stored in thin film batteries and distributed throughout the system through conductive, printed circuits and organic thin film transistors. The foil is further equipped with polymer-based **OLEDs** for lighting and electronic displays, and with chromatic solar protection for adjusting the transmission of light and heat. The inner skin contains pockets of aerogels for insulation and phase-change materials for heat storage. A small portion of the building envelope was demonstrated in August 2003 at the SOLOS exhibition at the Cooper Hewitt National Design Museum (Ritter 2007, p. 140).

Phase-change materials have also been used by the Swiss architect Dietrich Schwarz in the design of his Senior Citizens' Apartments building in Domat/Ems, 2004 Fig. 2.19. The 148 m² southern glass facade of the building is made of a latent heat-storing insulation glass, which employs a light-directing prism panel to reflect direct light radiation during summer but permit light penetration in the winter. The low-angled light then passes through the glazing where it hits salt hydrate panels on the inside of the structure and gets stored by melting the material. When the room temperature falls below 26 °C the salt hydrate crystallizes and releases its



Fig. 2.19 The retirement community in Domat Ems, Switzerland by Schwarz Architekten integrates phase-change materials for latent heat storage within its glazed facade (Kretzer 2015)

energy back into the room. When charged the opaque panels turn translucent, making the heat-storing effect visible (Schröpfer and Carpenter 2011, p. 168).

On occasion of the international building exhibition IBA in Hamburg four Smart Material Houses have been built in 2013. The model homes are ought to demonstrate new technological approaches for creating more sustainable and energy efficient buildings. The project BIQ by Splitterwerk, Graz incorporates a bioreactor glass facade, which cultivates green microalgae to produce energy and control light radiation and shading. Zillerplus Architekten from Munich created a building that has phase-change materials embedded into its external skin and is able to produce more energy than its residents require. Woodcube by the architektenagentur, Stuttgart is a five-story apartment building that consists almost entirely of wood and demonstrates how traditional techniques can be reinterpreted in a modern way. And the Soft House by Kennedy & Violich Architecture uses photovoltaic cells incorporated into a dynamic textile facade that turns toward the sunlight to harness energy (International Building Exhibition IBA Hamburg).

2.7.5 Material Behavior in Regards to Energy, Time, and Space

Evaluating the above-described examples, it is interesting to observe that while the earlier, more

artistic ones focus on emphasizing particular material effects for their entertaining value, the latter, increasingly architectural works deal mainly with energy related issues. Affordance and affordability thus seem to be key aspects for the rise and usage of any smart technology either by in itself being extremely economical or by adding extra value through increased performance, including additional safety or long-term cost reduction in regards to maintenance. Thomas Schröpfer argues that “with buildings and their associated systems contributing [...] an average of 32 % of all greenhouse gases in the US” architects have a certain responsibility to address and prioritize “issues of sustainability, energy efficiency, and material lifecycles” (Schröpfer and Carpenter 2011, p. 178). Yet, as textile designer and researcher Aurélie Mossé points out, that while “sustainability is predominantly understood as a practice aimed at reducing and minimizing the impacts of human actions on the environment,” it is “not only an issue of space and matter, but more fundamentally a temporal aspect,” and should include an understanding of what to sustain, in whose interest, and for how long it is to be sustained (Mossé 2014, p. 88).

Considering time an essential characteristic of both sustainability and materiality, especially in relation to *information materials*, Sheila Kennedy argues that when designing in the fourth dimension:

The question for architecture thus becomes not what is a material but when is a material; when does it change from one state to another, and how may its dynamic behavior be designed and experienced in the space of architecture? (Schröpfer and Carpenter 2011, p. 120).

In *Smart Materials and new Technologies* Addington and Schodek note that nowadays many products are labeled green in terms of energy usage. However, the assumption that an accumulation of more powerful products will automatically result in more efficient buildings and settlements and thus less fossil fuel consumption and global greenhouse emissions is misleading since “energy boundaries do not fall into a vertical or horizontal arrangement with a neatly additive accounting system.” To them buildings are first of

all units of private property, which might eventually be considered “a collection of behaviors that intervene at many different locations in the energy network,” but should not be seen as energy systems or as containers for energy systems (Addington and Schodek 2005, p. 220).

