Complexity in Architecture and Design

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Architecture is successful by connecting visually, emotionally, and viscerally with the observer/user through its complexity. For this reason, complexity is a generative tool. All traditional societies developed an individual architectural form language, transitioning into the complex design language of artifacts and the arts. Internationalization in the early twentieth century erased all of those traditions, with a vast concomitant reduction in design complexity. How do we re-embody complexity into architectural form, space, and surface? Intelligent guidelines come from science. First, we can distinguish between different types of complexity, something that few people have been clear about. Second, we estimate the degree of complexity using a simple model. Organized complexity elicits a harmonious response; versus disorganized complexity that is perceived as randomness. Only the former produces an emotionally nourishing state in human beings, whereas randomness increases anxiety. An architect needs to understand complexity: its intentional generation, and how to manage emergent complexity as a design tool. It is essential to stop using complexity as a metaphor detached from reality, in a random process without any underlying reasoning, and adopt instead a practitioner's perspective.
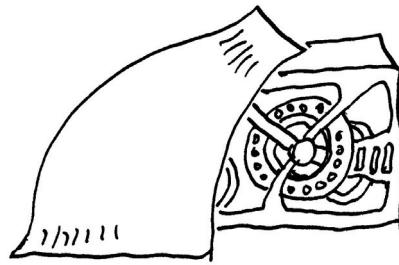

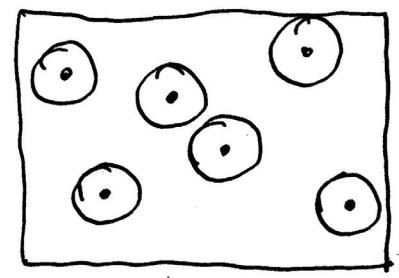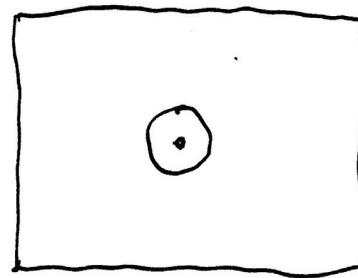*Figure 1. This system's organized complexity is hidden behind a misleadingly simplistic cover.*

Figure 2. Verbal descriptions of complexity. Left: "Circle of radius 1 in center". Right: "Circle of radius 1 centered at point A, circle of radius 1 centered at point B, circle of radius 1 centered at point C, ..."

Defining Complexity

Complexity represents intricacy of structure, stored information on how the system actually works and its own makeup. This internal complexity is independent of whether the system "looks" complex or not. Something empty, excessively plain, containing no structural information, is not complex. The system itself would not exist without a sufficient internal complexity to make it run or stand up structurally. Disguising complexity is not really being honest about the design, yet the visual surface information of some man-made architectural and design objects is kept low for stylistic reasons.[1] As architects place an inordinate emphasis on visual appearance, a confusion about superficial "look" versus substance permeates and disorients many discussions of complexity in architecture.

A useful but limited measure of complexity is the Kolmogorov-Chaitin complexity: how many words are needed for a fairly accurate description.[2] For example, on a blank or uniform computer screen, where all the pixels are exactly the same color, the complexity is zero, since the whole can be specified by a single word (the color of the screen). I have taught this model in Architecture Class, asking my students to catalogue the elements of a form language that was used to construct their favorite building.[3] Descriptions varied from one to four pages, since students chose very different buildings. The students then did a word count of their description. The raw word count measured the degree of complexity of their building. Clearly, minimalist buildings required only a very brief description, hence a low word count; whereas complex buildings needed more description, giving a higher word count.

Two Types of Complexity: Disorganized Versus Organized

Having established the two opposites of *low* versus *high* complexity according to the word count of their description, it's time to clarify a longstanding enigma of complexity theory. There exist two entirely distinct types of complexity: *disorganized* and *organized*.[4] Both types require a high word count when describing examples, but have distinct internal mathematical structure. They represent departures from low-complexity minimalist structures, yet the way their respective complexity is generated is very different.

