# 1

# MANUFACTURING / MATERIAL / EFFECTS

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Materials and surfaces have a language of their own. Stone speaks of its distant geological origins, its durability and inherent symbolism of permanence; brick makes one think of earth and fire, gravity and the ageless traditions of construction; bronze evokes the extreme heat of its manufacture, the ancient processes of casting and the passage of time as measured in its patina. Wood speaks of its two existences and time scales; its first life as a growing tree and the second as a human artefact made by the caring hand of a carpenter or cabinetmaker. (Juhani Pallasmaa)[1]

Over the past decade we have seen in architecture the (re)emergence of complexly shaped forms and intricately articulated surfaces, enclosures, and structures, whose design and production were fundamentally enabled by the capacity of digital technologies to accurately represent and precisely fabricate artifacts of almost any complexity. Some buildings produced by this digital technological shift feature smooth, "liquid" forms, while some are simple "boxes" with complexly patterned envelopes; many blend both approaches. These new buildings are attractive to many who relish their innovative potential; to others they are merely provisional distractions from the historically distilled essences of the discipline. Beyond the valuation verdict ("good" or "bad"), the proliferation of these types of expressive projects is undeniable; often lacking historically affirmed subtleties, they provoke established formal and material conceptions of architecture. For example, the first projects that exploit the newfound capacity to digitally design and manufacture highly crafted surface effects are being realized, featuring series of panels with unique decorative reliefs, cut-out patterns, striated surface configurations, etc., hinting at the emergence of new "ornamentalism" in contemporary architecture. Experimental building skins with dynamic, adaptive behavior are also beginning to materialize, challenging prevalent assumptions about tectonics and the permanence of material conditions in buildings. Fundamental to this technological and material experimentation is that *atypical* buildings realized over the past decade or so – whether complexly shaped, complexly patterned, or behaving dynamically – are *affecting* in novel ways our perceptions of surface, form, and space through carefully crafted *effects*, explorations of inventive material organizations pursued across a wide range of scales.

In addition to new forms of architectural expression, and new means of conceptual and material production, increasing advances in material science have radically affected architectural thinking. New materials are offering unparalleled thinness, dynamically changing properties, and functionally gradient compositions. Coupled with the means of digital technology, advances in material science have led to renewed interest among architects in tectonic expression, material properties, and the ability to produce the desired surface and spatial effects, both with emerging materials and with innovative applications of "conventional" materials. A particularly interesting trajectory is the pursuit of material and tectonic unity of skin, structure, and effect (as a contemporary expression of Vitruvius' *firmitas*, *utilitas* and *venustas*) that provides variability in volume, shape, composition, texture, and appearance in a single material product. To that end, composite, layered materials, commonly used in automotive, aerospace, shipbuilding and other industries, are directly interrogated for possible architectural applications, as they offer the unprecedented capability to directly formulate material properties and effects by digitally controlling the production of the material itself. The composition of such materials can be engineered precisely to meet specific performance criteria, so that properties can vary across the section to achieve, for example, a different structural capacity in relationship to local stress conditions, or variable fiber density to achieve different opacity and appearance. By manipulating material variables in composites for local performance criteria, entirely new material, tectonic, and ornamental possibilities open up for architecture. Furthermore, wiring, plumbing, and mechanical systems can be embedded into layers of the composite material. The design and tectonic ambition are remarkable: the manufactured material *is* the building component, or as Toshiko Mori recognized, the "production of materials and fabrication of building components will soon be simultaneous."[2]

## MANUFACTURING

Recent advances in digital technologies of design, analysis, and production have set in motion a remarkable affect not only on the practice and the discipline of architecture, but on the entire disciplinary and professional structure of the building industry.[3] Technology, as has always been the case, lies at the core of the examination of new working protocols in architecture and building. Today, the effective digital exchange of information is vital to the realization of the new *integrative* capacity of architecture.[4]



*Manufacturing of material effects* is a powerful contemporary actualization of the potentialities opened up by highly collaborative, highly integrated design, engineering, fabrication, and construction knowledge. It is intriguing to note that this emerging, technologically-enabled transformation of the building industry in the "digital" age has led to a much greater integration of "mechanical" age processes and techniques into conceptual building design. The twentieth-century separation of the disciplines and the standardization of components have given way to the collaboration of diverse interests and a rigorous exploration of distinctive, atypical, non-standard design solutions, often realized in close association with the manufacturing sector. As observed by Toshiko Mori, "The age of mechanical production, of linear processes and the strict division of labor, is rapidly collapsing around us."[5]

Accepting informed *manufacturing* potentialities is a principal strategy in realizing innovative contemporary architectural design intentions. Thus, a close, collaborative relationship with industry is critical early on, during the conceptual stages of design development. Such an approach confronts traditional modes of practicing architecture with an exchange of information unrestricted by antiquated legal mechanisms, i.e. the legal "firewalls" designed to keep architects (and the risk of litigation) away from the shop floor and the construction site. While much of industry has not "retooled" to take advantage of the digitally-driven design and production, each new experiment and each new collaborative pursuit will help broker the change as projects move towards redefining techniques and methods of design conception and material realization.

1.1.
The structural enclosure of the *Japan Pavilion* at *Expo 2000*, Hannover, Germany, designed by Shigeru Ban, is made from paper tubes.

In light of these technologically-enabled changes, innovative practices with cross-disciplinary expertise are forming to enable the design and construction of new formal complexities and tectonic intricacies. *Front, Inc.* from New York is perhaps the most exemplary collaborative practice to emerge over the past decade; acting as a type of free agency, they fluidly move across the professional and disciplinary territories of architecture, engineering, fabrication and construction, and effectively deploy new digital technologies of parametric design, analysis, and fabrication. Similarly, entrepreneurial enterprises, such as *designtoproduction* from Zurich, Switzerland, have identified an industry niche in the translation of model scale prototypical designs into full-scale buildings. Design firms, such as *SHoP Architects* and *LTL Architects* in New York and *Gang Studio Architects* from Chicago, have integrated in-house design and production in many of their projects. Meanwhile, informed fabrication specialists such as *3form, Inc.* in Salt Lake City, *A. Zahner Company* in Kansas City, and *Octatube* in Delft, the Netherlands, represent an industry-oriented broadening to engage the emerging innovative design processes directly and more effectively through close collaboration with designers.

## MATERIAL

In a dramatic departure from the formally and materially reductive norms of much twentieth-century architecture, it is now possible to materially realize complex geometric organizational ideas that were previously unattainable. Furthermore, in a paradoxical way, the new techniques and methods of digitally-enabled making are reaffirming the long forgotten notions of craft, resulting from a desire to extract intrinsic qualities of material and deploy them for particular effect. As such, interrogating materiality is fundamental to new attitudes towards achieving design intent. (After all, architecture is fundamentally a *material* practice.)

Utterly conventional materials are put to unexpected uses: Shigeru Ban has used paper tubes as structural material on projects of different scales (figure 1.1). New technical capacities are uncovered in traditional materials by out-of-the-box thinking: glass is used in compression, as shown by the work of *Front Inc.*, and stone in tension, as in Jeanne Gang's *Marble Curtain* installation at the National Building Museum in Washington, D.C. These material experiments result from a much more informed knowledge base of material performance and the systemic behavior of its assembly.

1.2.
*LiTraCon*: light-transmitting concrete panel.

Concrete, metal, and wood are losing their *opacity*. In the past few years, we have seen the emergence of *translucent* concrete,[6] developed by *LiTraCon* from Hungary (figure 1.2), and *translucent* metal and wood panels, developed by *3form Inc.* of Salt Lake City, Utah. Such unconventional articulation of conventional materials brings into focus long-established notions of material *truth* and *signification* in architecture. The new *effects* teased out of "old" materials are deployed to *affect* in new ways the "old" perceptions of space, precisely because of the expectations of how the familiar materials should behave.

Aluminum is applied in new ways, as doubly-curved structural skins. The curvaceous building envelope of the *Media Centre* at the *Lord's Cricket Grounds* in London (1999), designed by *Future Systems*, is a semi-*monocoque* aluminum shell, inspired by "stressed skins" long used in automotive, aerospace, and shipbuilding production. In airplanes, for example, the cage-like structure called the *airframe*, made from aluminum alloys, is covered by aluminum panels to form a semi-monocoque envelope in which the structure and skin are separate tectonic elements acting in unison to absorb stresses. By defying the binary logics of the Modernist tectonic thinking, structure and skin are re-unified into one element in semi-monocoque and monocoque shells, thus creating self-supporting forms that require no armature.

Other commonly available materials, such as fiberglass, polymers and foams, rarely used in the building industry, are being closely scrutinized today for potential because they offer several advantages over typical materials. They are lightweight, high strength, and can easily be shaped into various forms, making them ideal for structural skins. These "old," overlooked materials, however, require curvilinear geometries to enable the monocoque skins to perform structurally. Thus, an interesting reciprocal relationship is established between the new geometries and new materialities: complex geometries open up a quest for new materials and vice versa.

