*Symmetry: Culture and Science*
*Vol. 31, No. 3, 231-260, 2020*
*https://doi.org/10.26830/symmetry_2020_3_231*

*SYMMETRY: SCIENCE AND ART*

# SYMMETRY GIVES MEANING TO ARCHITECTURE

Nikos A. Salingaros*

* Department of Mathematics, University of Texas at San Antonio, One UTSA Circle, San Antonio, Texas 78249, U.S.A.
*E-mail*: salingar@gmail.com; http://zeta.math.utsa.edu/~yxk833
*ORCID*: 0000-0002-8856-9175

**Abstract**: *Coherent structure affects us viscerally. Human perception relies upon combined symmetries to reduce information overload but random (disorganized) information is too much for us to process. Our brain automatically compares and groups architectural elements into larger wholes. We unconsciously analyze and process the information in any composition using mathematical relations that endow meaning to our environment. Design elements of the same size and shape can be aligned, reflected, or rotated. Their repetitions are regularly spaced; otherwise there is no symmetry. Scaling symmetry links components visually through magnified or reduced versions of the same element. Self-similarity at different magnifications is a basic feature of a 'fractal', and is a dominant feature in traditional and vernacular architectures. This is one reason why different architectural form languages have meaning for us. Mathematics also relates components of a whole via their relative number and size. In a stable complex system, there are few large objects, more intermediate-size objects, and many smaller objects, roughly in an inverse-power relationship.*

**Keywords**: symmetry, composition, architecture, design, fractal, information compression, inverse-power scaling, coherence, systems theory, plane transformations.

# 1 INTRODUCTION: BEAUTY AND MEANING

"Symmetry" in the title does not refer just to bilateral mirror symmetry. It includes a variety of complex symmetries and related mathematical operations that arise more or less spontaneously both in nature and in human creations. An increasing number of persons today recognize that an essential ingredient is missing from the built environment and from human artefacts in general. This loss may be interpreted as an impoverishment of meaning. It is vital that we re-discover what generates meaning in architecture, in order to bring it back into what we create, and thereby enrich our world.

Mathematics has historically been one of architecture's most important tools. In eras that produced great architecture, an architect combined the professions of architect/mathematician. Architects and structural engineers need mathematical knowledge to make a building stand up. Another application of mathematics relates aesthetic expression to form. For example, proportional ratios have been used to determine relative dimensions of architectural components (Kapraff, 2016). Yet in contrast to the down-to-earth applications of mathematics to the engineering and tectonics of buildings, the aesthetic part is full of mystery and romanticism.

These questions prompt the search for a mathematical definition of beauty. Can we define formulas for beauty? It is very difficult to do so, although this has not stopped many authors from trying. The results are mixed: at best confusing and of doubtful practical value (Forsythe and Sheehy, 2011; Zeki, 2019). Yet how do we explain the undeniable positive examples? The neurological intuition of the designer underlies hidden mathematical methods used to shape design. One confusing case is the much-discussed "Golden Ratio" or "Golden Mean", which plays a role in scaling but does not endow rectangles with a magical aspect ratio (Salingaros, 2018).

The key to understanding the role of mathematics in design is how patterns in nature became embedded into our neurological systems (Coburn *et al.*, 2019; 2020; Murray *et al.*, 2002; Tyler *et al.*, 2004). Intuitive beauty summarizes our evolved computational algorithms for survival in an informational environment. Beauty attracts us because we unconsciously interpret certain patterns as beneficial or nourishing; it's that special type of coherent structure that heals us. "Beauty" then represents those hard-wired patterns we respond to for reasons that guaranteed survival during our evolution (Biederman and Vessel, 2006; Mattson, 2014). By investigating those patterns, we come up with a set of basic tools for assessing architectural compositions (Alexander, 2001; Salingaros, 2006; 2010; 2011; 2019).

A geometrical necessity for coherent structure is built into our brain, and co-exists with separate aesthetic instincts arising from what is biologically "useful". Our ancestors created bilaterally symmetric axe-heads half a million years ago (Hodgson, 2011). A visceral kind of beauty is independent of anybody's opinion because it arises from the wiring of neural circuits. There is more to beauty than utilitarianism: complex recurring patterns are found in inanimate physical structures in the universe; hence some of our key notions of beauty originate with the structure of matter itself (Alexander, 2001). This is physics, not biology. Furthermore, it cannot possibly have anything to do with evolutionary adaptation, because it goes far deeper and was defined before life evolved.

"Alien" shapes in our immediate surroundings represent the opposite of what our body senses as beautiful. Because those do not remind us of natural shapes that our evolution has programmed us to interpret, they disturb us. Our brain could and does ignore unnatural forms, regardless of their size, as if they weren't there (Salingaros and Sussman, 2020; Seresinhe *et al.*, 2017; Sussman and Hollander, 2015; Sussman and Ward, 2017; 2019). Otherwise, alarm and the automatic "fight-or-flight" response take over our body until we either have enough information to judge that some object is harmless, or decide to flee (Ruggles, 2018).

Finally, this essay's title needs to be explained. What is meant by "meaning"? In traditional societies, historical and religious symbolism endowed meaning to architecture (Hersey, 1988; Maas, 2008). But architects in the $20^{th}$ Century started to inject ideas coming from an image or some abstract concept into their design. For them, this act of imposition endows "meaning" to their work in an intellectual sense. Nevertheless, such esoteric meaning is neither universal, nor visceral. It is known that the population at large does not share architects' peculiar aesthetics, at least since the 1920s when Bauhaus industrial minimalist became the default style for building (Mehaffy and Salingaros, 2011). Nor does this procedure lead to a structure the user feels unconsciously to be "natural" (Alexander, 2001).

Without getting too far into philosophy, "meaning" as discussed in this paper refers to "structural meaning", which is rooted in our biological selves and in the natural world (Mehaffy, 2004a; Whitehead, 1929). It is a deep, shared sense of meaning that emerges from structure, and above all, from natural structures. Inanimate nature and life forms possess an emergent kind of complex coherent structure, to which humans respond in a measurable way with attachment and emotions. Biologically-inspired architecture taps into that source of meaning (Hersey, 1999). The physical world is structural, and our survival depends upon interpreting its meaning from geometry and information.

But there exists another, distinct realm of “meaning” that arises out of human hypothesizing. Structural meaning contrasts with “semiotic meaning” derived from abstractions, images, language and signs (Mehaffy, 2004a). Groups of people construct their own distinct models of the world, in the tradition of explanatory mythologies. All of those worldviews are incomplete, while some are wildly inaccurate at describing physical reality. Oblivious of such defects, a power group successfully imposes its own modelling system over competing ones, making up spurious justifications for its validity. This is not scientific, because it denies what our intelligence has discovered about the world and how we interact with it. Semiotic meaning is turned to destructive ends when we shape the world according to fictitious intellectual constructs.

Architectural criticism and theory during the 20th Century focused almost exclusively on semiotic meaning, displacing structural meaning from professional practice and from the education of architects (Jencks, 1969). During that period, and continuing today, professional leaders adopted this position as the ideological/theoretical basis for architecture. Yet it is the salient characteristics of coherent structure that unconsciously produce emotional meaning, which is termed “wholeness” by Christopher Alexander (Alexander, 2001; Jiang, 2015; 2019; Mehaffy, 2004b). It might surprise readers to discover that Bauhaus modernism relied entirely upon semiotic meaning, and not structural meaning as was misleadingly claimed (Curl, 2018; Hodne, 2016; Katona, 2019).

Recent neurophysiological studies clarify the situation in a definitive manner. The way that the human brain interprets a scene relies upon two components: (i) actual information from the environment, and (ii) comparison with internally-stored biological/geometrical references (Kravitz, Peng, and Baker, 2011; Malcolm, Groen, and Baker, 2016). The two neural mechanisms are linked to the ability of the human brain to predict situations based upon both innate and learned patterns. This is how we interact visually with our world. Intelligence—which is a manifestation of the ability of predicting from available data—is also a mechanism for interpreting structural meaning.

## 2 GROUPING REDUCES INFORMATIONAL OVERLOAD

Even the simplest mathematical notions turn out to be important for how we perceive our environment. An observer unconsciously compares one geometrical component with another to check whether they match or not. Design elements could be grouped when they have more or less the same size, shape, and orientation. Redundancy and similarity of shape then reduce information overload. The brain treats copies as repetitions of the same element. If, on the other hand, dissimilar elements appear in a composition, they need to be accounted for individually, which takes up information processing that our brain needs for other urgent life tasks.

