The Laws of Architecture from a Physicist's Perspective

Nikos A. Salingaros
Division of Mathematics
University of Texas at San Antonio
San Antonio, Texas 78249 U.S.A.

Abstract
Three laws of architectural order are obtained by analogy from basic physical principles. They apply to both natural and man-made structures. These laws may be used to create buildings that match the emotional comfort and beauty of the world's great historical buildings. The laws are consistent with Classical, Byzantine, Gothic, Islamic, Eastern, and Art Nouveau architectures; but not with the modernist architectural forms of the past 70 years. It seems that modernist 20th century architecture intentionally contradicts all other architectures in actually preventing structural order.

Key words: structural order, architecture, design rules

1. INTRODUCTION

Architecture is an expression and application of geometrical order. One would expect the subject to be described by mathematics and physics, but it isn't. There is no accepted formulation of how order is achieved in architecture. Considering that architecture affects mankind through the built environment more directly than any other discipline, our ignorance of the actual mechanism is surprising. We have concentrated on understanding natural inanimate and biological structures, but not the systematic patterns reflected in our own constructions.

There exist historical buildings that are universally admired as being the most beautiful (Section 2). That includes the great religious temples of the past [1], and the cultural wealth contained in various indigenous architectures [2, 3]. Both were built by following some rules of thumb, and these rules can be deduced from the structures themselves. This set of empirical rules has been analysed and collected in the "Pattern Language" of Alexander [4].

Structural laws underlie physics and biology, and we expect similar laws to hold for architecture as well. Alexander proposes a set of rules that govern architecture, derived from biological and physical principles [5]. They are based on the hypothesis that matter obeys a complex ordering on the macroscopic scale. Even though forces such as electromagnetism and gravity are too weak to account for this, volumes and surfaces apparently interact in a way that mimicks the microscopic interaction of particles. Architecture can be reduced to a set of rules that are akin to the laws of physics.

Using analogies with the structure of matter, three laws of architectural order are postulated here (Section 3). They are checked in three different ways: (a) by agreeing directly with the greatest historical buildings of all time [1]; (b) by agreeing with fifteen properties abstracted by Alexander from creations throughout human history [5]; and (c) by agreeing with physical and biological forms. This result represents a successful application of the physicist's approach to a highly complex problem, which has up until now resisted a scientific formulation.

What we obtain are really rules of beauty. The laws can be applied to classify architectural styles in a way that has not been done before (Section 4). Whereas most traditional architectures follow the three laws, modernist buildings do the opposite of what the three laws say. This result categorizes traditional and modernist architectures into two separate groups. It appears that all buildings are created by a systematic application of the same three laws; whether in following them, or in opposing them.

Thus far, the results do not distinguish which architecture, traditional or modernist, is "better". Nevertheless, Alexander, in company with Charles, the Prince of Wales, prefer traditional architecture. They are also convinced that traditional architecture is more suited to mankind for fundamental reasons, and not merely as a matter of taste. Section 5 presents arguments to support this view. The basis of those arguments is the sense of comfort one feels from a building, and the uniqueness of structural order.

2. RULES OF BEAUTY AND ORDER IN PAST TIMES

Every distinct civilization or different period in the past has left us a set of rules, usually implicit, that help produce the ultimate ideal in beauty. Each set of rules is relevant to a particular time, the availability of indigenous materials, the local climate, or an underlying religious ritual, and defines architectural forms that are beautiful. What is important is that these very different buildings and objects are seen as beautiful by most people today, who live outside the time and culture that produced them. This implies the existence of universal laws governing structural order.

There is no difficulty in applying a traditional set of rules to contemporary architecture. A Greek temple in Japan (as a bank), or a Chinese temple in the USA (as a restaurant) can be beautiful, if built by following the appropriate rules. Such rules tell us how to duplicate something from an earlier culture or different people. Rather what we need, and what architects are always looking for, is a prescription for building something beautiful that is not constrained by a rigid and possibly irrelevant tradition.