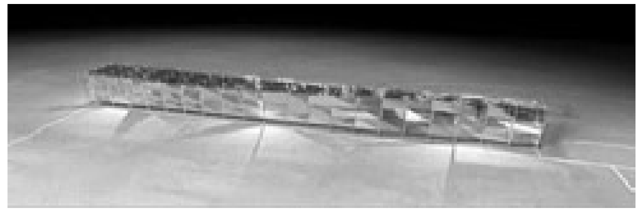
The physical characteristics of fiberglass make it particularly suitable for achieving complex forms. It is cast in liquid state, so it can conform to any mold shape and produce a surface of exceptional smoothness – a liquid, fluid materiality that produces liquid, fluid spatiality. The "liquid" materials arousing particular interest among architects today are composites whose composition can be precisely designed and manufactured to meet specific performance criteria. Composites are actually solid materials created, as their name suggests, by combining two or more different constituent material components, often with very different properties.[7] Together the constituents make more than the sum of their individual parts. The result is a new material that offers a marked qualitative improvement in performance, with properties that are superior to those of the original components. Among composites, the *polymer* composite materials (or simply "plastics") are being considered anew by some architects, primarily because of their high formability,[8] relatively low cost, minimum maintenance, and a relatively high strength-to-weight ratio.

By optimizing material variables in composites for local performance criteria, entirely new material and tectonic possibilities open up in architecture: transparency can be modulated in a single surface, and structural performance can be modulated by varying the quantity and pattern of reinforcement fibers,[9] etc. For example, *structural polyurethane foam*, produced by *reaction injection molding* (RIM), enables a wide range of density and rigidity to be designed and engineered into a wall panel. Two liquids are injected into the mold, reacting upon entry, and forming the polyurethane with the desired properties.[10] A solid surface with a foam core is easily achieved using this process.

Mutability of materials is also recognized as a design opportunity. The capacity of materials to transform and change over time, i.e. deteriorate through ageing, weathering, and use, was something to be avoided in much twentieth-century architecture, and was rarely embraced as a design opportunity. Decay is seen as the enemy in buildings, and a great deal of technical effort is aimed at combating and arresting it. However, weathering is a potent surface strategy[11] and has been pursued by a number of well-known architects, such as Peter Zumthor, whose work



1.4a–c. (below)
*Chromogenic Dwelling*, proposed by Thom Faulders, features a constantly changing pattern of visible solids and voids.



1.3a–b. (left)
*Liquid Crystal Glass House*, proposed by Michael Silver, features an adaptive glass enclosure that can shift from transparency to opacity and vice versa.

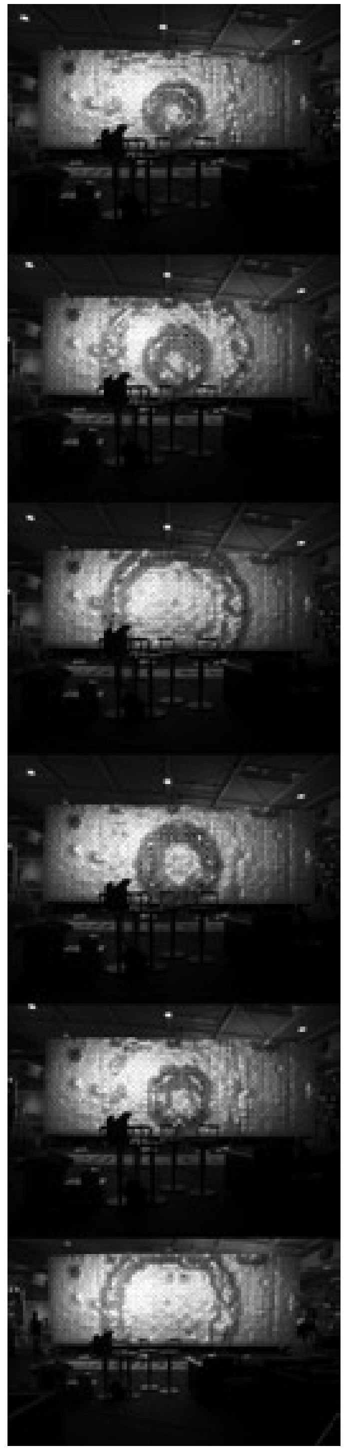
expresses a profound understanding of materials. The contemporary successor to this legacy can be found in the digitally designed and fabricated patterns of perforation and embossing in the skin of the *De Young Museum* in San Francisco, designed by *Herzog & de Meuron* in collaboration with the *A. Zahner Company*. Over time the copper skin will take on an anticipated patina, whose green coloration will eventually blend the dotted field of abstract tree canopies of the building skin with the verdant greenery of the park in which the building is situated, and thus realize a design intent in partnership with nature that will be years in the making.

Other possibilities are opened up by materials that change their properties dynamically in direct response to external and internal stimuli, such as light, heat and mechanical stresses. Sulan Kolatan and William MacDonald have explored materials such as "plastics that undergo molecular restructuring with stress," "smart glass that responds to light and weather conditions," "anti-bacterial woven-glass-fiber wall covering" and "pultruded fiberglass-reinforced polymer structural components."[12] Michael Silver's *Liquid Crystal Glass House*[13] (figures 1.3a–b), proposed for a site in Malibu, California, features a responsive, constantly adapting electronic building skin made from panels which consist of a layer of liquid crystals sandwiched between two sheets of glass, enabling an electronic shift from transparency to opacity and vice versa.[14] The interconnected liquid crystal glass panels are computationally controlled and can create different patterns of transparency and opacity, producing an envelope that is infinitely variable and visually unpredictable. Thom Faulder pursued a similar strategy in his *Chromogenic Dwelling* design proposal (figures 1.4a–c) for the Octavia Boulevard Housing Competition in San Francisco (2005). *Electrochromic* glass was used to create a changing pattern of visible solids and voids, where the building's occupants could electronically switch the exterior glass into an opaque, transparent, or translucent surface in response to climate, light effects, and privacy requirements.[15]

*UN Studio*, the Dutch design practice led by Ben van Berkel and Caroline Bos, has developed a polychromic laminated glass, with a reflective thin film between two sheets of glass that changes color depending on the light angle. It was used for the first time in the *La Defense* office complex in Almere, the Netherlands (2004); depending on the angle of incidence of sunlight, the façades facing the courtyard of this office complex change across the entire color spectrum during the day, from yellow to blue and red and from purple to green (figures 1.5a–b). The architects van Berkel and Bos were interested in "painting space,"[16] by testing "the malleability of colors almost as if [they] were de Chirico or Jeff Koons," achieving "both phenomenological and literal transparency."[17]

1.5a–b.
*La Defense* office complex in Almere, the Netherlands (2004), designed by *UN Studio*.

1.6a–f.
The dynamic skin of the *Aegis Hyposurface*, designed by Mark Goulthorpe/*dECOi*.



New skins can change not only their transparency and color, but also their shape in response to various environmental influences, as demonstrated by the *Aegis Hyposurface* project (figures 1.6a–f) by Mark Goulthorpe/*dECOi*. It features a faceted metallic surface, which is deformable, resulting from a flexible rubber membrane covered with tens of thousands of triangular metal shingles. The surface can change shape in response to electronic stimuli resulting from movement and modification of sound and light levels in its environment, or through parametrically-generated patterns. It is driven by an underlying mechanical apparatus that consists of several thousand pistons, controlled digitally, providing a real-time response.[18]

Goulthorpe's *Aegis Hyposurface* dynamic skin, a highly complex, electro-mechanical hybrid structure, whose sensors, pneumatic actuators, and computational and control systems provide it with what could be called "smart" behavior, points to a material future in which a building envelope could become a fairly thin, single "intelligent" composite material[19] with a "neural" system fully integrated into its layers. Such a possibility has been already demonstrated in the *SmartWrap* project[20] (figures 1.7) by *KieranTimberlake*, a Philadelphia-based design firm. This "building envelope of the future," as it is referred to by its designers, is an ultra-thin composite material that integrates separate functional components of a conventional wall into one single element. The polymer-based material consists of a substrate (the same material used in plastic soda bottles) and printed, laminated layers that are roll-coated into a single film. This multi-functional building envelope prototype, besides providing shelter and interior climate control, also differentiates its aesthetics by changing color and appearance, as well as providing light and power to the building. Light and heating technology are simply printed on the surface.

Finally, designers and researchers increasingly are looking for inspiration in nature to discover new materials and new material behaviors, so that buildings (or rather, building enclosures) can respond dynamically to changing environmental conditions. In

1.7.
*SmartWrap* ultra-thin building envelope developed by *KieranTimberlake*, a Philadelphia-based design firm.


addition to mimicking the intricate complex *appearance* and *organization* of patterned skins and structures in nature, their *behavior* is also being investigated for possible new ideas about the performance of building skins and structures. In such "form follows performance" strategies, the impulse is to harness the generative potential of nature, where evolutionary pressure forces organisms to become highly optimized and efficient (nature produces maximum *effect* with minimum means). A nature-imitating search for new material effects, based on biological precedents – often referred to as *biomimicry* or *biomimetics*[21] – holds much promise as an overarching generative driving force for digitally driven contemporary architecture.[22]

## EFFECTS

There is a close relationship of materiality in architecture to the extended realm of *effects* and *affects*. Articulation of surface and formal effects can have a tremendous affect on the experiential veracity of architecture. Peter Eisenman makes the distinction between effect and affect rather clear.[23] He states, "*Effect* is something produced by an agent or cause. In architecture it is the relationship between some



1.8.
Detail of the *Goldman and Salatsch Building* ("Looshaus") at Michaelerplatz in Vienna (1911), designed by Adolf Loos.