Ludger Hovestadt vigorously criticizes the current fixation with terms like sustainability and energy efficiency and proposes to (intellectually) liberate ourselves from energetic constraints and scarcities. He believes that through our knowledge on how to, for example, produce functional materials like solar cells and thus harvest electricity from sunlight, we have in principle access to an abundant source of continuous supply, providing us with “roughly 10,000 times our overall energy consumption today.” To him energy is thus not about declining resources, nor about inefficient technology, and certainly not about sustainability, but simply a matter of the unrestricted and far-reaching distribution of knowledge and intellect (Hovestadt 2014, p. 64).

Together with Vera Bühlmann in their book *Printed Physics—Metalitikum I*, they highlight yet another essential aspect of *information materials*, which often tends to be overlooked: the novelty of their fabrication process “using printing technologies.” Drawing direct analogies to the revolutionary importance of Gutenberg’s printing press in the fifteenth century, which “promoted the secularization of mental horizons in philosophy and modern science,” they argue that we are now witnessing an equally important moment in time, initiating the “secularization of a naturalized rationality principle.” Just as the invention of the printing process made formerly inaccessible text available as a descriptive medium to society and essentially reformed dominant belief structures, brings “information-technological printing technology” unprecedented new possibilities that might reach far beyond general anticipations.

Bühlmann and Hovestadt build their thesis upon two major lines of argumentation. The first is based on the conception that information technology is profoundly distinct from both matter and energy, since unlike mechanics “it controls the physical conditions symbolically.”

The second statement emphasizes the industrial production of such ‘symbolic physics’ which thus are able to quickly reach a substantial mass, powerful enough to have global effects (Bühlmann and Hovestadt 2013, pp. 12–15). Referring to both the vast impact of Google as well as cellular phone technology on society Hovestadt exemplifies a number of decisive digitally enabled novelties, which are all based upon similar information technological phenomena. These include **microelectromechanical systems** (MEMS), piezoelectronics, semiconductors (like LEDs or OLEDs), but most of all photovoltaics and their potential for an abundance of clean energy (Hovestadt 2013, pp. 60–67).

Such an assumption, challenging not only some of the core principles of contemporary architectural design but our present attitude toward the planet and nature in its entirety, might be hard to simply accept and is in its practical implementation still far from realization. Yet its theoretical foundation provides an immensely powerful base to liberate oneself from the externally imposed burdens of environmentally friendly and ecologically aware design politics and allows the designer to explore *information materials* in relation to other fundamental aspects of architecture, such as space, time, and particularly people (Kolarevic 2014, p. 150). Moreover, the hypothesis of an abundant availability of not only resources but especially possibilities poses extremely challenging tasks and uncovers our current impotence in addressing far-reaching value and context, which are often concealed behind formal aesthetics and eye-catching effects.

Addington and Schodek expand upon this issue and emphasize the responsibility of architects and designers in purposefully integrating novel technologies into our environment. As basic guidelines they formulate six key aspects in relation to energy theory and the essentials of material structure:

- Energy is about motion, and motion can only occur if there is a difference in states between a system and its surroundings.

- The exchange of energy can only take place at the boundary between a system and its surroundings.
- Energy must be accounted for during exchange processes. Any energy exchange that is not 100 % efficient will produce heat. As such, all real world processes produce excess heat.
- Usable energy is lost in every exchange. When there is an energy input in one form, the usable energy output is always lower.
- Material properties are determined by either molecular structure or microstructure. Any change in a material property, such as what happens in a smart material, can only occur if there is a change in one of the two structures.
- Change can only occur through the exchange of energy, and that energy must act at the scale of structure that determines the material property (Addington and Schodek 2005, pp. 221–222).

Building upon this Addington and Schodek declare that any kind of material behavior can be understood by relating to these basic principles, which will empower architects to focus on phenomena and environments rather than material artifacts. Calling for the active exchange of knowledge with other disciplines they highlight the potential of *information materials* as being more than just an exciting new technology but a powerful impulse and chance to question the status quo. This will allow architects to depart from established models, beyond “the notions of efficiency and expediency” and create results that “are not buildings or urban infrastructure, but places of human interaction” (Addington and Schodek 2005, p. 227).