We can describe a complex structure, but only up to a point, beyond which a complete description exceeds our
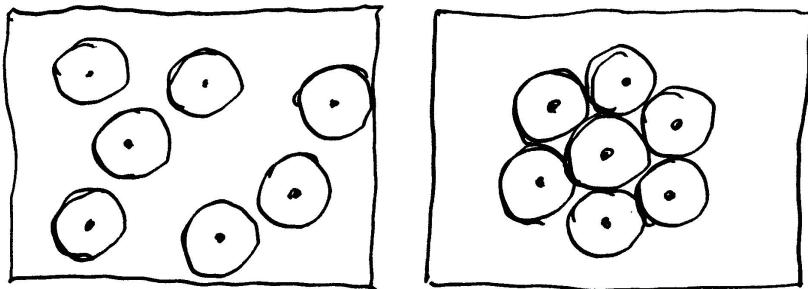
Figure 3. Disorganized versus organized. Left: seven circles centered on different points. Right: seven circles arranged in a rotationally-symmetric pattern. The same raw complexity, but different organization.
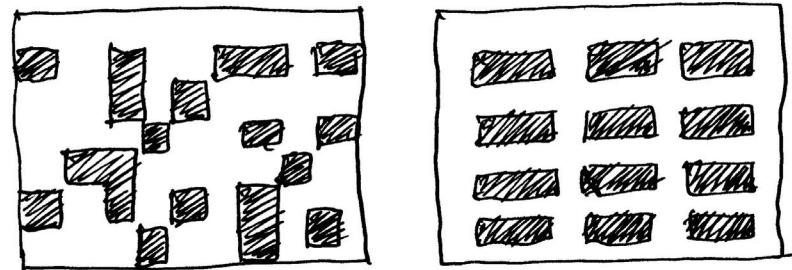

Figure 4. Organization economizes description. Left: each subunit has to be individually specified. Right: one basic subunit repeated vertically and horizontally.

capacity. Take a computer screen for example. The most complex case would show a perceivable random pattern: to describe this requires specifying each and every distinct portion of the image. That's a lot of information. Organized complexity avoids informational overload. Any image that has organized patterns, regularity, or represents some cognitively graspable information needs a far shorter informational description. (But be careful, since if every pixel on the screen is random, we cannot distinguish it from its neighbors, and only see the overall screen as uniformly gray, which has zero complexity).

Organizing complexity reduces the raw amount of information that is needed to specify an object or system. The human cognitive system is able to comprehend complexity only if it's organized in some way.

There exist many ways of doing this, involving continuity, different types of symmetries, scaling, correlations, harmony, etc. All of these have been invented and applied at some time in the past in creating traditional art, artifacts, and architecture. They form an essential part of the human creative heritage. And they also correspond directly to how complexity is organized in natural settings, including in organisms. Since our perceptive systems evolved to interpret our natural surroundings and other life forms, we resonate with organized complexity but are alarmed by disorganized complexity.

The Organization of Complexity

The Kolmogorov-Chaitin complexity (i.e., the length of its description) is a first step in measuring a system's complexity. To what extent existing complexity is organized still has to be measured by using entirely different tools. We need to determine—and somehow measure—the organization of a complex structure. Specific design and structural features organize design components, and distinguish ordered from disordered forms. We can count the organizing features, or estimate their number as either low or high. Those tools include the following:

A. Linear continuity among different pieces: forms flow into their neighbors and do not break off abruptly.

B. Different symmetries on the same scale: translational (moving along a single line); reflectional (mirror); rotational; glide reflections (move along some distance then reflect).

C. Scaling symmetry: the same or similar form repeats at a higher or lower magnification, which links two or more scales together visually.