1.9.
The *Barcelona Pavilion* (1929), designed by Mies van der Rohe, features a broad material palette, including richly patterned onyx and Tinian marble.

object and its function or meaning; it is an idea that has dominated Western architecture for the last 200 years." In contrast, "*Affect* is the conscious subjective aspect of an emotion considered apart from bodily changes. Affect in architecture is simply the sensate response to a physical environment."[24] As architecture privileges human engagement, interaction, visual and sensual reading, well-crafted material effects can engender powerful affects.

Material effects are *performative*: we can verify how materials work by sensing what they do. Performative dimensions of materiality in architecture are primarily physical and perceptual: how the material looks matters as much as how the material performs structurally, thermally, acoustically, etc. Building materials can be manufactured mechanically through slicing and cutting, for example, shaped by force through bending, extruding, expanding, casting, etc. They are used in structural systems, in building envelopes, as surface finishes, etc., i.e. for different *effects*. More importantly, however, they are used to *affect* the perceptions and experience of the forms, surfaces, and spaces; they can embody meanings, evoke feelings …

Materials and their particular properties make architecture multi-sensory – we not only see the material surfaces, but also touch and hear them, all of which contribute to our comprehension and experience of spaces. In other words, material effects are not only visual effects; they are *experiential effects*. According to Juhani Pallasmaa, "Authentic architectural experiences derive from real or ideated bodily confrontations rather than visually observed entities. … The visual image of a door is not an architectural image, for instance, whereas entering and exiting through a door are architectural experiences."[25]

To inform our discourse today, it is useful to examine the notion of material effects from previous eras. As observed by Juhani Pallasmaa, Modernist architecture preferred materials and surfaces that could provide the "effect of flatness, immaterial abstractness, and timelessness."[26] In other words, the Modernists were after the *immaterial effects*:

> The Modernist surface is treated as an abstracted boundary of volume, and has a conceptual rather than a sensory essence. These surfaces tend to remain mute, as shape and volume are given priority; form is vocal, whereas matter remains mute. The aspiration for geometric purity and reductive aesthetics further weakens the presence of matter.[27]

But, it wasn't so in the early days of Modernism. The rich, "organic" decorative qualities of materials (often richly patterned marble) were often used to counterbalance the sensory reductivism of the Modernism's formal minimalism. Adolf Loos, who at the beginning of the twentieth century decried the use of ornament in architecture,[28] in his buildings extensively deployed the natural decorative qualities of materials. In the *Goldman and Salatsch Building* ("Looshaus") at Michaelerplatz in Vienna (1911, figure 1.8), the exterior of the lower stories is surprisingly ornate, primarily through the use of richly veined green marble. Mies van der Rohe's *Barcelona Pavilion* (1929) was an ode to the sensory richness of materials, with walls made from four different kinds of stone, including richly patterned, rust-colored onyx, green Tinian marble, and white travertine (figure 1.9), cruciform chrome-plated columns, tinted glass (green, white, and clear), black carpet, scarlet velvet, plus shallow, reflective pools of water. In these examples of early Modern architecture, the material expression operates on human scale and as such elicits a more acute sensory response from the observer.

1.10.
The "*Bubble*," BMW's pavilion at the *IAA'99 Auto Show* in Frankfurt, Germany, designed by Bernhard Franken.

1.11. (far right)
The "*Dynaform*," BMW Pavilion at the *IAA'01 Auto Show* in Frankfurt, Germany, designed by Bernhard Franken.

If we examine the deployment of material-driven ornamental strategies in the context of formal minimalism in early modern architecture, we realize that, while not intended as decorative, there was an inherent expression of material in its natural form, or even as affected by the machine process that manufactured it.[29] In fact, there is a subtext of manufacturing that underlies the material realization during the mechanical age, in its perfectly sliced and polished marble, repetitive standardized components, etc. According to Umberto Eco, in Renaissance and Baroque times, machines were used periodically to achieve effects, but it was the ornamental result of the effect that was celebrated, and not the procedural mechanic (machinic) operations, as we see in early Modernism. "Machines were definitively associated with the production of aesthetic effects and were used to produce 'theater,' or stunningly beautiful and amazing architectures."[30]

Phenomenological potency of material is increasingly given primacy over fluid, supple potential of the digitally derived complex form and further is in opposition to the Baroque attitude. This recognition of the affective appeal of the material affirms the significance Gaston Bachelard assigned to "material imagination." In *Water and Dreams*,[31] his phenomenological investigation of poetic imagery, Bachelard makes a distinction between two forms of imagination: a formal imagination ("images of free forms") and material imagination ("images of matter"). According to Bachelard, both are present in nature and in mind; in nature, the "formal imagination" creates the beauty it contains; the "material imagination," on the other hand, produces that which, in being, is both primitive and eternal. For Bachelard, "images of matter" project deeper and more profound experiences than "images of free form." In acknowledging Bachelard's phenomenological distinctions between the images of matter and the images of form, Juhani Pallasmaa notes that "matter evokes unconscious images and emotions, but modernity at large has been primarily concerned with form."[32]

In his essay in 1992, Peter Eisenman went a step further, and lamented: "Architecture not only does not deal with affect but it no longer deals with effect."[33] That is no longer true: in contemporary architecture, materials and their inherent properties are often fundamental points of departure for discovering and exploring new spatial possibilities (*effects*) and for designing different perceptions and experiences of architecture (*affects*). For example, as discussed later in this chapter, in many projects by *Herzog & de Meuron*, the material is often foregrounded as an effect; the effect cannot be decoupled from the material.

In returning architecture to both the realm of effects and affects, we should avoid instrumentalizing the links between design intentions and their material manifestations. The typical tactic is to resort to material "determinism" by presuming that "correctly" selected materials will provide the desired effects both aesthetically and performatively. That passive mode of material deployment must be challenged. As Toshiko Mori noted in *Immaterial/Ultramaterial*, "By understanding materials' basic properties, pushing their limits for greater performance, and at the same time being aware of their aesthetic values and psychological effects, an essential design role can be regained and expanded."[34]

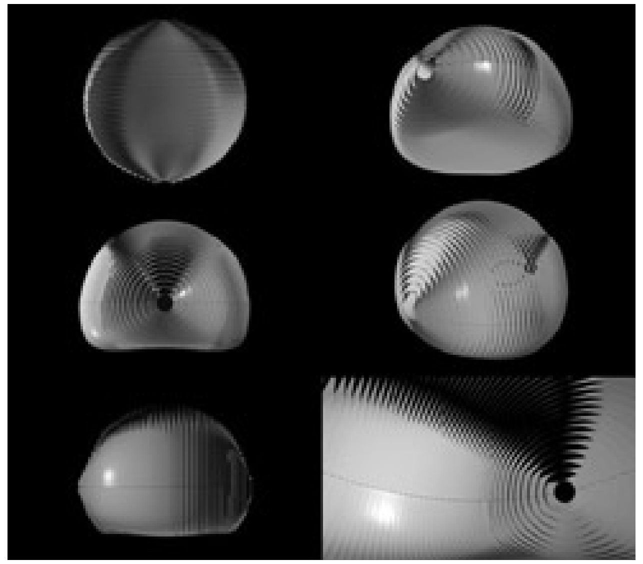
## FROM SMOOTH TO PATTERNED

Digitally-based technologies and techniques have introduced new spatial and formal capacities in architecture.[35] This digital technological shift led to several lines of investigation in contemporary architecture: one aimed at seamless materiality, in which fluid smoothness was a primary design consideration, a second trajectory explored the outcome of digitally crafted, two- and three-dimensional non-uniform patterns and textures, and a third sought out the unity of skin, structure, and pattern.

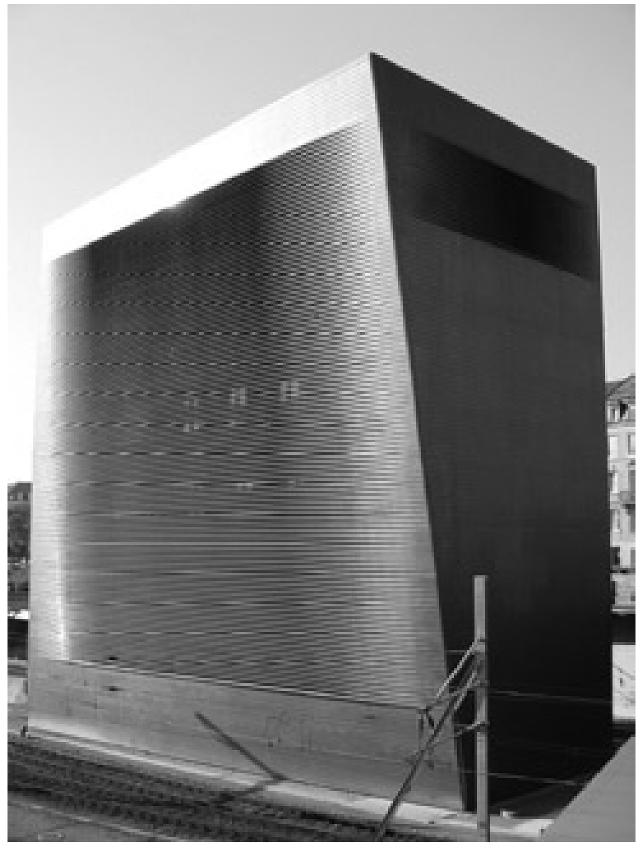
Soon after the curvaceous forms started to appear on computer screens in early 1990s, the ambition in the material realm was to express the seamlessness and the smoothness of form. Bernhard Franken, for example, described several of his projects[36] for BMW (figures 1.10 and 1.11) as an explicit attempt to hide the connections between components and achieve the smooth appearance characteristic of the cars manufactured by his client. *Future*



1.12. (left)
The *Media Centre* at the *Lord's Cricket Grounds* in London (1999), designed by *Future Systems.*



1.13. (right)
The "shredded" skin of the *Embryological House* proposed by Greg Lynn.