Rules that are genuinely independent of any specific culture and time can be derived by approaching architecture as a physics problem. We give universal laws governing architectural order that include, as special cases, most of the previous sets of rules for creating beautiful buildings — except those for modernist buildings. We then show that the rules for building modernist structures are simply to do the opposite of what is needed to achieve natural order. This result singles out modernism as a distinct class in the history of human construction.

Modernist buildings are perceived as unpleasant by many people. This is true for their visual aspect, and is especially so for the practical functions (entry and exit, working, circulation, etc.) that are supposed to take place in those buildings. Public reaction against modernism has been noted before [6, 7], and is forcefully expressed by Charles, the Prince of Wales [8, 9]. Despite all these criticisms, however, the modernist aesthetic remains deeply entrenched in our society.

Proponents of modernism have identified their credo with the technological progress of the 20th century. In the minds of many people, post-war industrial progress is linked to, if not outright due to, the expansion of modernist architecture, and for this reason they are reluctant to question it. It has become automatic for third-world countries to build the most modern-looking buildings as the first step towards modernization. Nevertheless, it is now accepted that modernist building programs in the pre-industrialized world have largely been disastrous [6].

3. THE THREE LAWS OF ARCHITECTURE

I am postulating these laws for the first time here. They have grown out of my discussions and interaction with Alexander over the past fifteen years.

(i) *"Order on the smallest scale is established by paired contrasting elements, existing in a balanced visual tension".*

(ii) *"Large-scale order occurs when every element relates to every other element at a distance in a way that reduces the entropy".*

(iii) *"The small scale is connected to the large scale through a linked hierarchy of intermediate scales with scaling factor* $e \approx 2.7$*".*

Several independent arguments supporting these laws are presented below. The first two laws govern the two extremes of scale: the very small, and the very large; and the third law governs the linking of the two scales. Each law gives rise to several distinct consequences; together these define a set of master rules for architecture. They are validated because their immediate consequences correspond to reality.

3.1 Order on the Small Scale

We will establish an analogy with the way that matter is formed out of contrasting pairs of elementary components. From the vacuum in quantum electrodynamics arising out of virtual electron-positron pairs; to nuclei formed from bound neutrons and protons with opposite isospin; to atoms formed of bound electrons and nuclei of opposite charge, matter follows a basic pattern. The smallest scale consists of paired elements with the opposite characteristics bound together. Coupling keeps opposites close to each other but does not allow them to overlap, because they would mutually annihilate: this creates a dynamic tension.

We now apply this concept to architecture. *"Order on the smallest scale is established by paired contrasting elements, existing in a balanced visual tension".* There are several ways to achieve contrast with materials: shape (convex-concave); direction (zig-zags); color hue; and color value (black-white). Local contrast identifies the smallest scale in a building, thus establishing the fundamental level of geometrical order. The scale is relevant to the observer — in regions where a person walks or sits or works, contrast and tension are needed at the smallest perceivable detail; in areas far from human activity, the scale is necessarily much larger.

Structural order is a phenomenon that obeys its own laws. Its fundamental building blocks are the smallest perceivable differentiations of color and geometry. Whereas visible differentiation on the small scale is not necessary to define structure, it is necessary for structural order. This is demonstrated in architecture and in most objects made before the 20th century. Classical Greek temples have marvellous contrasting details. This was also true of color, but the original coloration has been lost with time. To see the effective use of color contrast, look at the extraordinary 15th century tiled walls in Islamic Spain and Morocco.