This is not the end of the story, however. The mere presence of several copies of the same element can still lead to information overload if their positions are unrelated. Our brain fixes the relative positions of elements in the visual field. Symmetries in arrangement and positioning reduce the information needed to specify the location of elements distributed in space into a more manageable amount. Visual techniques for doing this use multiple symmetries to group elements, and also to define a wide border to contain such a group (Alexander, 2001).

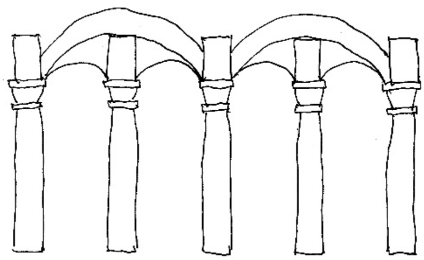

**Figure 1**: Arches group three columns into a larger repeating unit.

Information coming from numerous unaligned copies of the same repeating element is difficult to grasp, since our sensory system perceives numbers visually as patterns (except for some autistic persons who can instantly count a large number of randomly-distributed objects). Psychologically, this effect is known as the “cognitive limit of 7”, which is the maximum number of easily remembered digits, such as a phone number (Miller, 1956). A large number of elements can be better handled cognitively by grouping them, so that we count the groups instead of the individual elements.

Drawing upon an original idea by Christopher Alexander (Alexander, 2001), cognitive grouping mimics the “entanglement” of wave functions in quantum mechanics (Salingaros and Sussman, 2020). This phenomenon is revealed dramatically in eye-tracking simulation experiments analyzing building façades. The human mind tries to group design elements such as windows into cognitively coherent units. If the symmetries among those elements forbid cognitive entanglement, then the eye simply refuses to fixate on the building. The effect is to render such a structure invisible, hence any semiotic meaning attached to that design is lost to the user.

In order for repeating design or structural elements to be aligned, they need to have common dimensions, with possible variations. Either the repeating elements are regularly spaced, or they are grouped into a more complex unit, which then repeats regularly (Salingaros, 2006). A tilted copy, however, is not subject to the same simple grouping as are those elements with strict translational symmetry without rotation. The increased similarity distance of tilted figures weakens any correlation.

Cognition includes the mechanism of “perceptual invariance”, which matches a pattern after displacement, rotation, or scaling of the original. A similarity distance between two visual elements is the number of transformations needed to get from one to the other. The shortest measure equals 1 in the case where an exact copy is displaced by some physical distance. Scaling of concentric figures again equals 1 (no displacement), whereas scaled-up or scaled-down copies at some separation from each other count as 2 (displacement plus the scaling transformation).

## 3 REFLECTIONAL, ROTATIONAL, AND TRANSLATIONAL SYMMETRIES

There is a long history of models trying to predict human visual response, and those rely on combinations of symmetries together with well-defined edges (Itti, Koch, and Niebur, 1998; Kootstra, de Boer, and Schomaker, 2011). The undoubted success of those theoretical models in agreeing with real-time eye-tracking experiments shows that the brain relies upon geometrical principles for interpreting environmental information. The present paper investigates mathematical symmetry, not neuroscience, yet it is reassuring to know that the models discussed here do underlie cognition. As the most sophisticated known computer, the human brain evidently uses symmetry-based algorithms to interpret the world.

Architectural elements are automatically combined and compared in our mind as visible coherent structure. Relationships are derived from aligning and grouping the repeating elements in a composition. These combinatoric design operations, performed unconsciously, trigger our physical response to visual input. The overall impression of ensembles is what determines our visceral experience of any structure.

We interpret our world by grouping adjoining geometrical elements via symmetries into larger wholes. For example: (i) juxtaposed mirror images are joined to make a bilaterally symmetric whole; (ii) aligned repetitions of the same element are joined to make a larger whole with translational symmetry; and (iii) juxtaposed elements that are related via rotation can be grouped into a larger round whole. Symmetric relations order our environment; they also work at a distance, although their strength decreases. We can combine elementary symmetries such as translation with reflection into what is known as a “glide symmetry”.

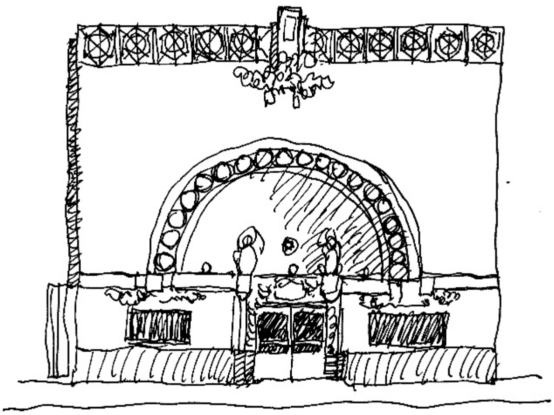

**Figure 2**: Rotational symmetry with repeating elements focuses on an entrance.

To implement translational symmetry in a composition, repeating design elements need to be regularly spaced; otherwise there is no positioning symmetry. These minimal requirements influence architectural composition to develop a coherent structure echoing traditional and vernacular styles. This comes from mathematics—supplemented by neuroscience working with physics, which privilege the horizontal and vertical symmetry axes because of gravity—and helps to determine an architectural “form language”.

Grouping presupposes some measure of affinity among the constituent elements, whether those are simple or compound. Design and tectonic elements could share the same material, shape, texture, etc. Commonality makes it possible to relate spatially-separated elements, whereas too great a dissimilarity (similarity distance) marks them as incompatible. If they cannot be related by symmetry, then they cannot contribute to coherent structure. Coherent structure is impossible when components clash geometrically, creating a fragmented or otherwise inharmonious juxtaposition.

For example, aligning complementary pairs leads to “Alternating Repetition”, a geometrical property necessary for structural meaning as documented by Alexander (Alexander, 2001). This characteristic is very different from monotonously repeating a single simple element (Salingaros, 2011). Alexander has already detailed operations—his “15 Fundamental Properties”—that bring matter together in a way that generates coherent structure. Multiple symmetries create wholeness in the sense of Alexander out of a complex set of components (Alexander, 2001; Jiang, 2015; 2019; Mehaffy, 2004b; Salingaros, 2010; 2015).

## 4 PRIVILEGING THE VERTICAL AXIS

Mathematical notions of “beauty” correspond to what our sensory system favors, which is distinct from what people may learn later. We are constantly processing information in our immediate environment, comparing and looking for groupings, a task that consumes a lot of metabolic energy. We are often overloaded with environmental information, and rely on built-in algorithms to reduce and organize it. If we cannot instantly classify and categorize forms and shapes surrounding us, then we continue to process the information indefinitely, which tires us. This effect is known as “cognitive fatigue”.

Evolving in a complex natural environment, our brain developed its hard-wired computational algorithms to search for possible benefits or dangers. This process is unconscious and very rapid. If we detect neither advantage nor threat, nor even the preconditions for those things that would necessitate further analysis, then the information is ignored, and our attention diverted to other spots. Fatigue sets in, however, in situations where the information does not give us a clear indication of its meaning.

Humans have the ability, along with few other organisms, to shape our environment and thus influence its information content. There exist two means of actively molding disorganized environmental complexity: (i) eliminate it, or (ii) organize it. Only the second option endows meaning to the environment. Unfortunately, dominant architectural culture adopted the first option universally in the 1920s. The design profession failed to consider human interface requirements set by our cognition. But minimalist environments have no structural meaning, and their creators have had to invent intellectual constructs (semiotic meaning) to justify their implementation. Reacting consistently with its survival mechanisms, the human body perceives such places as meaningless (Mehaffy and Salingaros, 2011; 2013).

Neurophysiology supports this line of reasoning because specialized brain cells are designed to recognize shapes and symmetries. Individual neurons respond to specific colors, simple geometric shapes, distinct orientations (angles) and rather complex shapes essential to our evolutionary survival. Among the latter are "face-recognition" cells, which respond to bilateral symmetry about a vertical axis, and to a generic facial structure of "mouth" with two "eyes" above (Chang *et al.*, 2017; Ruggles, 2018; Sussman and Hollander, 2015). Our brain is wired to recognize symmetric combinations of simpler elements into more complex wholes.

An upright "face" and vertical axis trigger the face-recognition mechanism, but the response weakens if there is a rotation. Our cognitive/physiological system is biased, since it privileges the vertical axis. This is due to our body's sensor for vertical orientation. Imposing a strict neurological constraint, our inner-ear mechanism controlling balance prefers a vertical axis. Consequently, unbalanced diagonals could and do trigger nausea in the observer. This is the reason why, over millennia, symmetry axes never departed from the vertical, and if they did so by accident (such as in the leaning Campanile of the Cathedral of Pisa, Italy), the result became notorious.