1.14.
*Signal Box* in Basel, Switzerland (1999), designed by *Herzog & de Meuron.*

*Systems* expressed a similar strategy for smoothness of appearance in several of their projects, such as the *Media Centre* at the *Lord's Cricket Grounds* in London (1999, figure 1.12). To a large extent, the smoothness and seamlessness provided only one reading that mattered in those projects: overall form and shape were primary – nothing was allowed to distract from the articulation of the expressive and atypical geometry of the exterior skin.

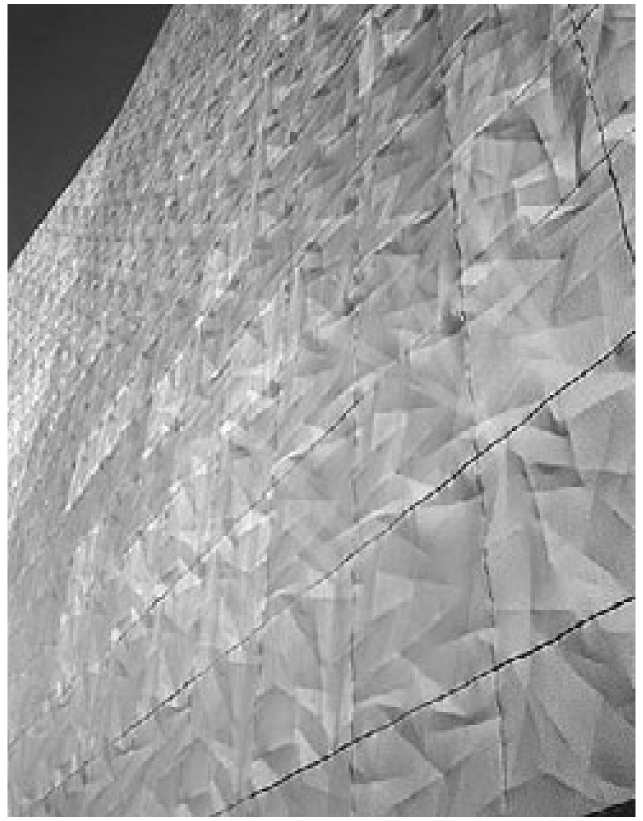
The infatuation with complex geometry in mid-1990s soon was replaced by the exploration of highly crafted, non-uniform *surface effects* based on complex *patterning*, *texturing*, or *relief*. This aesthetic shift led to a reemergence of the discourse related to ornament and decoration, out of favor with architecture for a large part of the twentieth century. The reasons for this move towards the ornamental or decorative stemmed partly from pragmatic requirements that building skins have to satisfy, partly from purely aesthetic considerations, and partly because of the old-fashioned need for scale and tactility in buildings.

Greg Lynn, for example, developed various strategies of creating apertures in the curvy skins of his buildings through "shredding;" the smooth morphology was adapted to the pragmatic requirements of bringing light and air into the buildings. The resulted striated, shredded surfaces attain a changing, but smooth rhythm, a pattern of alternating voids and solids that can dematerialize parts of the skin or render it almost entirely opaque depending on the viewing direction (figure 1.13); the "shredding" also adds a much needed sense of scale. In addition, the "shredding" can provide a subtle, dynamic optical effect resulting from the changing angle of the viewer's eyes to the surface, which was aptly demonstrated by the "shredded" skin of twisted copper strips in the *Signal Box* in Basel, Switzerland (1999, figure 1.14), designed by *Herzog & de Meuron*.

Among contemporary design practices, *Herzog & de Meuron* stand out in their unapologetic exploration of pattern, texture, and relief and the resulting material and surface effects they can produce. The "ornamented minimalism" – a seemingly minimalist geometry of the building, often wrapped with a highly decorative skin – has become their signature. In the Library of the *Eberswalde Technical School* in Eberswalde, Germany (1999), a

1.15. (far right)
Library of the *Eberswalde Technical School* in Eberswalde, Germany (1999), designed by *Herzog & de Meuron.*

1.16. (right)
New addition to the *Walker Art Museum* in Minneapolis, Minnesota (2005), designed by *Herzog & de Meuron.*

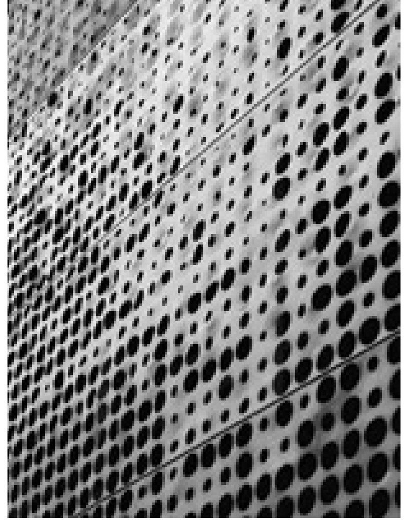


conventional, "box" building with horizontal, alternating strips of concrete and glass, images were silk-screened onto glass and concrete panels, literally blurring the material distinctions between the two (figure 1.15). The new addition to the *Walker Art Museum* in Minneapolis, Minnesota (2005, figure 1.16), for example, features a skin made from crumpled, aluminum mesh panels, "a blur between solid, translucent, and transparent" in the words of Jacques Herzog. The "ornamental" is not limited to the building skin only; the interior surfaces of the museum addition are decorated by swirling, lacy patterns cut in wood (figure 1.17) or embossed in metal panels (figure 1.18).

1.17. (right)
*Walker Art Museum*: Swirling, lacy patterns were cut in wood in the interior surfaces.

1.18. (far right)
*Walker Art Museum*: Swirling, lacy patterns were embossed into panels in the auditorium.





1.19. (above)
The embossed and perforated rain screen panels in *De Young Museum* in San Francisco (2005), designed by *Herzog & de Meuron.*

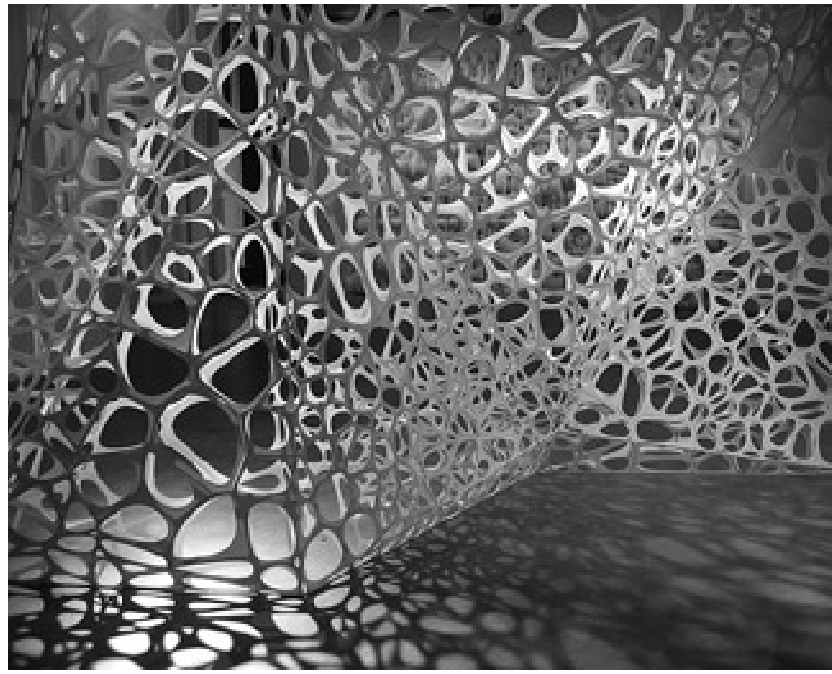
1.20a–b. (right)
The *Airspace* façade in Tokyo, Japan (2007), designed by Thom Faulders/*Beige Design.*

The scale of decoration in the buildings by *Herzog & de Meuron* can vary greatly, from several feet to several hundred feet. The large surfaces of the rain screen at the *De Young Museum* in San Francisco are made from over 7,000 copper panels, each of which features unique halftone cut-out and embossing patterns abstracted from images of the surrounding tree canopies (figure 1.19). The rain screen cladding is obviously decorative, but it also has a purely functional purpose – to hide an integrated ventilation system and to diffuse exterior light falling into the galleries. Such a *functional* approach to ornamentation is typical of many of the projects by *Herzog & de Meuron.* A project with a similar functional intent can be found in the Thom Faulders-designed layered, porous skin of the *Airspace* façade in Tokyo, Japan (2007, figure 1.20a–b): "sunlight is refracted along its metallic surfaces; rainwater is channeled away from exterior walkways via capillary action; and interior views are shielded behind its variegated and foliage-like cover."[37]