2.8 Final Summary and Conclusion

The present chapter sets forth to investigate the meaning of materiality and how the role of materials in architecture changed and evolved over the course of time. The first part of the chapter is split into the topics *Natural Materials*, *Industrial Materials*, and *Synthetic Materials*, while the second part covers the areas *Digital Materials* and *Information Materials*.

In comparison to the first part, the latter obviously has a much smaller theoretical foundation, spanning a little more than two or three decades, yet in both cases the chosen positions are not intended to reflect a general tendency but rather specific opinions within a diverse context. While the phenomenon of digital materials in regards to freeform or nonstandard architecture is by now largely accepted and publicly renown they do remain exceptional cases and the majority of practices still designs and builds in a fairly traditional sense. In that context it is interesting to observe that the very inventor of CAD systems, Ivan Sutherland, proclaims that using digital tools is only helpful if the result is superior to what can be done by hand.³ Obviously computer-aided drawing has greatly sped up the design process and being able to copy–paste or delete elements on the fly was not as easy before, yet it was possible. In that sense it remains questionable where the true benefits of these new technologies lie and how to adequately assess them. Robert Aish from Autodesk Research transfers the responsibility to the user and argues:

A creative tool is one that facilitates [...] customization and can be used beyond what was envisaged by the original tool builder.

He encourages us to challenge both the instruments and ourselves in a critical and reflective way (Sheil and Glynn 2011, p. 11). In relation to *information materials* the reluctance of the discipline is even higher, mostly because the technology still seems too far off in order to be considered serious. However, there are other factors such as scalability, longevity, costs, sustainability etc., as well as the fact that the materials are usually designed and developed for particular situations and purposes, which mutually hinder the progressive advancement in an architectural context.

In both cases a closer cross-disciplinary exchange could prove helpful, especially since

much of the technological development happens in other sectors, such as the aerospace, automotive, and military industries. Moreover, despite the time it takes to create and establish new technologies on the market so they can be promoted to other areas, it might be the very standards and norms, which emerged during Industrialization, that impede their architectural application and which might require reassessment in respect to the current era.

What however remains striking and highly motivating is the observation of an underlying desire for the creation of more dynamic, more fluid, flexible, or liquid spaces, which seems to have (re)emerged with the occurrence of digital technologies around the turn of the century. While these formulations were in the beginning mostly tied to virtual environments, akin to Markos Novak's liquid architecture, forerunners in digital fabrication like Greg Lynn manifest them physically, and visionaries such as Kas Oosterhuis even attempt to maintain the dynamism of the digital design process through the creation of (inter)active spaces. As such it remains very likely that both digital materials as well as *information materials* will influence architecture on a variety of levels and scales. Yet considering the duration of a building's construction and the time it is ought to last, as well as its tightly tied cultural and social implications, meaning, and value it is very possible that change will not emerge from within the architectural discipline but rather through user demands, applications, and products. Often such shifts are much more subliminal than initially anticipated. While plastics, for example, did not, or only for a short period, lead to the architectural revolution its supporters proclaimed, the material is more than omnipresent today. In a similar sense might *information materials*, at least for the time being, be much more powerful in smaller scales emerging from particular consumer related demands.

In that sense a reformulation of the architectural practice and the development of new instruments will be the keys in order to remain up-to-date. Concluding from such a demand a fundamental evolution of architecture both

³See Sect. 2.6.1 *The Emergence of Digital Design and Fabrication Techniques* for more details.

topologically and formally might however still require decades of integrative research and collaboration. What can be hoped for in the nearer future is a more comprehensive and less hierarchical exchange among adjacent disciplines and thus a smoother integration of technologies into space and structure. This will require architects to (re)formulate contexts and visions, within which they position their work both in terms of origin and perspective, rather than just updating existing systems with new technologies or celebrating them for the sake of their spectacularity.

In order to provide a fertile ground for such explorations it is necessary to develop or use methods for the dissemination and access to knowledge that feel appropriate and contemporary. While many of the described treatises in this chapter were intended as references for education and training, relating to the then state-of-the-art, today's material world is much more complex and multifaceted for to be approached in such a didactic manner. Retaining the necessary broadness while avoiding superficiality, yet providing depth and credibility will be the key to create a general awareness of related technological progress among the architectural discipline. The following chapter will thus set out to explore novel ways for knowledge mediation and teaching in order to incept such understanding early on during an architect's career.

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