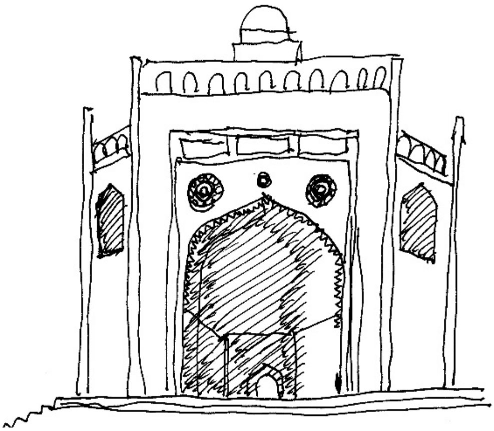

**Figure 3**: Bilateral symmetry in a building that is reminiscent of a “face”.

Violating the vertical axis, and neglecting reflectional symmetry about a vertical axis, create anxiety in the viewer. Building façades that lack such bilateral symmetries either repel us or simply do not register, even as we look directly at them (Salingaros and Sussman, 2020; Sussman and Ward, 2017). Furthermore, if a building’s entrance is not marked using our innate preference for a symmetrical, face-like design, it’s easy to miss. In general, a composition must employ scaling and bilateral symmetries to focus on the entrance to the building. Deliberately avoiding this cognitive rule compromises so many buildings built since the end of World War II, where the design style conspires to hide the entrance.

## 5 SCALING SYMMETRY

Scaling symmetry is something entirely distinct from the other types of positioning symmetries, and links magnified and reduced versions of the same element. This is the basic feature of a fractal (think of a cauliflower), which contains a large number of nested substructures, all of which are self-similar at different magnifications. Scaling symmetry is a dominant feature in traditional and vernacular architectures, and is one reason those quite different form languages appeal to our innate sense of structural meaning (Crompton, 2002; Goldberger, 1996; Joye, 2006; 2007; Taylor *et al.,* 2005).

Multiplication by a scaling factor either magnifies or reduces an architectural element without changing its internal relationships. This operation scales a figure up or down in size. A key feature of traditional architectures is that they include scaled-up or scaled-down copies of elements such as rectangles (door and window openings), and the curves defined in domes and arches. Those shapes are sometimes repeated further in a much scaled-down version employed in the ornamentation.

Borders, boundaries, and frames are mathematically essential for denoting the edge of an area. And they cannot be too thin. Together, bilateral and scaling symmetries define frames that provide structurally meaningful transition regions. A simple estimate shows the advantages of "Thick Boundaries" (Alexander, 2001). Take a rectangular element such as a door, panel, or window, or an arch, and magnify it, for example, by the Golden Ratio $\varphi \approx 1.62$ (Salingaros, 2018). Nesting the original element symmetrically within the magnified copy creates a boundary or frame. The width of the frame extending all around is computed to be 0.31 of the original element's width (i.e., a door is approximately 3 times as wide as its frame).

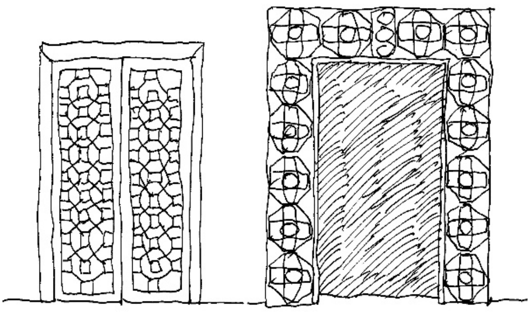

**Figure 4**: Fractal scaling with magnifications that obey a scaling factor.

It is found that scaling in situations with structural meaning only occurs in a discrete hierarchy, so that the architect determines larger and smaller sizes by using a fixed scaling factor. The mathematics describes a discrete group of elements related by powers of $e \approx 2.7$, or**,** in general**,** some scaling ratio anywhere from 2 to 5. The maximum power is determined by the size of the building. (Exponentials are preferable to Fibonacci numbers, which do not close under multiplication because of Carmichael's Theorem (Salingaros, 2018)). The scaling hierarchy defined here requires all copies of an element scaled by the factors $e^n$ to be present in the composition.

In practice, the scaling process selects a discrete set of scaled copies from all possible scaled copies to include in a design (whereas including all possible magnifications of elements would leave no space for anything else). A fractal is an assembly of self-similar copies defined by some scaling factor. Architectural elements can be spatially quantized by the necessity for fractal scaling, to make them compatible with hierarchical systems. The scaling ratio of $e \approx 2.7$ is proposed because that seems to satisfy an innate biological preference (Salingaros, 1998; 2006).

Studies referenced throughout this paper imply that humans have a deep cognitive need for coherent structure, which is largely absent from the dominant architecture of the 20th century and after. This is a direct result of an ideological/theoretical position adopted by the dominant architectural culture (Mehaffy, 2004a). As a consequence, those "mainstream" buildings are weak on structural meaning. Because of this history, it now becomes necessary to explain how to achieve scaling symmetry in a number of steps (Alexander, 2001; Sessions and Salingaros, 2010).

## 6 SCALING AND ALEXANDER'S FIFTEEN FUNDAMENTAL PROPERTIES

Alexander's 15 Fundamental Properties of coherent structure are of central importance in endowing structural meaning to architecture. Those were discovered heuristically and presented in a directly applicable format that does not, however, focus attention on their deeper significance (Alexander, 2001; Jiang, 2015; 2019; Mehaffy, 2004b; Salingaros, 2010; 2015). Alexander's geometrical properties are strictly evidence-based; yet coming from architecture, which usually relies upon circular and self-referential reasoning, they are separate from science. It is helpful to associate them with a mathematical description of the processes generating coherent structure. As Edward O. Wilson explained, consilience across distinct disciplines validates novel and unfamiliar results (Wilson, 1998).

Simplifying the procedure somewhat, steps towards scaling symmetry can be described in terms of four basic qualities: (1) scale range, (2) scale hierarchy, (3) scale connection and (4) scale tightness (Sessions and Salingaros, 2010).

These factors of coherent structure are themselves hierarchical in that each builds upon the previous ones. Scale range, the first basic requirement for structural meaning, constrains the scales to range from the very small to the very large, with a number of scales in-between. There should be a stepwise progression between scales so that the jump from one scale to another is never too large. Scale range is related to Alexander's properties of “Levels of Scale” and “Thick Boundaries” (because a thick boundary can be the next-smaller level of scale).

Suppose there is a scale range from the smallest to the largest, which is the entire building. Scale hierarchy requires that each scale is related to every other scale in a hierarchical manner. Elements of smaller scales are contained within elements of larger scales: every element is hierarchically linked to those elements at the next highest and the next lowest scales (Salingaros, 1998). Hierarchical ordering helps to establish structural meaning. Scale hierarchy is related to Alexander’s properties of “Levels of Scale”, and “Echoes” (which refers both to similarity-at-a-distance and scaling similarity).

Scale connection requires that like elements connect to like elements. Coupling occurs among elements having similar geometry and either different or similar materials. This coupling is “horizontal” in the system sense that it links elements on the same scale via reflectional, rotational or translational symmetries. Large elements are connected to other large elements, mid-sized elements are connected to other mid-sized elements, and small elements are connected to other small elements. Scale connection is related to those Alexander’s properties of “Alternating Repetition” and “Local Symmetries”.

Scale tightness requires more connections between smaller elements, and those connections to be much tighter than the connections between larger elements. So as we move up the scale hierarchy from small to large, we find fewer and weaker connections. Scale tightness is possible only if the first three factors (scale range, hierarchy and connection) are also present. Tighter connections are those that are harder to change without impacting the overall architectural stability (Salingaros, 1998). Scale tightness is related to Alexander’s properties of “Strong Centers” and “Deep Interlock and Ambiguity” (where forms interpenetrate to bind together).

Very few elements exist at the highest level of scale. Connections are few and looser, so that large elements being connected are relatively independent of each other. We could replace a major building segment by another (containing a comparable distribution of smaller elements) with little impact on other building segments of its size. Going down in scale, elements become greater in number and more “tightly connected”. It would be harder to replace any cluster without degrading coherent structure. At the lowest level of scale, couplings connecting the smallest elements are strongest because they act over a shorter distance.

Many buildings lack all of these factors for scaling symmetry. They have only a limited scale range, with far fewer scales than a building of their size calls for. Nested symmetric magnifications that generate frames are invariably missing. Furthermore, the scales that are present are not arranged hierarchically (with scale jumps of 10× or more), while couplings are forced between non-like elements. And the tightness of couplings does not follow the scale range. Such buildings can be quite unsettling when you first see them. The reason is that the scaling factors contributing to structural meaning are absent.