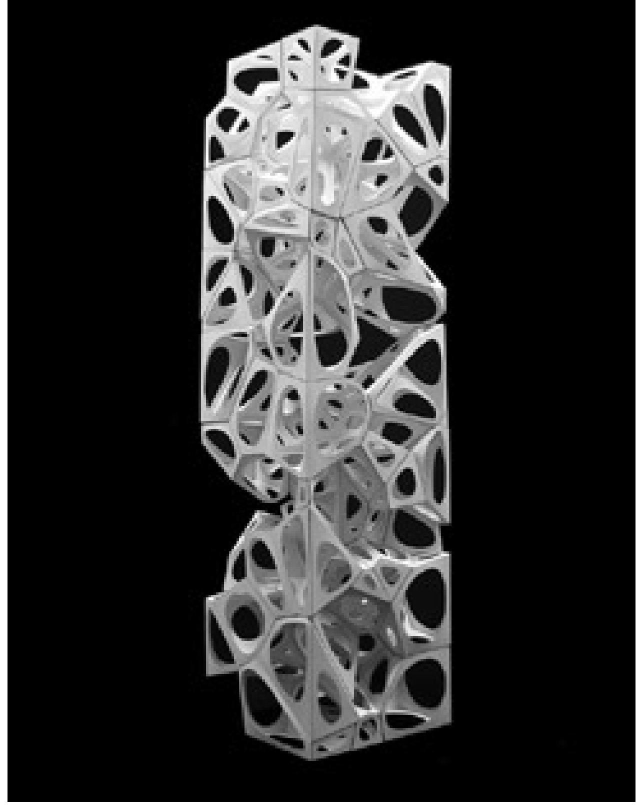
Patterned surfaces of the *Federation Square* building in Melbourne (figure 1.21), designed by *Lab Architecture Studio*, are based on what is known in mathematics as *pinwheel aperiodic tiling*, enabling the designers to apply different scales of the same pattern across the building as needed. There are other notable examples in which patterning is based on mathematics. For example, *Voronoi tessellation*[38] is a particularly popular algorithm today (figure 1.22). Daniel Libeskind, as well, proposed a patterned skin based on fractals for the extension he designed (with Cecil Balmond of *Arup*) for the *Victoria & Albert Museum* addition in London (figure 1.23).

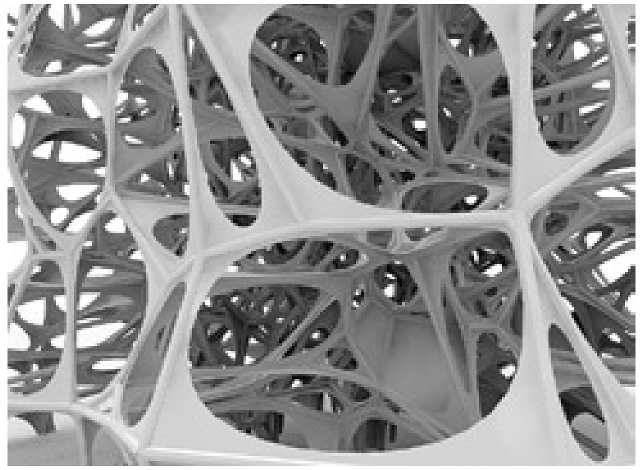
1.21. (right)
The *pinwheel aperiodic tiling* in the patterned skin of the *Federation Square* buildings in Melbourne, Australia (2002), designed by *Lab Architecture Studio.*

1.22. (far right)
The patterning of the *C-wall* project by Andrew Kudless is based on *Voronoi tessellation.*



1.24a–b.
The three-dimensional *Voronoi* patterning by Andrew Kudless.





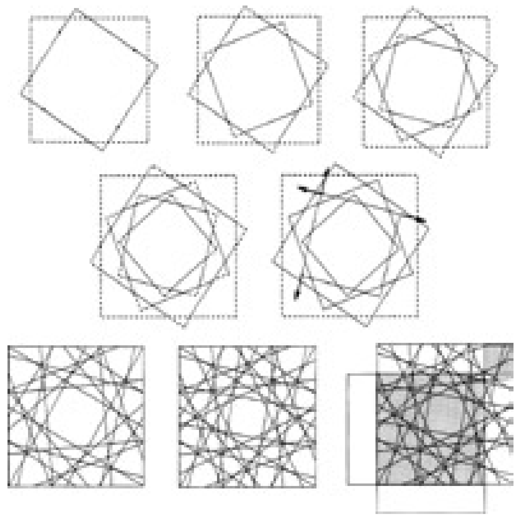
1.23. (right)
The fractal skin of the proposed *Victoria & Albert Museum* addition in London, designed by Daniel Libeskind.

Many of these patterning schemes can be extended from a two-dimensional to a three-dimensional realm (figure 1.24a–b) and emerge from basic mathematical operations in order to achieve complex results. A simple patterning scheme was used by Cecil Balmond and Toyo Ito in their design for the *Serpentine Pavilion* in London (2002, figure 1.25) to produce a complex-looking outcome. The apparently random patterning that wraps the entire pavilion is produced by incremental scaling and rotation of a series of inscribed squares, whose edges were extended and trimmed by the pavilion's unfolded box shape (figure 1.26) to create a beautiful, seemingly irregular-looking pattern of alternating voids and solids. The "bird nest" random-looking structural pattern for the *National Stadium* in Beijing, China (2008, figure 1.27), designed by *Herzog & de Meuron*, is also based on a relatively simple set of rules to create the "extra-large" material effect. The nearby *National Aquatics Center* (2008, figure 1.28), designed by *PTW Architects* from Australia, provides another example of a large-scale material effect. The *Water Cube*, as the project is nicknamed, is a simple box that features a complex three-dimensional bubble patterning. Its geometric origin is the so-called *Weaire-Phelan* structure[39] (figure 1.29), an efficient method of subdividing space using two kinds of cells of equal volume: an irregular *pentagonal dodecahedron* and a *tetrakaidecahedron* with 2 hexagons and 12 pentagons. This regular three-dimensional pattern was sliced with a non-aligned, i.e. slightly rotated rectilinear box to produce the seemingly irregular patterning effect on the exterior. Voids between structural members on the exterior and interior of the building are filled with inflated, pillow-like layers of plastic film called *ethylene tetrafluoroethylene* (*ETFE*).[40] The material effects of this translucent, white, bubble-like skin is ethereal, literally inducing a sensation of being immersed into a giant foam-like structure. Finally, the *Central China Television Center (CCTV)* located further away in the newly emerging Beijing's business district (to be also completed in 2008), also features an extra-large complex patterning scheme (figure 1.30), resulting in this case from the structural analysis of the stresses in the envelope of the building's simply shaped spatial loop.

In many recently completed projects, patterning, however, is primarily decorative, i.e. there is little of the "functionalist ornamentation" as seen in the work of *Herzog & de Meuron*, described earlier. A good example of this purely decorative application of patterning is the recently completed *Ministry of Culture and Communication* in Paris, France (2005), designed by Francis Soler, wrapped in what C.C. Sullivan referred to as a "tech-nouveau" latticework screen of stainless steel with six recurring, symmetrical motifs[41] (figure 1.31). The function of this decorative "wrapper" is to create a visual unity of two distinctly different buildings: the old, neo-classical building and its contemporary glass addition; technically, it is largely superficial.

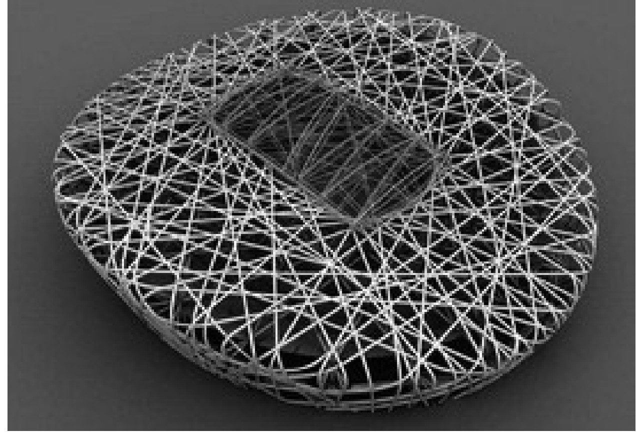
1.25. (right)
The *Serpentine Pavilion* in London (2002), designed by Cecil Balmond and Toyo Ito.

1.26. (far right)
*Serpentine Pavilion*: the irregular-looking pattern is based on incremental scaling and rotation of a series of inscribed squares.

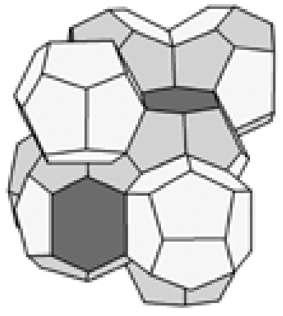




1.27.
The "bird nest" structural pattern of the *National Stadium* in Beijing, China (2008), designed by *Herzog & de Meuron*.



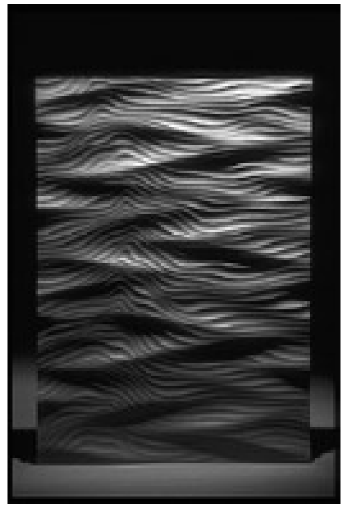
1.29. (right)
*National Aquatics Center*: the three-dimensional pattern is based on *Weaire-Phelan* structure made from *dodecahedrons* and *tetrakaidecahedrons*.