All of these methods help to organize visual complexity through symmetry mechanisms acting on different scales. Moreover, our perceptive system is designed (evolved!) to recognize the above symmetries automatically. Objects lacking such organizing mechanisms are perceived as random, disordered, not stably put together. This impression most often causes alarm.
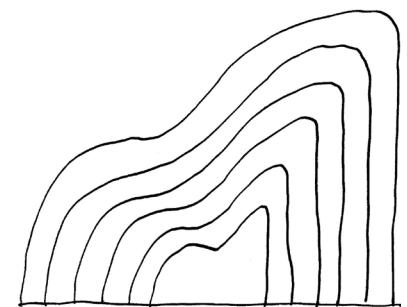

Figure 5. Scaling symmetry relates similar shapes at different sizes.

Monotonous Repetition and Informational Collapse

Symmetries in structures and designs repeat portions that are "symmetric." Translational symmetry repeats units along a line; rotational symmetry repeats units after a rotation by some angle; reflectional symmetry uses the mirror image to complete the other half of the design; etc. Generating larger structures via symmetries is a useful tool for creating complex objects from smaller units.

Nevertheless, a careless use of symmetries to generate larger-scale forms leads to informational collapse: when the information contained in the whole is no more than that contained in the repeating unit used to generate it5. Then, the information of the whole collapses into that of the single unit. Say that a repeating unit has information content X. According to the Kolmogorov-Chaitin complexity, the description of the whole would be "repeat X a number of times in this direction", which is no more complex than the original unit.

The phenomenon of "monotonous repetition" affects human perception responding to designs and structures in the built environment. Confronted with objects that repeat without variation, we feel that they are boring, uninteresting, depressing, and even oppressive if large enough. This is simply a reaction to the lack

of complexity defined on the large scales: complexity could exist on the smaller scale (the scale of a unit), which is repeated to generate the larger scale, but nothing intrinsic to the large scale. Worst of all is when giant structures monotonously repeat an empty module. Complexity that is most psychologically satisfying exhibits information on each and every scale.

The twentieth century's fascination with industrial mass-production celebrates a design complexity for architectural and city form that embodies monotonous repetition and informational collapse. From

Figure 6. Monotonous repetition of a unit without any variation is subject to informational collapse.

Figure 7. Variation of a repeating unit prevents informational collapse and helps to stably define the larger scale.

repeating blocks of social housing, to the vertically-repeating stories of a rectangular glass skyscraper, to the repeating cookie-cutter houses in suburban sprawl, our environment suffers from complexity deficit on some levels, and complexity overload on others. Consequently, the industrial large-scale has no intrinsic complexity: any complexity (or not) is contained in the repeating unit.

Adaptive design responds to different forces acting on many different scales; therefore, by definition, it is incapable of generating monotonous repetition. Designing a doorframe, a room, a house, an apartment build-

ing, or a cluster of buildings surrounding an urban space should pay attention to human sensibilities to spaces, circulation realms, pedestrian movement, the physical fit to the human scale, etc. These design forces acting together on different scales guarantee that the result will exhibit complexity on every distinct scale of the structure, and this is what we find in traditional architecture and urban design, and also in the layout of informal settlements.

The industrialization of design does not permit such a multiplicity of scales, nor the differentiation of complexity on each scale. The industrial practice in fact suppresses the natural response to adaptive design forces, in order to make a formal geometrical statement. Such mechanical typologies exhibiting informational collapse have become standard in the twentieth century. Consequently, students find this discussion disturbing because it forces them to reconsider design principles that were presented as fundamental.