## 7 CLOSURE AND VISUAL COMPLEMENTS

Through the process of ordering our environment cognitively, the human brain created mathematics (Lakoff and Nuñez, 2001). Seeking patterns of coherence and consistency, visual classification simplifies informational disorder. It is reassuring and satisfying to unconsciously sense coherent structure, defined according to relational rules. Experiencing an environment where its elements obey a closure property—rather than randomly-shaped elements randomly distributed—endows it with structural meaning. Closure in this sense satisfies the brain’s informational need for regularity relations among visual elements that we confront in our daily lives.

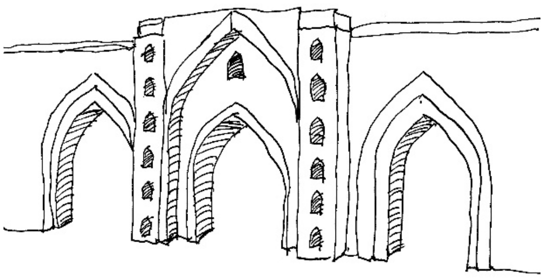

**Figure 5**: Self-similar arches on different scales.

Our brain relates the components of what we see in two ways: (i) compares them visually at a distance to determine whether two or more components could be grouped by similarity; and (ii) links components by scaling, where we see magnified and reduced versions of the same thing. These notions correspond in a deep way with our evolved perceptive apparatus, which is tuned to seek and recognize scaling similarity.

Design that adapts to our advanced cognitive capabilities incorporates a sophisticated mathematical framework linked to mechanisms of human perception. The treatment of architectural elements relies to a large extent on techniques used in computer graphics to compress information and optimize the visual interface. We can perceive whether two components, either adjoining, or situated at some distance from each other, group together to create a harmonious larger whole. This is the concept of addition in systems theory, where components combine to create a larger system.

The absence of elements, or the “zero element”, must be something that is perceived as nothing at all. Candidates for the architectural “zero element” are flat white or gray walls, plate glass, curtain walls, or purely reflective surfaces. Perfectly smooth white, transparent or totally reflective surfaces do not offer the human eye anything to focus on, and therefore the brain interprets that there is nothing there (Sussman and Hollander, 2015; Sussman and Ward, 2017). We need to handle three tectonically distinct types of “zero element”: colorless flat, transparent or reflective walls. Note that those have become the default architectural surfaces ever since the 1920s.

Alexander’s 15 Fundamental Properties represent a set of heuristically-derived**,** geometrical properties of coherent structure (Alexander, 2001). One of those is “The Void”, which denotes the necessary presence of a “zero element” in any complex configuration. Its purpose is to provide contrast that lends emphasis to an adjoining region of high complexity. Just as the analogy with mathematics points to the importance of the “zero element” in defining a logically consistent set of elements, Alexander discovered it as an essential quality in an architecture of adaptive complexity.

A serious problem occurs when all the other 14 of Alexander’s Fundamental Properties are violated, as is often the case in minimalist-modernist design (Salingaros, 2010). Ideological/theoretical positions have influenced the dominant architectural culture by imposing total design homogeneity, in which only the “zero element” is used in a composition. Almost nothing else is allowed. Despite being ubiquitous, however, such minimalist buildings can have no structural meaning.

Basic mathematical structures such as groups, vector spaces, and algebras always obey completion, in the sense that there is a negative or inverse element corresponding to each element. Working by analogy, the same property appears to apply to our cognitive system. Namely, the brain seeks a visual "complement" in order to establish closure and some sort of visual balance among diverse components. Our cognitive system is satisfied by a grouping and completion that reduces the informational overhead locally, while indicating closure globally.

The "complement" of an architectural element could be its mirror reflection across some axis in the 2-dimensional visual plane (a wall that we are facing). An element coupled together with its reflection creates a bilaterally symmetric pair, in which each half reinforces the other. Two smaller architectural units couple into a larger one. Closure under reflection corresponds to the inclusion of all elements together with their reflections. A design could then collect compound elements that possess bilateral symmetry. Additionally, the brain prefers a vertical axis of reflection rather than accommodating every possible axis in each design.

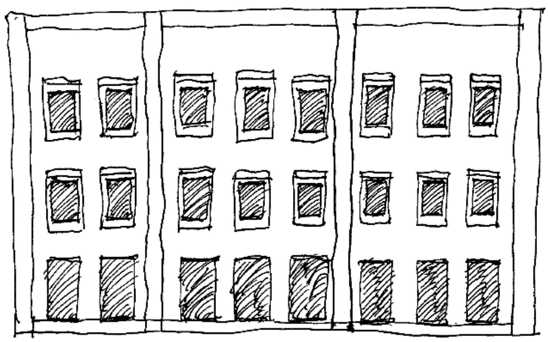

**Figure 6**: Multiple horizontal and vertical sub-symmetries generate a mathematically coherent façade.

There is a second type of "complement" of an architectural element that is created in the third dimension, which is along the line of sight. Imagine a bas-relief compared with its negative mould. Push-and-pull creates a 3-dimensional "reflection" in a direction orthogonal to the visual plane. Here, one defines a same-size element with opposite characteristics in the depth dimension. If we virtually superimpose such an architectural element with its opposite in depth, normally those would cancel out to leave nothing, i.e., a smooth flat surface. This process is analogous to the mathematical cancellation of opposites that results in the "zero element".

Juxtaposed concave and convex moldings do not actually cancel, since they are spatially separated, and instead reinforce each other through contrast. Having pairs of matching, but opposite, elements implements complementarity according to depth (Salingaros, 2006). This application provides a practical working rule that moldings should be present in equal numbers so that concave and convex parts are balanced visually. This is the case with moldings in traditional and vernacular architectures: a reason those are used—other than their utilitarian purpose—is to create structural meaning.

Our cognitive system relies on contrasting edges to interpret visual information (Itti, Koch and Niebur, 1998; Kootstra, de Boer, and Schomaker, 2011). "Contrast" is one of Alexander's 15 Fundamental Properties of coherent structure (Alexander, 2001). Using strongly contrasting elements coherently can lead to strong connections. Contrast is necessary to establish distinct subunits, to distinguish between adjoining units, and to provide figure-ground symmetry between opposite elements (Salingaros, 2006; 2010). Reducing contrast, as seen for example in the overall application of the "zero element" in design, loses structural meaning. The search for a false transparency and the elimination of the inside/outside transition thus weakens coherent structure.

## 8 UNIVERSAL (FRACTAL) DISTRIBUTION OF SIZES

Mathematics also relates the components of a whole via their distribution according to size. That is, quite apart from the multiple symmetries that contribute to coherent structure, the actual size and relative numbers of the components can be perceived as harmonious or not. A harmonious distribution will include elements of different sizes in a fairly exact correspondence. A skewed distribution that is missing some essential scales will unconsciously strike the observer as unnatural, hence leading to stress and unease.

The universal distribution law states: "In a complex system, there are few large objects, more intermediate-size objects, and many smaller objects, roughly in an inverse-power relationship" (Salingaros and West, 1999). This implies that the number of elements of different sizes we perceive at the same time should be inversely proportional to their size: multiplicity is related to the reciprocal of the size. More-refined versions of this law follow a scaling index that corresponds to the negative of the fractal dimension (a number between 1 and 2) and not simply –1.

The components of a fractal are self-similar through scaling (an additional relationship), which gives it its geometrical coherence. Let $p_i$ be the number of design elements of a certain size $x_i$. Then, the number of elements of each size is inversely proportional to their size, $p_i = C/(x_i)^m$ , where the constant $C$ is fixed by the largest size, and the power $m$ corresponds to the fractal dimension. In a frequency distribution, sizes $x_i$ are measured as lengths, whereas the multiplicities $p_i$ are integers. Mathematical fractals are generated as an infinite series of scaled-down copies of a single element, and illustrate ideal cases of this law (Crompton, 2002; Joye, 2006; 2007; Taylor, 2006; Taylor *et al.*, 2005).

Let us take two common examples. For the Sierpinski gasket, where the area of a triangle gets progressively subdivided into smaller and smaller triangles, the scaling factor is 2 and the scaling index equals the fractal dimension $m = D = \ln 3/\ln 2 \approx 1.58$. For the von Koch snowflake, where the sides of a triangle get progressively subdivided into smaller and smaller triangles, the scaling factor is 3 and the fractal dimension is $m = D = \ln 4/\ln 3 \approx 1.26$ (Salingaros and West, 1999). In practice, however, the simplest choice is $m = 1$ for architectural applications.