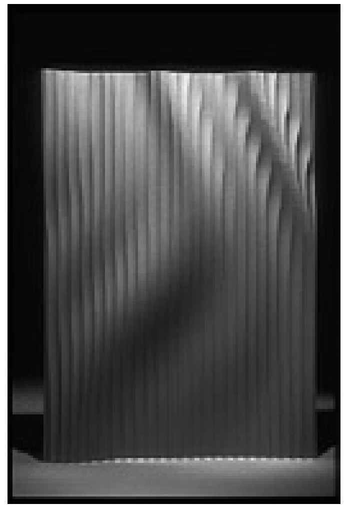


1.28. (right)
The *National Aquatics Center* in Beijing, China (2008), designed by *PTW Architects*.

1.30. (right)
The *CCTV* building in Beijing, China (2008), designed by *OMA* in collaboration with *Arup*.

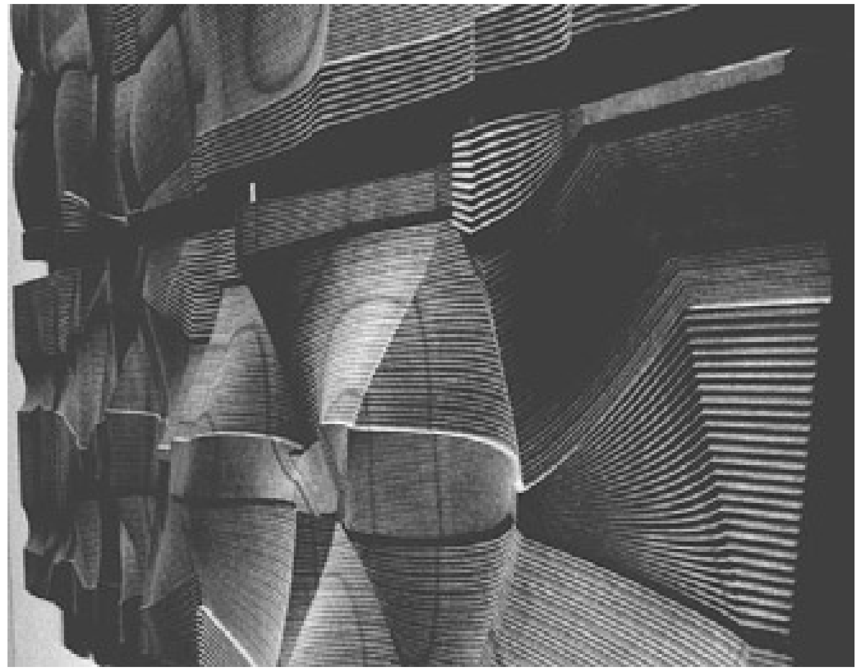
1.31. (far right)
*Ministry of Culture and Communication* in Paris, France (2005), designed by Francis Soler.





1.32a–b.
*Objectiles*, parametrically designed and produced by Bernard Cache.

1.33.
The use of CNC "corrugation" in Greg Lynn's work.

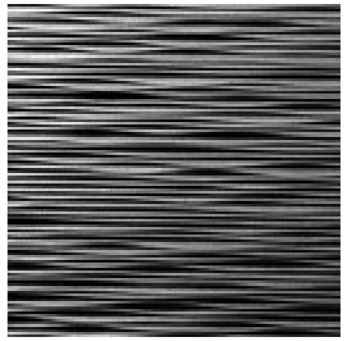


Working on a much smaller scale, Bernard Cache explored the decorative realm of pattern, texture and relief, which also seems to be the current preoccupation of Greg Lynn, who, for example, in recent projects uses "surface geometry to emit texture information so that, like an animal skin, the pattern and relief is intricate with the form."[42] For Cache, "objects are no longer designed but calculated,"[43] allowing the design of complex, variable shapes and laying "the foundation for a nonstandard mode of production."[44] His *objectiles* (figure 1.32a–b), mainly furniture and paneling, are procedurally calculated in modeling software and are industrially produced with numerically-controlled machines. The modification of parameters of design, often random, allows the manufacture of unique objects in a same series, thus making mass-customization, i.e. the industrial production of unique objects, possible.[45]

In many of his *objectile* designs, Cache exploits the decorative effect of the tooling path patterns that can be produced in the material by CNC milling machines. These material effects are directly related to how the surfaces are crafted in CNC milling.[46] In CAD/CAM post-processing software, a NURBS surface is interpreted and converted into precise tool paths that produce a corrugated pattern in the material.[47] By designing the tool paths carefully, richly patterned surfaces can be produced by carefully choreographing the milling sequence. Slight deviations in tool paths can produce surprisingly interesting effects in the material. The same two-dimensional (XY) tooling pattern, if varied in Z direction for each manufactured instance, can produce a series of repetitive, yet differentiated objects. This and similar carefully crafted tool path strategies have been used by Cache very effectively in a number of his *objectiles*;[48] they appear as the information-driven, machinic tectonics inheriting (and redirecting) the modernist notions of ornament as resulting from manufacturing processes. Similar patterning techniques were used by Greg Lynn for interior wall panels (figure 1.33), as an "ornament [that] accentuates the formal qualities of the surface."[49] There are now several commercially available product lines that feature paneling systems with repetitive and differing patterning produced in automatic fashion through CNC milling[50] (figure 1.34).

Finally, evocative visual effects can be produced by mimicking the appearance of one material in another; this is a time-tested technique practiced by stone masons over centuries. *Belzberg Architects* produced fabric-like simulated effect in wood panels for the *Patina Restaurant* (in Frank Gehry-designed *Walt Disney Concert Hall*) in Los Angeles (figure 1.35) by laminating standard wood planks and then CNC milling the desired curtain-like "topography" in the resulting laminate. Such visual and tactile material strategies need not be (entirely) digitally driven. In the *p-wall* project, Andrew Kudless, used elastic fabric to cast a series of plaster panels, arranged in a large field (figure 1.36). This project, inspired by the experiments in flexible concrete formwork by Spanish architect Miguel Fisac in the 1960s, is based on a cloud of points generated from the grayscale values of pixels in a digital image. The points are used to constrain the elastic fabric in the formwork, as it expands under the weight of poured plaster. As observed by Kudless, "The resultant plaster tile has a certain resonance with the body as it sags, expands, and stretches in its own relationship with gravity and structure." The resulting supple surface invites visitors to touch it, to sense its smooth undulations. *The affect is in the material effect, whether small, medium, large, or extra-large.*

1.34. (below)
CNC-carved panels are commercially produced in variable series (*Esthetic Panels*, manufactured by *Marotte*, France).





1.35.
The *Patina Restaurant* in Los Angeles, designed by *Belzberg Architects*.

## MATERIAL AND SURFACE EFFECTS: ORNAMENT REDUX?

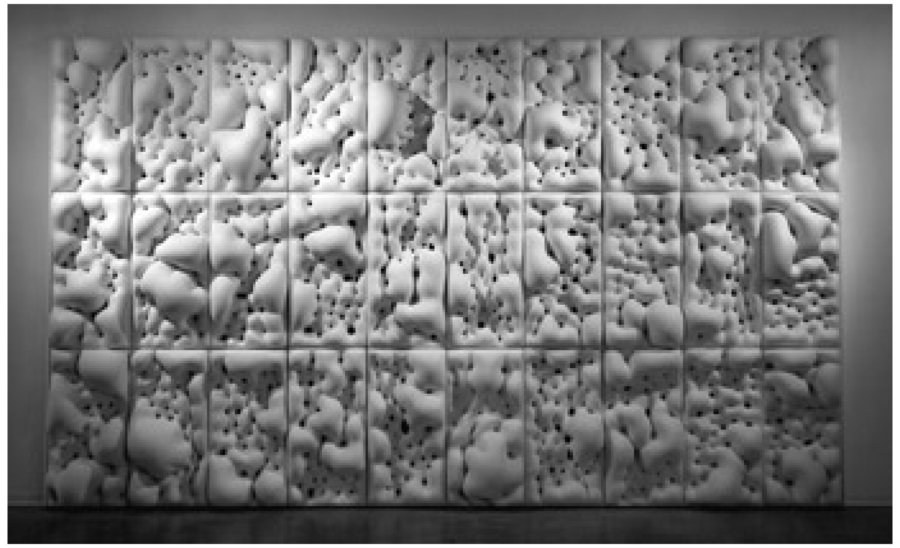
> Ornament shapes, straightens and stabilizes the bare arid field on which it is inscribed. Not only does it exist in and of itself, but it also shapes its own environment – to which it imparts form. (Henri Focillon)[51]

The projects presented so far raise the perennial questions of surface and form versus structure, of *appearance* versus *substance* (or *superficiality* versus *essence*, as seen by some) in contemporary architecture. While the digital technologies of parametric design and fabrication opened new possibilities for non-uniform, non-monotonous, variable patterning and texturing of surface, the question of appropriateness, i.e. of cultural significance of such ornamental treatment of surfaces in a contemporary context also emerged.