Symmetry Breaking: Variation within Symmetry

How then do we build up a larger-scale complex whole using repeating individual units? The answer is again to be found in cultural artifacts and traditional methods of design. We simply vary the repeating units suffi-
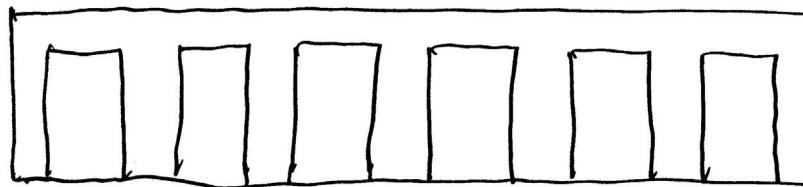
ciently to distinguish them from each other, but not enough so as to remove their basic similarity.[6] That is, we make small changes among units that are the same on a particular scale. Use the convenience of repeating the same unit, but then distinguish units through variations on different scales. This is called "breaking the large-scale symmetry," since an otherwise perfect symmetry (translational, rotational, reflectional, etc.) is no longer strictly valid, although it obviously still dominates.
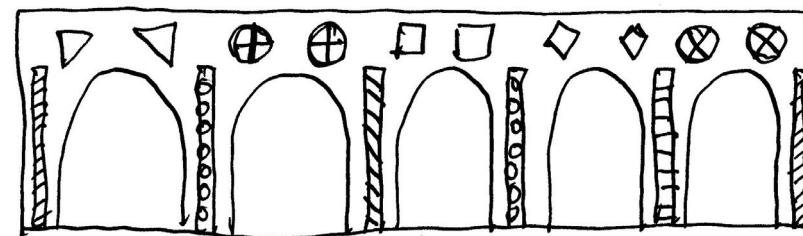
Limited variation on a smaller or larger scale (symmetry breaking) prevents informational collapse. If we break the repetition symmetry, then we require additional information to specify the whole structure, more than was necessary when perfect symmetry was present. It is still much more economical to build up complex structures through combinations and ordering rather than to have an entirely random structure, since the approximate symmetry saves an enormous amount of information specifying the overall complexity.

Traditional artifacts from all over the world such as pottery, carvings, textiles, and oriental carpets show, upon closer inspection, that every repeating unit has been made slightly different in order to prevent informational collapse. Vernacular architectures are replete with approximate symmetries and more formal architectures often

exhibit requisite variety: e.g., individualized Byzantine and Romanesque capitals; imperfectly symmetrical Gothic façades; architectural elements repeated with variations; etc.

And symmetry breaking also makes sense from an informational point of view. One intuitively expects that a large-scale complex whole will have much more information content than a single unit used to generate it: there should be a match between amount of complexity corresponding to the size of the system. By breaking the symmetry through the injection of additional information on smaller scales, there is indeed more information contained in the large-scale system than was present in an isolated unit.

Complexity and Life: Biophilic Patterns

Life is the transformation of energy into information. Organisms developed a means of preserving their discovered/evolved structure by means of genetic information. Otherwise, each life form would be accidental, extremely primitive, and exist only briefly. Life as we know it, with its continuity and evolutionary mechanisms striving towards greater complexity and systemic sophistication, would not exist.

A lot of information needs to be specified when constructing a living organ-

ism. The encoding of the structural complexity had better be efficient; otherwise the genetic blueprint could not be transmitted. We know that patterns of organized complexity (rather than disorganized random patterns) are more efficiently transmitted. Thus, complex blueprints can be coded, but not if every single molecule has to be independently specified. For this reason, we see the same types of regularity and symmetries in living forms as are found in traditional art and artifacts (albeit in more sophisticated yet approximate versions in Nature).

Discovered complexity is also culturally transmitted, mimicking the genetic transmission of biological complexity. Patterns represent repeating groups of codified information. Non-visual patterns are recurring socio-geometrical solutions found across different regions, climates, and cultures. Traditional practices discovered invariant design solutions for how human beings live better, whose biological basis is now being discovered in the new discipline of Biophilia.[7] Biophilia privileges an environment rich in complex patterns over plain industrial surfaces, independently of style.

Biophilic patterns have been shown to be clinically healing: exposure to the patterns of living forms helps accelerate post-operative recovery.[7] The measured effect is noticeable, though

less pronounced, with surrogate natural settings. Thus, a particular type of organized complexity present in our environment is essential for our health.