The inverse-power law is derived from proportionally distributing entropy among all the available scales in a complex structure (Salingaros and West, 1999). It is also related to the allometric growth law satisfied by many natural and especially biological systems. This requirement governs subdivisions of a design or structure, and a scaling law checks those different scales. The universal distribution is independent of simple geometric shapes and leads to the coherent structures found in the plant world, where nothing is truly straight. Artificial complex systems also evolve toward such a distribution as they acquire “emergent properties”. Examples include electrical power grids, ecosystems, Internet links, and the structure of languages (Zipf’s Law).

The universal (fractal) distribution underlies human perception. Details on the smaller scale help to establish structural meaning for what we see. Contours, sharp details and edge features (high spatial frequency information) are actually more important than larger shapes (low spatial frequency information) for interpreting a complex scene. Clinical *fMRI* studies of brain responses reveal that “representations of scene content are also more strongly conveyed by high than low spatial frequencies” (Berman *et al.*, 2017). This is true even though the global forms are processed first by the eye.

Coincidentally, linking high spatial frequencies to an image’s meaning explains why a successful line drawing can capture the character and expression of a person in a portrait sketch. It’s only a few selected details that make all the difference. The opposite weighing—as occurs in minimalist design—eliminates all but the largest shapes, which is the cognitive equivalent to blurring an image (resulting in the loss of all higher spatial frequencies). People who prefer to live with minimalist design willfully reject information the visual system evolved to provide their brain.

## 9 WHY MONOTONOUS REPETITION IS BAD FOR US

Our neurophysiology interprets spatial data by performing something akin to a Fourier decomposition. Individual brain cells in the visual cortex perceive different spatial frequencies and orientations, which are then combined (DeValois and DeValois, 1988). There are two separate lessons here for design, since both situations disturb our cognitive system: (i) A single spatial frequency depends upon regularity, i.e., translational symmetry. Departures such as irregular spacings are felt as visually dissonant because their encoding requires more neural processing. We instantly notice a spacing that is off, because it creates disjoint regular sequences. (ii) Scenes with one predominant spatial frequency are trivial. Since the brain is designed to analyze complex information having the full range of spatial frequencies it evolved to handle in natural environments, we perceive that something is missing.

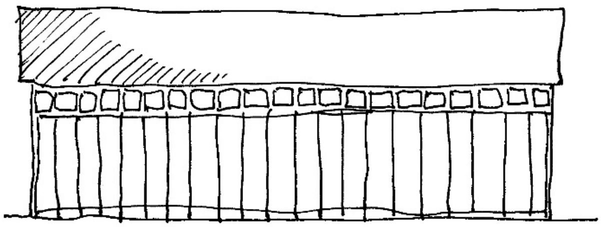

**Figure 7**: Monotonous repetition violates the fractal distribution law by eliminating intermediate scales.

Monotonous repetition makes us uncomfortable because it breaks the fractal distribution law (Salingaros, 2011). Copies of the same empty element along some axis generate a trivial sequence; but without intermediate grouping, the smaller components cannot generate coherent structure. Such uniformity disturbs our cognitive experience because of the gap in scales. There is no distribution of sizes here: only the single repeated unit and the overall size of the whole, but nothing in-between. A large object that consists of exactly repeated units (spatial periodicity) is perceived as unnatural, and such buildings actually induce headaches in the viewer (Wilkins, 2015; 2018).

A separate conjecture for why monotonous repetition gives us headaches comes from "cognitive fatigue" (Salingaros, 2010; 2011). Unlike an empty surface, which contains only the zero element and hence fails to attract our attention, repeating units demand combinatorial analysis. We try to interpret the simplistic translational symmetry further, to extract useful cognitive information. But there are no local sub-symmetries, no groups with bilateral symmetry, and no coupling of complements. The brain keeps working trying to discover non-existent symmetries, or non-existent edges, and the effort increases with the number of repeating identical elements and size of the structure.

Much of modernist-minimalism is characterized by extreme design uniformity, which is the minimal variety of all possible symmetries. Quite simply, the "zero element" is repeated throughout the design to the exclusion of everything else. Following the arguments put forward in this paper, structural meaning can only arise when such a minimalist symmetry is broken by introducing coherent structure. Otherwise, the building, even when it is an imposing skyscraper, is necessarily devoid of structural meaning.

Preventing information collapse extends the above arguments against homogeneity. Monotonous repetition of a single element $A$ is almost uniform, hence informationally trivial. To code this signal, it suffices to describe it as "$A \times 50$" (Salingaros, 2010; 2011). Beyond a simple repeating unit $A$, and the number of times it repeats, there is no further information other than the alignment giving us the translational symmetry. Yet our brain evolved to analyze complex information rich in meaning, and reacts negatively to informational starvation.

Eye-tracking experiments show that our attention is not drawn to buildings with monotonous repetition: we don't even look at them (Sussman and Ward, 2017; 2019). An interesting Virtual Reality experiment compared user experience of two similar urban squares flanked by rows of buildings in distinct architectural styles (Ellard and Condia, 2020). The experimenters used electrodermal sensors together with a questionnaire to determine arousal (i.e., sensory stimulation). Measures of "restorative potential"—how far an environment makes the user feel refreshed and relaxed—strongly favored the more traditional setting containing structural meaning over the other setting with monotonous repetition.

## 10 SYMMETRY BREAKING PREVENTS INFORMATIONAL COLLAPSE

Symmetry represents information compression that optimizes the working of a complex system. Multiple nested sub-symmetries might act as “Markov redundancies” to help a system continue to function even as it repairs itself (Adams and Ferrante, 2007; Ram, Singh, and Varshney, 2013). These sub-symmetries certainly aid visual processing, yet that cannot be their purpose, since our visual system evolved in response to existing natural symmetries and not the other way around.

Animal structure shows bilateral symmetries. Smaller animals such as insects and corals show rotational and translational symmetries, whereas plants employ more helical, rotational, and scaling symmetries. All of those symmetries result from optimizing organismic structure for life (Marijuán, 1996). Life creates symmetries that appear structurally meaningful to us. Additionally, symmetries in plants (especially flowers) appear to be an adaptation for attracting animals (Giurfa, Dafni, and Neal, 1999; Krishna and Keasar, 2018).

The mechanism of symmetry breaking produces a deeper set of mutually-reinforcing symmetries, leading to increased logical depth, or computational irreducibility (Collier, 1996; Wolfram, 2002). A simple repetition of elements is redundant from the viewpoint of information theory, and hence has little structural meaning. Introducing more information at smaller scales partially breaks the simplistic symmetry, and at the same time increases the scale range. This process of selectively adding information prevents information collapse, i.e., an easy compression to a trivial generating code. Symmetry breaking increases coherent structure—hence meaning that emerges from structure—with only a slight increase in raw information.

The concept of “symmetry breaking” comes from biology, mathematics, and physics (Li and Bowerman, 2010). Although highly speculative, there is an analogy here with the creation of mass in gauge field theories. Perfect symmetry is mathematically elegant, but it does not allow for the massive particles that constitute matter in the universe. Mass arises from symmetry breaking via the Higgs-Goldstone mechanism. Does this have any bearing on architecture? Not directly, yet the implication is intriguing. The most viscerally attractive architectural creations are characterized by local multiple sub-symmetries embedded within imperfect (though very carefully controlled) overall symmetry (Alexander, 2001).

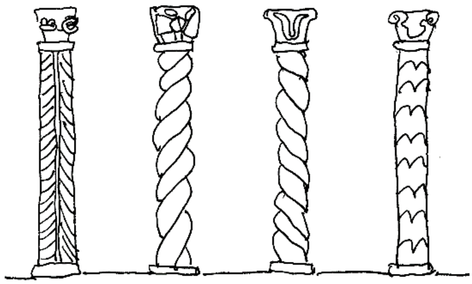

**Figure 8**: Repetition with variety maintains translational symmetry but prevents informational collapse.

Humans unconsciously avoided reductive situations by breaking simplistic symmetry in artefacts and buildings (Phillips, 2018; Salingaros, 2010; 2011). Variation within symmetry has to maintain large-scale symmetry while introducing variety into the smaller scales. Take a repeating unit and: (i) maintain the translational symmetry by keeping the unit's dimensions and alignment; (ii) vary each unit with smaller-scale details so that copies are only approximately similar, but not identical. This process breaks perfect translational symmetry while the variety gives structural meaning to the configuration. Most importantly, it can no longer be described by "$A \times 50$", but requires a much longer description (while not going so far as to need 50 different descriptions, which would be too much).