Following the famous manifesto Adolf Loos published in 1908, polemically entitled "Ornament and Crime," in which he described ornament as a need of the primitive man, arguing that the lack of decoration is a manifestation of a progressive, advanced culture,[52] the emergence of the Modern Movement entrenched a perception that to be authentically "modern," one has to categorically remove all ornament, which consequently led to the barren surfaces of much twentieth-century architecture. It was the absence of historically traditional surface ornamentation that arguably made the minimalist aesthetics of Modernism less *affectionate*, contributing in part to its demise. The façades didn't shed the rhythm and the pattern – but their monotonous grids didn't give much to the eye. Moreover, in Loos' articulation of the minimal ornamental expression of modern architecture, he decried the potential for lineages in this manner of thinking: "Modern ornament has neither forbears nor descendants, no past and no future."[53]

We take the "Semperian" position that "architecture comes to be defined in its essence as an ornamental activity."[54] After all, throughout history (bar the second half of the twentieth century) ornamentation was used in buildings, both on the exterior and in the interior, to enhance and amplify presence and appearance, give scale and texture through intricate treatment of surfaces, and demonstrate the mastery of artisans and craftsmen. Ornamentation had largely a symbolic function – it embodied values and ideals that defined a particular culture, simultaneously acting as a symbolic construct and enabling the construction of symbolic meaning. Such an approach to ornamentation is in line with the view that the buildings are shaped by and are expressive of the social, economic, political and cultural context, i.e. buildings are *representational*, while simultaneously being active agents in defining that very same context.

1.36.
The *p-wall* project by Andrew Kudless.



Given the increasing presence of ornamentation in contemporary design (and not just in architecture but also in a range of design disciplines), an obvious question to ask is if there is any deeper significance, some kind of profound relevance of ornamentation today. A possible answer to that question could start with a definition of what constitutes an ornament in a contemporary context. As there are many possible definitions, perhaps it would be more appropriate to begin by making some basic distinctions about different kinds of ornament in architecture.

In general, ornamentation can be *decorative* or *applied*, *functional* or *integral*, and *mimetic* or *imitative*. Ornament, when purely decorative, relies on its application to an already existing surface or an object; hence, such ornamentation could be classified as *applied*. Structural ornament is considered an integral part of the building's structure, i.e. the structural components act simultaneously as ornaments, as was the case, for example, in gothic architecture. Such ornamentation can be described as *functional* or *integral*. *Mimetic* or *imitative* ornamentation is characterized by unambiguous meanings or symbolic significance – it is purely representational.

Today, however, when "decorative" is used to describe an artifact, the meaning is negative in most cases, suggesting that the work itself is superficial, devoid of any deeper meaning. The perception of superficiality often stems from the surface application of ornamentation – it is often seen as nothing more than an (unnecessary) embellishment to an "other," as was the case for most of the twentieth century.

When decoration is deployed in a contemporary context, it is often used to hide something unpleasant to the eye – a *functional* application that is often judged as acceptable (*Herzog & de Meuron* used an ornamented rain screen to hide an integrated ventilation system on the façade of the *De Young Museum*). Decoration, however, is increasingly seen as *performative* as well, as it can produce effects that can directly affect an emotional response; it can be excessive or minimal, "loud" or "quiet," "serious" or "cheerful." It can accentuate a specific quality of the object or the surface to which it is applied.

Another way of understanding the significance of ornament is to compare it to pattern which could be described as an abstract construct characterized by repetition. As such, patterns exist in nature in all sorts of imaginable shapes, forms, and sizes. It is only when a particular pattern is recognized and represented in some physical manifestation, such as decoration, for example, that it becomes a cultural artifact – an ornament.

The human need to perceive, organize, and structure the world around us into patterns and rhythms is seen as intrinsic; decoration and ornament are recognized as indicators of neurological synergy of the eye and the brain. E.H. Gombrich offers evolutionary arguments that ornament is a result of a biological need to generate underlying structure in the surrounding environments: "I believe that in the struggle for existence organisms developed a sense of order not because their environment was generally orderly but rather because perception requires a framework against which to plot deviations from regularity."[55] According to Gombrich, the human mind has an intrinsic need for "careful balance" between complexity and order. The mind has no trouble deconstructing a simple, regular grid (i.e. recognizing the monotonous); it quickly "disconnects" in reading complex configurations if it cannot recognize an underlying structure. Gombrich argues that a "careful balance" between these two conditions, i.e. between monotony and complexity, is what the mind looks for in its constant processing of the surrounding environments.

In other words, one could argue that patterning – or ornamentation – is a necessity, and perhaps as such, it should be given back the significance it once had in architectural discourse. The challenge is to avoid creating a singular, outstanding image, pattern, or form (*the* effect), but a subtle, sensory, contextually responsive and responsible experience (*an* affect).



## AFFECTING ARCHITECTURE

It seems that the computational potential for generating complex forms and complexly patterned surfaces and structures is virtually inexhaustible. The precise digital representation of these complexities and the capacity of digital fabrication technologies to reproduce in material *any* shape or form regardless of its complexity seem to have expanded infinitely the boundaries of what is possible geometry- and material-wise. This liberation from the orthogonal grid and the constraints of standardization raises not only the obvious question of what (and where) the new *limits* are, but, more fundamentally, to what ends – to what *effects* and *affects* – should this new formal and material liberty be directed. If seemingly any complexity is describable and producible in a plane or in space, what is the new formal and material "discipline"?

Beyond the pragmatic instrumentality implications of manufacturing material effects lies a provocation of new (and old) ways of thinking about architecture. The idea of a harmonious "whole" being greater than, and dependent upon the sum of its "parts," is examined today directly through interconnected relationships, layers of information, and a search for "elegance" in architecture. An example of the integrated application of the multiplicity of information about a project can be seen in the proliferation of ecological and biological design considerations surfacing in contemporary architecture in relation to greater availability of information about natural and human circumstance.

Engineering, scientific, and aesthetic ideas are part of the great subtext of greater information and digitally driven methods. Concepts such as minimizing waste are engineering tactics that are increasingly applied to architecture as design intention, and stemming from a deeper and early connection to information about a given project. Other engineering concepts, such as optimization, are finding favor, not just in budgetary considerations and fabrication procedures, but also in formal and organizational strategies. Greater attention is given to calculating performance criteria and scientific analyses of simulated building behavior as essential feedback criteria in the design process. Refuting the longstanding aesthetic traditions arising from standardization of industrial techniques, we are also finding a much more productive position for the return of notions of ornament, eschewed from architectural fashion for much of the twentieth century.

Each new project brings us closer to a more complete picture of the implications of these new methods, although, the solutions will most likely be a range of possibilities. At present, more manageable scales dominate the cases of these new methods, as economies of scale in deploying these techniques have yet to be replicated in the complexity of major building projects. In most projects, the building skin and its surface effects remain the most potent territory for this discourse. The trajectory of these applications, however, lies not in the final form, but in the retooling of how we consider architecture. Manufacturing material effects is now finding increasing application, with growing scales and complexity resulting from closer relations between designers and fabricators, as the learning curve of adopting these techniques ripples through the discipline.

More fundamentally, the developing materials and the digital technologies of production, touched upon in this chapter, may substantially redefine the relationship between architecture and its material reality. Current research efforts, such as the *SmartWrap* project described earlier, point to a material future of architecture in which conventional building cladding will be compressed into a "plastic sheet" that is ultralight, fairly inexpensive, and that can be erected in a fraction of time compared to present practice. This is a dramatic technological development with the potential to transform all aspects of building design and production, with broad social, economic and cultural implications.

The *SmartWrap* project offers a glimpse of future building envelopes based on *functionally gradient polymer composite* materials, in which structure, glazing, mechanical, and electrical systems are synthesized into a single material entity. By producing materials in a digitally-controlled layer-by-layer fashion, as in *additive fabrication*, it is possible to embed various functional components, thus making them an integral part of a single, complex composite material. This, in turn, implies designing with heterogeneous and non-isotropic materials, i.e. with materials in which variation is present not only in surface articulation, but also in material composition.

We already have the technological capacity to design and manufacture materials that do not have uniform composition, properties, and appearance. With digital parametric design and production, variation becomes possible not only in spatial layouts and component dimensions, but also in material composition and surface articulation, offering unprecedented freedom from standardization that defined design and production for much of the twentieth century. Such variability presents a radical departure from the present normative practice. Whether the new "freedoms," afforded by almost infinite variability in design and production, result in better architecture remains to be seen.