There are several important consequences of the first law. (a) Basic elements, like elementary physical components, have to be simple. That means that the fundamental units are simple in shape, e. g., triangles, squares, and their combinations. (b) Basic units are held together by a short-range force. The only way to do this using geometry is to have interlocking units with opposite characteristics. (c) The smallest units occur in contrasting pairs, like fermions. When these pairs of units repeat, the repetition is not of a single unit, but of a pair, leading to alternation rather than simple repetition. (d) The contrast concept recurs on different scales, thus actually preventing detail from filling all the space. A region of detail will need to contrast with a plainer region, and the two regions combine to form a contrasting pair. In the same way, roughly-built areas are necessary to complement those areas built with a very fine finish.

Consider the nucleus, in which protons and neutrons are bound together by virtual pion exchange. The strong force is constantly reversing the nucleons' identity. A neutron is able to become a proton, then switch back again. A basic pair of contrasting units in a design, as described in (b), must also possess this duality. For an object and its surrounding space to be effectively bound into a contrasting pair, both the space and the object itself must have the same degree of structural integrity.

3.2 Order on the Large Scale

In physics, when non-interacting objects are juxtaposed, nothing happens. An interaction induces a re-arrangement that leads to higher order for the large-scale structure, and therefore to a reduction of the entropy. The process could be as complex as the growth in a crystal lattice, or as simple as the alignement of compass needles. This is the way that crystalline structures are formed, galaxies condense, etc. Action-at-a-distance, whether it is electric, magnetic, or gravitational, imposes a large-scale ordering that is characterized by geometrical connections.

One consequence of organization is that similarities appear between different subregions. This has to be mimicked in architecture, and used to tie the small-scale structures together into a harmonious whole. *"Large-scale order occurs when every element relates to every other element at a distance in a way that reduces the entropy"*. This basic prescription suffices to generate large-scale order in both color and geometry. Mimicking a long-range interaction determines the orientation and similarity of spatially-separated units.

Thermodynamic entropy relates different arrangements of the same number of particles according to their probability of occurring. Entropy applies to structural order in a slightly different way, because it relates different states with the same number of basic contrasting units. Architectural order is inversely proportional to the entropy of a fixed number of interacting structural components. The entropy of a design could be lowered by reducing the local contrasts, but this also reduces the structural order — that would be analogous to eliminating the molecules in a gas.

The consequences of the second law are the distinct ways in which global order is achieved. (a) Large-scale ordering arranges the basic units into highly symmetric combinations. As in crystallization, the global entropy is lowered by raising the local symmetries. The smaller scales are therefore characterized by a high degree of symmetry, which is not required of the large scales, however. (b) Order is also achieved by having units on a common grid, taking the cue from crystal lattices. Continuity of patterns across structural transitions raises the degree of connectivity. (c) In the absence of a physical force between areas, visual similarity connects two design elements through common colors, shapes, and sizes. Global harmony represents the opposite effect from local contrast. (d) Insisting on "purity" can destroy the connection process, because connections may be misinterpreted as impurities, and eliminated. Therefore, imperfections are both useful and necessary; just as in a doped crystal, where impurities enhance the structure.

The second law makes it easier to understand the visual interaction of two objects placed near each other, well-known from optical illusions. The brain creates connecting lines that appear to tie two units together. Now, if we take two objects, draw the virtual connections that we see on paper, then construct them from some material, the resulting structure will hold together against stresses. This establishes a physical relevance for a strictly visual phenomenon. It appears that the brain "sees" the proper physical connections for a stable structure.

The entropy of a design is perceived by our innate ability to visualize connections. The main spaces of any building, and their relation to each other, are governed by the mutual interaction of all the walls and any other structural elements. Certain dimensions, certain combinations, will appear to "resonate" when all components interact harmoniously. These correspond to the states of least entropy. Making adjustments to a complex structure so as to lower its entropy conforms precisely to the process that gives rise to natural forms.

3.3 The Natural Hierarchy of Scales

The third law of architecture is based on the idea of similarity and scaling. " *The small scale is connected to the large scale through a linked hierarchy of intermediate scales with scaling factor* $e \approx 2.7$". Surfaces interact; they define subdivisions; all that one has to do is to create structures at the appropriate scales, and link them together. The different scales have to be close enough so that they can relate, and the linking is accomplished through structural similarities.