"Alternating Repetition" using contrasting elements *A* and *B* improves the variety and still keeps a fairly compact description "$AB \times 25$" (Salingaros, 2010; 2011). This is one of Alexander's 15 Fundamental Properties of coherent structure (Alexander, 2001). The key to success in this binary case is to make sure that the juxtaposed contrasting units are coupled pairwise and also define multiple sub-symmetries. Alternation done right not only breaks monotony; it additionally introduces new local symmetries. One could repeat a more complex unit. These sophisticated mathematical solutions were derived by human intuition, and are found throughout traditional architectures.

Traditional artefacts from all over the world show the property of "Roughness", or relaxation of strict symmetry on the smaller scales, another of Alexander's 15 Fundamental Properties (Alexander, 2001). This quality is usually misinterpreted as carelessness on the part of the maker, or an unavoidable consequence of producing handicrafts. It is not that at all: upon closer inspection, it is seen that every repeating unit has been made slightly different on purpose, in order to prevent informational collapse. Both formal and vernacular architectures throughout history are replete with approximate symmetries and exhibit requisite variety. By successfully balancing global symmetry with local symmetry breaking, asymmetrical buildings with structural meaning appear at first glance to be perfectly symmetrical.

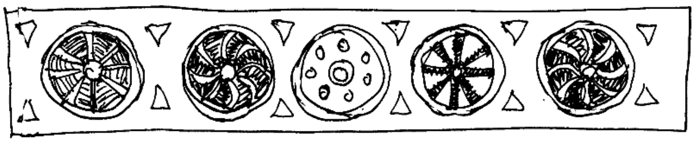

**Figure 9**: Combined rotational and translational symmetries on the large scale are "broken" by added variety on the smallest scales.

## 11 DELIBERATE RANDOMNESS

The ability to distinguish patterns with complex symmetries from random structures is a key human evolutionary development. Experiments using *fMRI* scans measured differential brain activation in Macaque monkeys—implying increased interest/preference—when shown visual patterns having reflectional and rotational symmetries as compared to random patterns. Human subjects showed a significantly higher difference reacting to those patterns in the same way (Sasaki *et al.*, 2005). Our brain obviously got better at it for a reason. Results from viewer preference studies using a similar set of symmetric versus random visual patterns confirm the *fMRI* evidence (Makin *et al.*, 2018).

Experiencing architecture is governed by those hard-wired preferences, which make cognitive engagement not automatic. Pilot-studies using eye-tracking emulation software reveal that we simply do not fixate on either minimalist, or deliberately random buildings (Salingaros and Sussman, 2020). Those fail to draw our unconscious attention. Our eye has to be attracted first to fixate on a building's façade, and only then can the brain apply analytical techniques to process the visual signal. If something does not draw our gaze instantly and unconsciously, then it has no meaning for life.

Other studies show that humans respond to randomness intellectually with anxiety. Reading antithetical verbal descriptions that the universe is random and meaningless as opposed to comprehensible triggers opposite emotional reactions (Tullett *et al.*, 2015). This effect is attributed to facing the possibility that our environment is incomprehensible, which would undermine prediction that the human mind requires in order to cope. The brain is tuned to seek out patterns that will help negotiate the world. Life depends upon our intelligence discovering and using causal relations. Reading about the possibility that the world is not comprehensible but random/meaningless triggers distress.

Actual randomness in the built environment diminishes comprehensibility, and impedes human emotional attachment (Coburn *et al.*, 2017; Coburn *et al.*, 2020). Designers who deliberately introduce randomness into their work frequently cite clouds, and the paintings of the American painter Jackson Pollock, as precedents to justify their action. But Pollock's paintings are not entirely random, even though they eschew bilateral, rotational, scaling, and translational symmetries. Richard Taylor has shown that they obey the universal (fractal) distribution of sizes (Taylor *et al.*, 2011).

Thermodynamic processes that generate clouds are not constrained by any geometrical symmetries, yet cloud shapes apparently satisfy some of Alexander's Fifteen Fundamental Properties that characterize coherent structure (Alexander, 2009). Therefore, in a cognitive sense, they are perceived visually as "natural", hence not entirely random.

Innately coherent architectural structures help to reinforce the reassuring idea that the world is comprehensible and meaningful. But by deliberately implementing randomness in their designs, architects express two disturbing messages: (i) the universe is random/meaningless; and (ii) the development of human cognitive intelligence counts for nothing. As there is considerable scientific evidence suggesting that the physical universe is not random/meaningless, our biology reacts with alarm to contrary assertions. Such architectural statements conflict with the innate cognitive mechanisms that humans use to make sense of the world around them. They also deny the evolution of societies that implemented meaning systems based on life.

This argument should not be misinterpreted as privileging an architecture with completely symmetrical ordering. At the opposite extreme of randomness lies monotonous repetition: both are stressful to experience on the large scale (Salingaros, 2011). As was described in the previous sections, what endows structures with meaning is a high number of local sub-symmetries, but not necessarily a simplistic overall translational or bilateral mirror symmetry. Indeed, eliminating small-scale symmetries while imposing large-scale perfect symmetry marks the architecture of totalitarianism, as it is felt psychologically to express oppressive power (Alexander, 2001; Hodne, 2016).

## 12 CONCLUSION: SYMMETRIES CREATE MEANING, BUT WHY DOES MAINSTREAM ARCHITECTURE REJECT THIS?

The human brain is an information processor that searches for structural meaning in the environment. Our evolution has prepared us to interpret patterns and classify information. Structural meaning embedded in architecture thus has a biological origin directly linked to our survival and has little to do with cult ideology, philosophy or politics. This is the reason why our body reacts with a positive visceral sense to “beauty” that has proven healing properties, and why children respond spontaneously to such beauty.

By some accident of history that is too involved to go into here, the teaching of design has become focused on doing the opposite of what our biology requires. Architects hold a mental model that does not seek to optimize the human-environment relationship. Fashionable design has over several decades eschewed anything other than trivial symmetries, violated the visual expression of gravity (through cantilevers, pencil-thin supports, and leaning forms), and eliminated the smaller elements that could define a fractal distribution on a structure’s façade or interior (Mehaffy and Salingaros, 2013). Science validates those missing characteristics as healing, suggesting the reason why our body identifies them as elements of “beauty”.

This conscious reversal began with an attempt at design innovation through breaking from traditional practices: yet it was those that implemented evolved mechanisms for achieving coherent structure necessary for our sensory well-being. By now this contrarian approach to design has been internalized as the standard and is no longer questioned (Mehaffy and Salingaros, 2011). Rejection of structural meaning has become the norm in design. Dominant architectural culture is unlikely to pay attention to the present exposition of what gives meaning to architecture. The mainstream profession is driven by money and power and finds the self-referential apologia based on semiotic meaning convenient (Cordova-Ramirez, 2020; Horacek, 2020; Mehaffy, 2020; Millais, 2020).

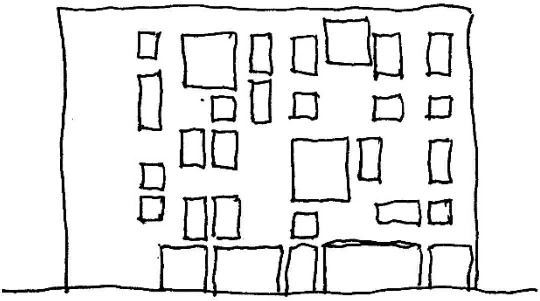

**Figure 10**: Building deliberately misaligns elements to violate architectural coherence.

Explanations within architecture avoid discussing human physiology altogether, and rely instead upon a design exegesis that ignores what science has discovered over the past century. For decades, architecture is no longer judged using architectural criteria, but using semiotic notions of "progress" instead. Buildings satisfying those esoteric notions are responsible for detaching culture from nature. Despite protests by ordinary people who are appalled at a damaged built environment that lacks structural meaning, the profession continues to justify its practices by reference to science-fiction fantasies.

Traditional and vernacular buildings aside, why is biologically-based beauty suppressed in the dominant architecture of our times? Practitioners are taught to design the form first as an abstraction, but will vehemently deny that they are rejecting beauty. Biological beauty has been replaced in the profession by top-down methods for disconnecting from the experiential world. The same denial comes from an intellectual community that praises buildings that deliberately reject the mathematical constructs presented here as necessary, and from an educational system that has been teaching our young architects to exclusively create abstractions.

**Acknowledgments**: Line drawings are by the author. Results presented in a Keynote at the *IV*[th] *Seminar of Architecture and Mathematics: Formulas in Architecture*, Universidade Lusíada de Lisboa, Lisbon, Portugal, 21 November 2019. Some material is re-worked from (Salingaros, 2019).

# REFERENCES


Adams, G. and Ferrante, F. (2007) Markov Modeling Application to a Redundant Safety System, *Proceedings of PWR2007 ASME Power Conference*, [17-19 July 2007, San Antonio, Texas, USA], 1–7. https://doi.org/10.1115/POWER2007-22119

Alexander, C. (2001) *The Nature of Order, Book 1: The Phenomenon of Life*, Berkeley, California: Center for Environmental Structure.