NOTES

1 Juhani Pallasmaa, "Hapticity and Time – Notes on Fragile Architecture," *The Architectural Review*, vol. 207, no.1239, May 2000. pp. 78–84.
2 Toshiko Mori (ed.), *Immaterial/Ultramaterial: Architecture, Design, and Materials*, New York: George Braziller, Inc., 2002, p. xv.
3 For an in-depth discussion of the structural shifts within the building industry, see Branko Kolarevic (ed.), *Architecture in the Digital Age Design and Manufacturing*, London: Spon Press, 2003, and Branko Kolarevic and Ali Malkawi (eds.), *Performative Architecture: Beyond Instrumentality*, London: Spon Press, 2005.
4 For more on the exchange of information, see the chapter by Kevin R. Klinger in this book.
5 Toshiko Mori (ed.), *Immaterial/Ultramaterial: Architecture, Design, and Materials*, New York: George Braziller, Inc., 2002, p. xv.
6 Translucent (light-transmitting) concrete is produced by mixing glass fibers with crushed stone, cement and water, introducing a slight variation to a process used for centuries. The process was devised by Hungarian architect Aron Losonczi in 2001, who founded the company that offers translucent concrete products under the name of *LiTraCon*.
7 A composite material is produced by combining two principal components – the reinforcement and the matrix, to which other filler materials and additives could be added. The matrix is, typically, a metallic, ceramic or polymer material, into which multiple layers of reinforcement fibers, made from glass, carbon, polyethylene or some other material, are embedded. Lightweight fillers are often used to add volume to the composites with minimal weight gain, while various chemical additives are typically used to attain a desired color or to improve fire or thermal performance.
8 The actual components made from composite materials are usually formed over CNC-milled moulds, as in boat-building to produce boat hulls or large interior components, or in closed moulds by injecting the matrix material under pressure or by partial vacuum, as is done in the automotive industry for the production of smaller-scale components. In the building industry, composite panels are produced either through continuous lamination or by using the resin transfer molding.
9 Bettum, Johan. "Skin Deep: Polymer Composite Materials in Architecture," in Ali Rahim (ed.), *AD Profile 155: Contemporary Techniques in Architecture*, London: Wiley Academy Editions, 2002, pp. 72–76.
10 A polyol and an isocyanate mixture are used in a product called *Baydur*, manufactured by *Bayer*, Germany.
11 For a discussion of weathering as a continuation of the building process rather than as a force antagonistic to it, see Mohsen Mostafavi and David Leatherbarrow, *On Weathering: The Life of Buildings in Time*, Cambridge, MA: MIT Press, 1993.
12 Sulan Kolatan and William MacDonald, Kol/Mac Studio, http://www.kolmacllc.com.
13 See http://www.vrglass.net.
14 This new category of glass is more commonly known as "smart glass" or "switchable glass." It is also technically known as *electrochromic* glass. Smart glass can change its light transmission properties when voltage is applied, i.e. it can switch from transparency to opacity, and vice versa. A thin film laminate of rod-like particles suspended in a fluid is placed between two glass layers. In the absence of electrical current, the suspended particles are randomly arranged and absorb light, and the glass panel looks opaque. When an electric current is applied, the suspended particles become aligned and let the light pass, thus making the glass transparent.
15 Described online at http://www.beigedesign.com/proj_chromogenic.html.
16 As quoted in Lucy Bullivant, "Non-standard Networking," *Atlas*, no. 23, November 2005, p. 99.
17 Ibid.
18 For more information about this project, see Mark Goulthorpe/dECOi, "Scott Points: Exploring Principles of Digital Creativity" in Branko Kolarevic (ed.), *Architecture in the Digital Age: Design and Manufacturing*, London: Spon Press, 2003, pp. 163–180.
19 "Intelligent," "smart," "adaptive" and other terms are used today to describe a higher form of composite materials that have sensors, actuators, and computational and control firmware built into their layers. According to another definition, intelligent materials are those materials that possess adaptive capabilities to external stimuli through built-in "intelligence." This "intelligence" of the material can be "programmed" through its composition, its microstructure, or by conditioning to adapt in a certain manner to different levels of stimuli. The "intelligence" of the material can be limited to sensing or actuation only. For example, a sensory material is capable of determining particular material states or characteristics and sending an appropriate signal; an adaptive material is capable of altering its properties, such as volume, opacity, color, resistance, etc. in response to external stimuli. An active material, however, contains both sensors and actuators, with a feedback loop between the two, and is capable of complex behavior – not only can it sense a new condition, but it can also respond to it. For an in-depth discussion of "smart" materials, see Michelle Addington, *Smart Materials and Technologies in Architecture*, Oxford: Architectural Press, 2005.
20 Described online at http://www.kierantimberlake.com/SmartWrap/index.htm.
21 The term *biomimetics* refers to man-made processes, substances, devices, or systems that imitate nature. It was coined by Otto Herbert Schmitt (1913–1998), an American engineer and biophysicist, best known for establishing the field of biomedical engineering. *Velcro*, the hook-loop fastener, is perhaps the best-known example of material *biomimetics*: it was created in 1948 by George de Mestral, Swiss engineer, who was interested in how the hooks of the burrs clung to the fur of his dog.
22 Imitating forms and structures found in nature also has a long history in architecture: Joseph Paxton's *Crystal Palace* was allegedly inspired by the lily pad's structure.
23 Peter Eisenman, "The Affects of Singularity," in Andreas Papadakis (ed.), *Theory and Experimentation, Architectural Design*, London: Academy Editions, 1992, pp. 42–45.
24 Peter Eisenman (ibid) goes on to discuss the technological shift vis-à-vis the notions of effect and affect: "The mechanical paradigm dealt with the shift in value from the individual hand, as in the hand of a painter as an original maker, to the value of the hand as intermediary, as in the developer of raw film; from the creation of an individual to the mediation of the multiple. The photograph can be manipulated by an individual to have more contrast, more texture, more tone. Thus there remains within the mechanical repetition of a photograph a unique, individual quality; it remains a particular object even within the idea of the multiple. And within the process, the individual subject is still able to effect as well as affect."
25 Pallasmaa, op. cit. p. 79.
26 Ibid.
27 Ibid.
28 Adolf Loos, "Ornament and Crime" (originally published in 1908) in Michael Mitchell (trans.), *Ornament and Crime: Selected Essays*, Riverside, CA: Ariadne Press, 1997.
29 "But what is most remarkable, in view of later developments, is to find within the line of descent from the English Free architecture and the Deutscher Werkbund, no sense of impropriety in the ornamentation of machinery, engineering structures and machine products. The development of such a sense is a tribute to the revolution in taste effected by Loos himself and the Abstract aesthetics of the war years." In Reyner Banham, "Adolph Loos and the Problem of Ornament," in *Theory and Design in the First Machine Age*, London: Architectural Press, 1960, p. 91.
30 Umberto Eco (ed.), *History of Beauty*, New York: Rizzoli International Publications, 2004, p. 388.

31 Gaston Bachelard, "Introduction," in *Water and Dreams: An Essay On the Imagination of Matter* (1942), Dallas Institute, Texas, 1983.
32 Pallasmaa, op. cit.
33 Eisenman, op. cit. p. 43.
34 Toshiko Mori, op. cit., p. xiv.
35 For more information, see Branko Kolarevic (ed.), *Architecture in the Digital Age: Design and Manufacturing*, London: Spon Press, 2003.
36 Bernhard Franken, "Real as Data," in Branko Kolarevic (ed.), *Architecture in the Digital Age*, pp. 121–138.
37 As described online at http://www.beigedesign.com/proj_airspace.html.
38 Voronoi diagrams are named after Russian mathematician, Georgy Voronoi, who studied the general n-dimensional case of the conceptually simple decomposition scheme in 1908. In *Voronoi tessellation*, the decomposition of space is determined by distances to a specified discrete set of objects (points) in space.
39 The *Weaire-Phelan structure* is a complex three-dimensional structure devised in 1993 by Denis Weaire and Robert Phelan, two physicists based at Trinity College in Dublin, Ireland.
40 This extremely lightweight material was also used in the enclosures of the *Allianz Arena* in Munich, Germany (2005), designed by *Herzog & de Meuron*, and the *Eden Project* in Cornwall, England (2001), designed by *Grimshaw and Partners.*
41 C.C. Sullivan, "Screen Gem," *Architecture*, September 2005, p. 67.
42 Online at www.glform.com.
43 Bernard Cache, *Earth Moves: The Furnishing of Territories*, Cambridge, MA: MIT Press, 1995.
44 Ibid.
45 The digitally-driven production processes introduce a different logic of *seriality* in architecture, one that is based on local variation and differentiation in series. In buildings, individual components could be customized using digital technologies of fabrication to allow optimal variance in response to differing local conditions in buildings, such as uniquely shaped and sized structural components that address different structural loads in the most optimal way, variable window shapes and sizes that correspond to differences in orientation and available views, etc.
46 In addition to careful crafting of the CNC tool paths (whether for milling or cutting) for each object produced in series, particular attention must be given to the overall *field effect* that is created by assembling the seemingly similar objects into a larger composition. This field effect can be described as a secondary pattern that emerges through the composition of primary, object-related tool path patterns. In many projects, however, it is the field effect that is the primary surface effect that is sought.
47 In a typical CNC production, however, the desired outcome is a smooth, featureless surface which is produced by using milling bits with a fairly small radius and tool paths that are closely spaced.
48 Another technique that Cache used was to work with flat-sheet laminated materials into which a certain topographic design is inscribed through milling, producing a contouring effect that reveals the laminate in subtle ways. In some projects, he used a parametrically controlled and varied spline curve to inscribe it into series of solid panels or to carve out complex shapes that can produce intricate screens with repetitive, yet differing patterns.
49 N. Leach, D. Turnbull and C. Williams (eds.), *Digital Tectonics*, London: Wiley-Academy, 2004, p. 65.
50 Cache's *Objectile* website, now defunct, permitted customers to design their own patterns by varying the parameter values that control the geometry of patterning. The parameter values are then automatically transmitted to the fabricator and translated into CNC machine code for manufacturing.
51 Henri Focillon, *The Life of Forms in Art*, (trans. George Kubler), New York: Zone Books, 1992, p. 66.
52 Loos, op. cit.
53 Ibid.
54 Godfried Semper (originally published in 1860–1863; Introduction by Harry Francis Mallgrave), *Style in the Technical and Tectonic Arts; or, Practical Aesthetics*, Los Angeles: Getty Research Institute, 2004.
55 E.H. Gombrich, *The Sense of Order: A Study in the Psychology of Decorative Art*, Ithaca, NY: Cornell University Press, 1979.