The physical reasoning is that material forces are manifested differently on different scales. The shape of natural structures is influenced by stresses, strains, and fractures in solids, and by turbulence in moving fluids. Matter is not uniform: it looks totally different if magnified by a factor of 10 or more. We want the scaling factor for which two distinct scales are still related — empirically, this factor is around 3. In fractal geometry, the Koch, Peano, and Cantor self-similar fractal patterns that most closely resemble natural objects have similarity ratio $r = 1/3$ or $r = 1/\sqrt{7} \approx 1/2.65$, supporting the scaling factor $1/r \approx 2.7$ (10).

These arguments may appear totally heuristic, and yet they reveal a basic phenomenon best seen in biological structures. The secret of biological growth is scaling, either via a Fibonacci series, or an exponential series. Ordered growth is possible only if there is a simple scaling so that the basic replication process can be repeated to create structure on different levels. Thus, different structural scales must exist, and they must be related, preferably by only one parameter. The exponential scaling factor e fits both natural and man-made structures.

Take one view of a building as a two-dimensional design. Then decide whether to measure areas, or linear dimensions, depending on the situation. Different substructures of roughly the same size will group themselves into distinct sets of measurements. The number of different scales will be denoted by N. Call the maximum scale $x_{\max}$ and the minimum perceivable scale $x_{\min}$. An ideal structure will have n sets of subunits with sizes corresponding to every element of the following sequence:

$$\{x_{\min}, e x_{\min}, e^2 x_{\min}, ..., e^{n-1} x_{\min} = x_{\max}\} \tag{1}$$

Solving the last term of the sequence (1) for n relates the ideal number of scales n to the smallest and largest measurements (in the same units). We have,

$$n = 1 + \ln x_{\max} - \ln x_{\min} \tag{2}$$

where n is the nearest integer value. One measure of structural order is how close the theoretical index n (2) comes to the number N of distinct scales in a structure. This rule measures only if the hierarchical scaling exists; it does not determine whether similarities actually link the different scales together.

For example, a 3-storey building with 1 inch detail requires n to be about 7. In many modernist buildings, however, N is nearer 2, regardless of size, because there are intentionally no structures in the intermediate scales. Modernist buildings are "pure", meaning that they have large empty surfaces. On the other hand, some post-modernist buildings with unorganized structures of many different sizes might have N higher than n . A building with a natural hierarchy of scales, regardless of what it looks like, should have N very close to the theoretical index n .

There are several consequences of the third law. (a) Every unit will be embedded into a larger unit of the next scale in size. This naturally leads to a very wide boundary for each object in a design. The whole design is a hierarchy of wide boundaries within other boundaries. (b) As already mentioned, similarity of shape should link the different scales together; for example, the same curve or pattern repeated at different sizes. (c) The different scales can collaborate to define a gradient through similar shapes of decreasing size. Each building requires an entrance gradient, as well as other functional gradients, and these succeed only when they correspond to structural gradients. (d) A building must be placed into the environment in a way that fits the existing hierarchy of scales. The surrounding nature and other buildings will then define the largest scales of the ensemble.

The wide-boundary principle (a) states that an interacting object has a boundary of similar size as the object itself. For example, a square embedded symmetrically in another square has a ratio of areas $A_2/A_1 \approx e$. This gives a ratio of the width of the border to the width of the smaller square as $w/x_1 = (\sqrt{e} - 1)/2 \approx 0.32$.

One illustration comes from physics. The magnetic field around a spherical dipole magnet of radius R goes out to infinity, yet the effective region of field is comparable to the size of the magnet. The field strength along the axis falls to $1/10$ of its surface value at $2.15R$, giving the thickness of field as 0.58 times the magnet's diameter [11].