Alexander, C. (2009) Harmony-Seeking Computations: a Science of Non-Classical Dynamics based on the Progressive Evolution of the Larger Whole, [Keynote Speech at the *International Workshop "The Grand Challenge in Non-Classical Computation"*, University of York, UK, April 2005]. https://www.livingneighborhoods.org/library/harmony-seeking-computations.pdf

Berman, D., Golomb, J. and Walther, D. (2017) Scene content is predominantly conveyed by high spatial frequencies in scene-selective visual cortex, *PLoS ONE*, 12, 12, [22 December 2017]. https://doi.org/10.1371/journal.pone.0189828

Biederman, I. and Vessel, E. A. (2006) Perceptual Pleasure and the Brain, *American Scientist*, 94, 3, 247–253. https://doi.org/10.1511/2006.59.247

Chang, L. and Tsao, D.Y. (2017) The Code for Facial Identity in the Primate Brain, *Cell*, 169, 6, 1013–1028. https://doi.org/10.1016/j.cell.2017.05.011

Coburn, A., Kardan, O., Kotabe, H., Steinberg, J., Hout, M., Robbins, A., MacDonald, J., Hayn-Leichsenring, G. and Berman, M. G. (2019) Psychological responses to natural patterns in architecture, *Journal of Environmental Psychology*, 62, 133–145. https://doi.org/10.1016/j.jenvp.2019.02.007

Coburn, A., Vartanian, O. and Chatterjee, A. (2017) Buildings, Beauty, and the Brain: A Neuroscience of Architectural Experience, *Journal of Cognitive Neuroscience*, 29, 9, 1521–1531. https://doi.org/10.1162/jocn_a_01146

Collier, J. (1996) Information originates in symmetry breaking, *Symmetry: Culture & Science*, 7, 3, 247–256. https://www.researchgate.net/publication/250825786

Córdova-Ramírez, M. (2020) A False Promise of Progress, *Inference*, 5, 2, [4 May 2020]. https://inference-review.com/letter/a-false-promise-of-progress

Crompton, A. (2002) Fractals and Picturesque Composition, *Environment and Planning B*, 29, 451–459. https://doi.org/10.1068/b12822

Curl, J. S. (2018) Loss of Meaning, In: Curl, J. S., *Making Dystopia: The Strange Rise and Survival of Architectural Barbarism*, Oxford: Oxford University Press, 361–364.

DeValois, R. and DeValois, K. (1988) *Spatial Vision*, New York: Oxford University Press.

Ellard, C. and Condia, B. (2020) Place, Peripheral Vision, and Space Perception: a pilot study in VR, In: Condia, B., Arbib, M., Ellard, C., Chamberlain, B. and Rooney, K., *Meaning in Architecture: Affordances, Atmosphere and Mood*, Manhattan, Kansas: New Prairie Press eBooks, No. 33, 33–54. https://newprairiepress.org/ebooks/33

Forsythe, A. and Sheehy, N. (2011) Is it not beautiful?, *The Psychologist*, 24, 7, 504–507. https://thepsychologist.bps.org.uk/volume-24/edition-7/it-not-beautiful

Giurfa, M., Dafni, A. and Neal, P. R. (1999) Floral Symmetry and Its Role in Plant-Pollinator Systems, *International Journal of Plant Sciences*, 160, 6, 41–50. https://doi.org/10.1086/314214

Goldberger, A. L. (1996) Fractals and the Birth of Gothic, *Molecular Psychiatry*, 1, 99–104. http://reylab.bidmc.harvard.edu/heartsongs/molpsy-1996-1-99.pdf

Hersey, G. L. (1988) *The Lost Meaning of Classical Architecture: Speculations on Ornament from Vitruvius to Venturi*, Cambridge, Massachusetts: MIT Press.

Hersey, G. L. (1999) *The Monumental Impulse: Architecture's Biological Roots*, Cambridge, Massachusetts: MIT Press.

Hodgson, D. (2011) The First Appearance of Symmetry in the Human Lineage: Where Perception Meets Art, *Symmetry*, 3, 1, 37–53. https://doi.org/10.3390/sym3010037

Hodne, L. (2016) Symmetry and Utopia: The Aesthetics of Early 20th Century Architecture, *Symmetry: Culture and Science*, 27, 4, 431–446. https://doi.org/10.26830/symmetry_2016_4_431

Horáček, M. (2020) Architects as Physicians, *Inference*, 5, 2, [4 May 2020]. https://inference-review.com/letter/architects-as-physicians

Itti, L., Koch, C. and Niebur, E. (1998) A Model of Saliency-Based Visual Attention for Rapid Scene Analysis, *IEEE Transactions on Pattern Analysis and Machine Intelligence*, 20, 11, 1254–1259. https://doi.org/10.1109/34.730558

Jencks, C. (1969) Semiology and architecture, In: Jencks, C. and Baird, G., eds. *Meaning in architecture*, London: Barrie & Jenkins, 11–25. https://www.atlasofplaces.com/essays/meaning-in-architecture

Jiang, B. (2015) Wholeness as a hierarchical graph to capture the nature of space, *International Journal of Geographical Information Science*, 29, 9, 1632–1648. https://doi.org/10.1080/13658816.2015.1038542

Jiang, B. (2019) Living structure down to earth and up to heaven: Christopher Alexander, *Urban Science*, 3, 3, 96. https://doi.org/10.3390/urbansci3030096

Joye, J. (2006) An Interdisciplinary Argument for Natural Morphologies in Architectural Design, *Environment and Planning B*, 33, 2, 239–252. https://doi.org/10.1068/b31194

Joye, Y. (2007) Fractal Architecture Could be Good for You, *Nexus Network Journal*, 9, 2, 311–320. https://doi.org/10.1007/s00004-007-0045-y

Kappraff, J. (2016) The Proportional System of the Parthenon, *Symmetry: Culture and Science*, 27, 4, 369–391.

Katona, V. (2019) Bauhaus 100: Symmetries and Proportions in Modern Architectural Composition, *Symmetry: Culture and Science*, 30, 4, 261–263. https://doi.org/10.26830/symmetry_2019_4_261

Kootstra, G., de Boer, B. and Schomaker L. (2011) Predicting Eye Fixations on Complex Visual Stimuli using Local Symmetry, *Cognitive Computation*, 3, 1, 223–240. https://doi.org/10.1007/s12559-010-9089-5

Kravitz, D., Peng, C. and Baker, C. (2011) Real-world scene representations in high-level visual cortex: it's the spaces more than the places, *Journal of Neuroscience*, 31, 20, 7322–7333. https://doi.org/10.1523/JNEUROSCI.4588-10.2011

Krishna, S. and Keasar, T. (2018) Morphological Complexity as a Floral Signal: From Perception by Insect Pollinators to Co-Evolutionary Implications, *International Journal of Molecular Sciences*, 19, 6, Article 1681. https://doi.org/10.3390/ijms19061681

Lakoff, G. and Nuñez, R. (2001) *Where Mathematics Comes From: How The Embodied Mind Brings Mathematics Into Being*, New York: Basic Books.

Li, R. and Bowerman, B. (2010) Symmetry Breaking in Biology, *Cold Spring Harbor Perspectives in Biology*, 2, 3, Article a003475. https://doi.org/10.1101/cshperspect.a003475

Maas, H. (2008) *Architectural Form Part 1: An introduction into understanding buildings*, Lulu.com, 244 p.