Three Factors Estimate the Degree of Organized Complexity

First, there is the raw information content: how many things are happening, such as internal differentiations, number and variety of components, contrasting elements, etc. Elsewhere, I have termed this aspect of systems the "architectural temperature."[4,8] Second, organization arises from symmetries and connections of all types, and this other quality of a coherent system is measured by the number of such organizing mechanisms. We can estimate whether a system has a small or large number of internal symmetries that tie all its components together into an easilygraspable whole.

This aspect of form I call "architectural harmony."[4,8] The simplest measure of organized complexity is to estimate both "architectural temperature" and "architectural harmony" on a scale of 0 to 10, then multiply those two numbers together. This gives a number corresponding to how much complexity there is, and how well it is organized. A complex but disordered form will score low in this model. So will an empty, minimalist form. Only

structures with evident complexity that is well organized will score high. Countless examples from historical and vernacular architectures all score high on this scale.[4, 8]

Third, the degree of organized complexity increases as the number of distinct structural scales increase. This is yet another independent factor. It relates to scaling symmetry, which can act to make a form more coherent only if there exists a sufficient number of scales. Therefore, an additional question to ask is: how many different recurrent sizes are well defined in a structure?[9] In nature (both in biological and inanimate forms), structure is clearly defined on all scales, from the size of an object down to its microstructure. We keep seeing more organized (not random) structure the more we magnify it. The more scales we perceive, the higher the complexity. If, in addition, the distinct scales are related by scaling symmetry, then the form has an additional dimension of organization.

For example, a house or two-storey building from before the twentieth century will show up to ten different scales, as defined by its forms, subdivisions, materials, construction components, etc. A traditional artifact—whether a utilitarian tool or a strictly ornamental object—will also exhibit up to 10 scales if we examine it up close with a magnifying glass.

It's no accident that well-loved artifacts and architectural interiors are made from natural materials such as polished stone and wood, which show fine-grained natural patterns. Unlike industrial materials, these continue the scaling hierarchy downwards into the microscopic scales. Glass, steel, titanium, and concrete, in contradistinction, show no ordered microstructure.

The "machine aesthetic" that came to dominate design in the twentieth century eliminates multiple scales in structures. The typical number of scales in a "designed" object or contemporary building tends to be closer to two rather than the number ten for traditional structures and artifacts. The more natural subdivision of a form into its components on a hierarchy of decreasing scales is avoided. Nevertheless, human beings perceive the machine aesthetic as unnatural, precisely because it lacks the hierarchy of scales common with natural structures. Regardless of the dominant aesthetic, which influences individual taste, our neurophysiology is tuned to recognize a natural scaling hierarchy.[10]

Hierarchy of Structural Scales

There is a structural reason for why complexity should be organized. In random, disordered structures each part is independent, and certainly does not support the other parts in

any way, visually or structurally. A complex whole in which the parts are unrelated would not hold together. And this is just for the static structure: disorganization is totally nonsensical in a dynamic system that has to work through multiple mechanisms. Therefore, the organization of structural complexity is a prerequisite of all complex structures.

It happened through historical accident that architects in the late twentieth century began to celebrate disconnected forms, following an earlier cue from fine artists who had abandoned all attempts at "natural-looking" art. So, now we are used to seeing buildings without internal coherence, in which the structural engineer uses a contortionist's toolkit of tricks to make the design stand up without revealing its structural system. This clever feat nevertheless

serves a stylistic agenda and does not help to understand a form's complexity.