4. A CLASSIFICATION OF ARCHITECTURAL STYLES

The three laws and their twelve consequences are verified in the historical buildings and artifacts from all over the world, throughout more than four millennia of civilization before the 20th century [1]. This validates our findings in an essential manner. We have used arguments from theoretical physics to obtain practical results that correspond to reality. Our derivation confirms something already established by Alexander in a strictly architectural context [4, 5].

All architects in history, including the modernists, probably had some knowledge of the three laws proposed here. These laws define the various forms and the basis of design and construction that mimic the beauty and order found in nature. Modernists, however, deliberately strive to produce human constructions that contrast with nature. The shock value of something unnatural gives modernist buildings their novelty. To achieve this, they do the opposite of what the three laws say.

Modernist buildings minimize their structural order. They invariably have a monumental bilateral symmetry, which is unwarranted, but none of the necessary small-scale symmetries. Both structure and function are deliberately disguised. Small-scale order is forbidden. There is no differentiation of the space; no contrast between outside and inside, or of busy with calm areas, or of areas having distinct function. If there is any repetition, it is monotonous and without contrast.

All parts of a building exist in isolation, and do not interact in any way. Connections between regions are suppressed. Different scales are allowed only if the scaling factor is 15 or more, so the scales are disconnected. There are no borders; no connecting boundaries; surfaces are sheer and come to straight edges and sharp corners. Finally, any natural or existing order is usually razed before building, thus preventing any connection to the surroundings.

We can classify all architectural styles into two groups: natural and modernist. This classification is based on whether they follow or oppose the three laws of structural order, and has nothing to do with the age of the buildings. Many people have always instinctively separated modernist from traditional buildings, but, without a set of written rules, there was never a systematic way of doing this. It is even possible to judge a "mixed" style by seeing which laws and sublaws it follows, and which it deliberately contradicts.

The architectural community distinguishes architectural styles according to the use of traditional materials such as stone and brick, versus modern materials such as steel, glass, and lightweight reinforced concrete. Our results show this distinction not to be very relevant, as constructions that contradict the three laws are possible using any materials. On the other hand, some of the most beautiful Art Nouveau buildings, which follow our laws, were made possible by modern materials [12].

5. THE UNNATURALNESS OF CONTEMPORARY BUILDINGS

This section discusses two criteria for choosing between natural and modernist architectures: (i) the emotional response to a building; and (ii) the deeper connection between architectural order and nature. Modernism was invented by a group of men in the 1920's who championed extreme political and philosophical ideas [6, 7]. They were obsessed by the urge to break totally with any existing historical order. Their aim was to transform society by making constructions that defied nature, going against people's instinctive feelings of beauty.

In Section 4 we showed how modernist architecture relies on rules that are logically the opposite of the three laws of structural order. Nevertheless, modern physics was also a deliberate break from classical physics, but that was not a reason to dismiss it. The crucial difference is that modern physics survived because of its agreement with experimental phenomena. This identifies a deficiency in architectural theory: the lack of an experimental basis or something analogous to it.

5.1 The Emotional Basis of Architecture

Successful buildings have one overriding quality: they feel natural and comfortable. Man connects with his surroundings on the small scale, and needs to feel reassured about any large-scale structure. There is a built-in human reaction to threats from the environment, and structures threaten our primaeval sense of security when they appear unnatural. A building, regardless of shape or use, is perceived as beautiful when an emotional link is established with the structural order. This is independent of opinion and fashion.

Emotional well-being can be used as an experimental criterion for judging a structure's effectiveness. Man relates to the detail in a design or structure immediately, because the connection to the small scale is emotional. By contrast, perceiving the overall form often requires some thought, which is a more intellectual process. According to the three laws of structural order, our connection to architecture occurs via the smallest scale, through the intermediate scales, and finally to the large scale — and is successful only if all the scales are connected.