Makin, A., Helmy, M. and Bertamini, M. (2018) Visual cortex activation predicts visual preference: Evidence from Britain and Egypt, *Quarterly Journal of Experimental Psychology*, 71, 8, 1771–1780. https://doi.org/10.1080/17470218.2017.1350870

Malcolm, G. L., Groen, I. and Baker, C. (2016) Making Sense of Real-World Scenes, *Trends in Cognitive Sciences*, 20, 11, 843–856. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5125545

Marijuán, P. C. (1996) Information and symmetry in the biological and social realm: New avenues of inquiry, *Symmetry: Culture and Science*, 7, 3, 281–294. http://symmetry-us.com/Journals/7-3/marijuan.pdf

Mattson, M. P. (2014) Superior pattern processing is the essence of the evolved human brain, *Frontiers in Neuroscience*, 8, Article 265, 1–16. https://doi.org/10.3389/fnins.2014.00265

Mehaffy, M. (2004a) Meaning and the Structure of Things, In: Steil, L., Hanson, B., Mehaffy, M. and Salingaros N. eds. *Katarxis*, No. 3, [September 2004]. http://katarxis3.com/Mehaffy_Meaning.htm

Mehaffy, M. (2004b) The New Modernity: The Architecture of Complexity and The Technology of Life, In: Steil, L., Hanson, B., Mehaffy, M. and Salingaros N. eds. *Katarxis*, No. 3, [September 2004]. http://www.katarxis3.com/Mehaffy_New_Modernity.htm

Mehaffy, M. (2020) An Obsolete Ideology, *Inference*, 5, 2, [4 May 2020]. https://inference-review.com/letter/an-obsolete-ideology

Mehaffy, M. W. and Salingaros, N. A. (2011) Architectural Myopia: Designing for Industry, Not People, *Shareable*, 5 October 2011. https://www.shareable.net/architectural-myopia-designing-for-industry-not-people

Mehaffy, M. W. and Salingaros, N. A. (2013) How Modernism Got Square, *Metropolis*, 19 April 2013, [Reprinted as Chapter 3 of *Design for a Living Planet* (2015) Portland, Oregon: Sustasis Press, and Kathmandu, Nepal: Vajra Books]. https://www.metropolismag.com/architecture/toward-resilient-architectures-3-how-modernism-got-square

Millais, M. (2020) The Origins of Architectural Barbarism, *Inference*, 5, 2, [4 May 2020]. https://inference-review.com/letter/the-origins-of-architectural-barbarism

Miller, G. A. (1956) The Magical Number Seven Plus or Minus Two: Some Limits on Our Capacity for Processing Information, *The Psychological Review*, 63, 81–97. https://doi.org/10.1037/h0043158

Murray, S. O., Kersten, D., Olshausen, B., Schrater, P. and Woods, D. (2002) Shape perception reduces activity in human primary visual cortex, *Proceedings of the National Academy of Sciences USA*, 99, 23, 15164–15169. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC137561

Phillips, A. (2018) Why symmetry gets really interesting when it is broken, *Aeon Magazine*, 10 April 2018. https://aeon.co/ideas/why-symmetry-gets-really-interesting-to-physics-when-it-is-broken

Ram, M., Singh, S. B. and Varshney, R. G. (2013) Performance Improvement of a Parallel Redundant System With Coverage Factor, *Journal of Engineering Science and Technology*, 8, 3, 344–350. http://jestec.taylors.edu.my/Vol%208%20Issue%203%20June%2013/Volume%20(8)%20Issue%20(3)%20344-%20350.pdf

Ruggles, D. H. (2018) *Beauty, Neuroscience, and Architecture: Timeless Patterns and Their Impact on Our Well-Being*. Denver, Colorado: Fibonacci Press.

Salingaros, N. A. (1998) A Scientific Basis for Creating Architectural Forms, *Journal of Architectural and Planning Research*, 15, 4, 283–293, [Revised version is Chapter 2 of *A Theory of Architecture*, 2nd ed. (2014) Portland, Oregon: Sustasis Press].

Salingaros, N. A. (2006) *A Theory of Architecture*, Portland, Oregon: Sustasis Press, [2nd ed. 2014].

Salingaros, N. A. (2010) *Algorithmic Sustainable Design: Twelve Lectures on Architecture*, 2nd ed., Portland, Oregon: Sustasis Press.

Salingaros, N. A. (2011) Why Monotonous Repetition is Unsatisfying, *Meandering Through Mathematics*, 2 September 2011. https://arxiv.org/pdf/1109.1461v1.pdf

Salingaros, N. A. (2015) Alexander's Fifteen Fundamental Properties, *ArchDaily*, 2 May 2015. https://www.archdaily.com/626429/unified-architectural-theory-chapter-11

Salingaros, N. A. (2018) Applications of the Golden Mean to Architecture, *Symmetry: Culture and Science*, 29, 3, 329–351, [Substantially revised version of an earlier article published in *Meandering Through Mathematics*, 21 February 2012]. https://doi.org/10.26830/symmetry_2018_3_329

Salingaros, N. A. (2019) How Mathematics Will Save the Built World!, *Common Edge*, 28 January 2019. https://commonedge.org/how-mathematics-will-save-the-built-world

Salingaros, N. A. and Sussman, A. (2020) Biometric pilot-studies reveal the arrangement and shape of windows on a traditional façade to be implicitly "engaging", whereas contemporary façades are not, *Urban Science*, [submitted]. https://doi.org/10.3390/urbansci4020026

Salingaros, N. A. and West, B. J. (1999) A universal rule for the distribution of sizes, *Environment and Planning B: Planning and Design*, 26, 6, 909–923, [Condensed version (without equations) is Chapter 3 of *Principles of Urban Structure* (2005) Amsterdam, Holland: Techne Press. 2nd ed. (2014), Portland, Oregon: Sustasis Press]. https://doi.org/10.1068/b260909

Sasaki, Y., Vanduffel, W., Knutsen, T., Tyler, C. and Tootell, R. (2005) Symmetry activates extrastriate visual cortex in human and nonhuman primates, *Proceedings of the National Academy of Sciences*, 102, 8, 3159–3163. https://doi.org/10.1073/pnas.0500319102

Seresinhe, C. I., Preis, T. and Moat, H. S. (2017) Using deep learning to quantify the beauty of outdoor places, *Royal Society Open Science*, 4, 7, Article 170170, [19 July 2017]. https://doi.org/10.1098/rsos.170170

Sessions, R. and Salingaros, N. A. (2010) Urban and Enterprise Architectures: A Cross-Disciplinary Look at Complexity, *Lecture Notes, International Association of Software Architects Webinar*, 15 October 2010. http://zeta.math.utsa.edu/~yxk833/urbanandenterprisearchitectures.pdf

Sussman, A. and Hollander, J. B. (2015) *Cognitive Architecture*, New York: Routledge. https://doi.org/10.4324/9781315856964

Sussman, A. and Ward, J. M. (2017) Game-Changing Eye-Tracking Studies Reveal How We Actually See Architecture, *Common Edge*, 27 November 2017. http://commonedge.org/game-changing-eye-tracking-studies-reveal-how-we-actually-see-architecture

Sussman, A. and Ward, J. M. (2019) Eye-tracking Boston City Hall to better understand human perception and the architectural experience, *New Design Ideas*, 3, 2, 53–59. http://jomardpublishing.com/UploadFiles/Files/journals/NDI/V3N1/SussmanA%20WardJ.pdf

Taylor, R. P. (2006) Reduction of Physiological Stress Using Fractal Art and Architecture, *Leonardo*, 39, 3, 245–251. https://doi.org/10.1162/leon.2006.39.3.245

Taylor, R. P., Newell, B., Spehar, B. and Clifford, C. (2005) Fractals: A Resonance Between Art and Nature?, In: Michele Emmer, ed. *Mathematics and Culture II: Visual Perfection*, Berlin: Springer-Verlag, 53–63. https://doi.org/10.1007/3-540-26443-4_6

Taylor, R. P., Spehar, B., Van Donkelaar, P. and Hagerhall, C. (2011) Perceptual and physiological responses to Jackson Pollock's fractals, *Frontiers in Human Neuroscience*, 5, 60, [22 June 2011]. https://doi.org/10.3389/fnhum.2011.00060

Tullett, A. M., Kay, A. C. and Inzlicht, M. (2015) Randomness increases self-reported anxiety and neurophysiological correlates of performance monitoring, *Social Cognitive and Affective Neuroscience*, 10, 5, 628–635. https://doi.org/10.1093/scan/nsu097

Tyler, C. W., Baseler, H., Kontsevich, L., Likova, L., Wade, A. and Wandell, B. (2005) Predominantly extra-retinotopic cortical response to pattern symmetry, *Neuroimage*, 15, 24, 306–314. https://doi.org/10.1016/j.neuroimage.2004.09.018

Whitehead, A. N. (1929) *Process and Reality*, New York: Free Press, [2nd ed. 1979].

Wilkins, A. J. (2016) A physiological basis for visual discomfort: Application in lighting design, *Lighting Research & Technology*, 48, 1, 44–54. https://doi.org/10.1177/1477153515612526

Wilkins, A. J. (2018) Looking at buildings can actually give people headaches. *The Conversation*, 5 July 2018. https://www.cnn.com/style/article/why-looking-at-buildings-can-give-people-headaches/index.html

Wilson, E. O. (1998) *Consilience: The Unity of Knowledge*, New York: Alfred A. Knopf.

Wolfram, S. (2002) *A New Kind of Science*, Champaign, Illinois: Wolfram Media.

Zeki, S. (2019) Beauty in Architecture, *AD Architectural Design*, 89, 5, 14–19. https://doi.org/10.1002/ad.2473