What interests us here is the dependence of distinct scales upon one-another. We discussed above how larger-scale structures could arise from combining smaller-scale units in a coherent manner. The generating symmetries are determined by adapting to the design forces. This is an essential mechanism for building organized complexity that is valid across all scales. Formal design could be useful for reducing randomness through ordering, but should not be imposed (as was the case during much of the twentieth century). The larger scales in a hierarchy thus invent new information not present in the smaller units, so that the structure shows emergent properties.
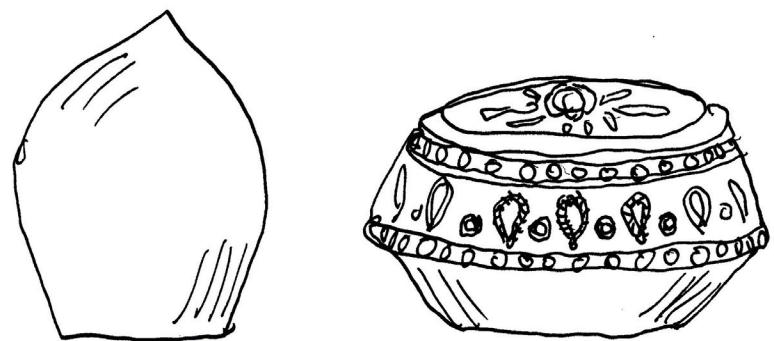

Figure 8. LEFT: minimalist design exhibits only one scale. RIGHT: traditional artifact shows 6 obvious scales, with 3 more if examined more closely.

At the same time, large-scale units by themselves cannot define a coherent design. Adapting to forces acting on all scales (a necessity for natural forms as well as in traditional and vernacular architectures), units have to accommodate a variety of forces acting on scales both smaller and larger than themselves. This requires plasticity and adaptation of larger forms so as to create a supportive framework on a smaller scale. Thus, adaptation necessarily generates smaller scales.

The corollary is also true: ruling out the smaller scales for stylistic or dogmatically ideological reasons guarantees that the forms can never adapt to all the design forces of the problem. You either adapt to the system's needs, or ignore them to impose your own design idea. This conclusion contradicts one of the founding principles of modernism, but there is no way to deny it.

How Can Architects Use Organized Complexity? Fractals and Alexander's 15 Properties

Ever since the early twentieth century, the overwhelming influence of industrialization and mass-production (and its associated way of thought) imposed changes on design that marked world architecture. This determining phenomenon of the architectural profession is best understood from the point of view of complexity.

If an architect is convinced to try and use organized complexity again in architecture, there are several handy tools available. One set of methods comes from mathematical fractals, which are objects that repeat similar patterns on increasing and decreasing scales. The idea here is to situate scaling symmetry at the heart of design, but only in an approximate, adaptive manner. Introduce many different scales in a structure—as required to make it more adaptive to the users—and strive for coherence across different scales. Practical design tools using fractals can make a design healthier for the user, since they generate biophilic patterns. [7, 11]

Another, related set of methods was developed by Christopher Alexander when he discovered what geometrical properties characterize organized complexity in all systems. He has distilled a working toolkit into his "Fifteen Fundamental Properties," which are essential features of both natural and man-made coherent systems.[12, 13] One property is scaling hierarchy; another is the need for contrast; yet another is the presence of abundant local symmetries but the relative insignificance of an overall symmetry; etc. A designer can use these either as tools to help guide the project towards increasing coherence; or as a check to see that competing design forces are properly accommodated.

A student might well ask: where have these fifteen morphological properties been all along for the past century of architectural training? They seem too important to be ignored; yet there is no mention of them anywhere. My answer will surprise some. Designers and architects have indeed developed an intuitive grasp of the fifteen properties, but only in order to violate them. The reason is that innovation in design has for the past many decades been judged by how far it deviates from and opposes natural order. Thus, anybody wishing to distinguish their designs from nature necessarily does the opposite of the fifteen properties, whose cumulative effect is organized complexity.[14]

Having worked with Alexander for years, I have tried to relate his 15 properties to organizing concepts in mathematics and physics to get a better grasp of their universal nature. An interested reader can follow those connections with my own "Three Laws of Architecture."[13, 14] Those postulate the essential need for a scaling hierarchy, how units couple through contrast, and how large-scale order is established through symmetries and alignment.