The fundamental human need for small-scale structural order is manifested in almost every object and building made before the 20th century. Modern architects, however, are relentless in attacking small-scale order as "criminal". This statement represents an extreme and overblown reaction to 19th century ornament. The solution to having too much decoration is not to banish detail altogether; it is to find the exact detail necessary for anchoring the larger forms. A minimum of detail, properly placed, establishes emotional well-being.

Modernist architecture disregards the basic human need for a comfortable mental environment in which to live and work. According to the founders of Modernism, one has no right to expect emotional comfort in buildings [6, 7]. Modern architects, moreover, deliberately seek to create emotional discomfort by introducing sharp corners, metallic edges, massive protruding overhangs, etc. They uncompromisingly insist on straight lines, even in situations where curves are clearly more appropriate. None of this is done for a functional reason, and often works against the functions in those buildings.

It is known from psychology that modernist structures make their inhabitants feel very uncomfortable. Human instincts towards the reduction of spatial discomfort try to reduce damage to the sense of well-being of the mind. This is analogous to our instincts in avoiding physical pain, which protect our body tissues from damage. No-one has paid serious attention to the human need for emotional well-being in an architectural setting: something vital in human consciousness could well be damaged by an environment that lacks structural order.

5.2 Uniqueness of Structural Order

There exist two opposite conceptions of structural order in the world today. Most people have been taught to think of "order" in modernist architectural terms: large-scale bilateral symmetry, flat empty surfaces, straight edges and right angles, etc. This essay argues that the structural order of our world as revealed by science is contradicted by the modernist built environment. We cannot justify two mutually contradictory definitions of structural order, which implies that the laws of structural order must be unique, and are the ones defined in this essay.

As pointed out earlier in Section 3, man can visualize connections intuitively. This innate ability has enabled humans to develop architecture early in the evolution of mankind. The mind establishes patterns and connections not only between objects, but also between ideas and concepts. To a physicist, it appears that our built-in intuitive notions of structural order arise from the same source as our ability to do physics. Instead of being nurtured, however, this ability is suppressed, as is described below.

Either we inherit an innate conception of structural order, or we learn it from our environment. People in the late 20th century are surrounded by modernist structures that purposely violate the three laws, yet they are constantly reminded that those buildings represent the only "true" order. If, as is claimed here, the laws are unique, then modernist buildings suppress the conception of structural order that we inherit. The consequence of this is to irreparably damage our ability to perceive connections, which affects more than just architecture.

6. CONCLUSION

Three laws of structural order were postulated from basic physical analogies. These laws were shown to have a scientific validity above and beyond any architectural fashion or opinion. Natural forms have an ordered internal complexity that mimics interacting physical processes, and this is reflected in the world's great historical buildings and vernacular architectures. The three laws derived here are eminently practical, and can be applied to create buildings of intense physical and emotional beauty.

At the end of the 20th century, modernist architecture dominates our entire world. This essay showed that modernist architecture deliberately opposes nature by minimizing structural order. This violates deeply-seated feelings that are an intrinsic part of human consciousness. Until now, people have been frustrated by the removal of structural order, and the imposition of buildings that make us feel uncomfortable. Our results should convince people that their intuitive feelings of architectural beauty are correct, and that a nourishing man-made environment is again possible.

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Résumé

Trois lois de l'ordre architectural sont obtenues par analogie à partir de principes fondamentaux de physique. Ces lois, qui s'appliquent aussi bien aux structures naturelles qu'à celles créées par l'homme, peuvent être utilisées pour construire des édifices qui sont comparables aux plus grands bâtiments historiques par leur sens de beauté et l'émotion qu'ils évoquent. Ces lois sont en accord avec l'architecture Classique, Byzantine, Gothique, Islamique, Orientale, et Art Nouveau; mais pas avec les formes architecturales des 70 dernières années. Apparemment, l'architecture moderne du 20ième siècle contredit intentionnellement toutes les autres formes d'architecture en niant l'ordre structurel.

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