All of these ideas—Alexander's "fifteen properties," my "three laws," biophilic patterns, scaling coming from mathematical fractals, rules for the generation and organization of complexity—are mutually-supporting, complementary aspects of a new and comprehensive design method. New in that it differs from both the early twentieth-century modernist and the late twentieth-century postmodernist and deconstructivist
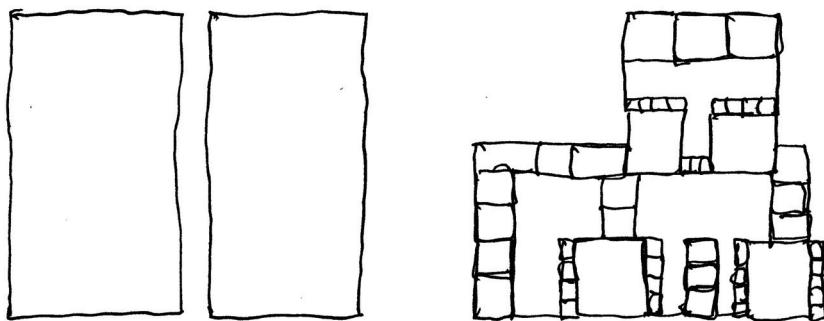

Figure 9. In order to adapt to forces acting on all scales, large-scale units partially break themselves up and generate supportive smaller-scale components.

design typologies, yet not really new since it relates strongly to traditional design methods. Nevertheless, these new design tools are not meant to reproduce traditional buildings, but to create new, innovative structures that adapt to human use and sensibilities.

Fractal patterns and cellular automata are capable of generating a new type of mathematical ornament. Biophilic information is mimicked using color, detail, variation (symmetry breaking), curves, and variety of materials within adaptive design rules. Lacking this range of scales in organized complexity from 1 millimeter–20 centimeters, even the more interesting buildings of the past few decades are disconnected from the small scale, and hence from intimate human experience.

Irrelevant and Possibly Damaging Complexity

Every design problem has to organize competing forces acting on many different scales: adapting the design to them generates emergent solutions incorporating a high degree of organized complexity. This complexity evolves from the process of adaptation. While there is no unique end-result, there are only a relative handful of optimal designs, which could however look very different. They all have in common a high degree of organized complexity that accommodates structural integrity, activities, and sustainability of the form.

When we instead see complexity imposed for reasons of fashion, having nothing to do with the multiple design forces, something is not right. The built configuration will always be at odds with the normal forces of the situation, which can never be satisfied. Form contradicts function. This much may be suspected from the homogeneous forms of excessively formal design. Some contemporary buildings have a more subtle contradiction because there is clearly complexity in the built form, yet this complexity is just as arbitrary for function as in the minimalist case. But now it's deceptive because it "looks" complex.

Disorganized complexity tends to be arbitrary, random, and willful. It

tires us, because we try to find meaning where none is present. There is an additional danger with injected random complexity, because it easily creates disturbing imbalances. Our experience of symmetries depends upon physiology: the vertical axis is tied to our inner-ear mechanism, so that leaning, unbalanced, or twisted buildings can generate nausea, alarm, and physiological distress.

Conclusion

Recent years have produced a remarkable development in understanding complexity, and in translating results from mathematics and science into practical design tools. Natural structure suggests the necessity for differentiation, followed by collective organization marked by a high degree of multiple symmetries. Architectural evidence reveals the principle of broken symmetry as a key feature of buildings that mimic living structure.

It's of course up to the individual architect to decide whether to apply these methods or not. Many students, teachers, and practitioners are unfortunately still tied to dictates of "style," even as it is becoming increasingly obvious that such an approach does not lead to adaptive, long-term sustainable architecture. Hopefully, the younger generation is becoming aware of the tremendous opportunities for new design thinking made possible by this input from the sciences.
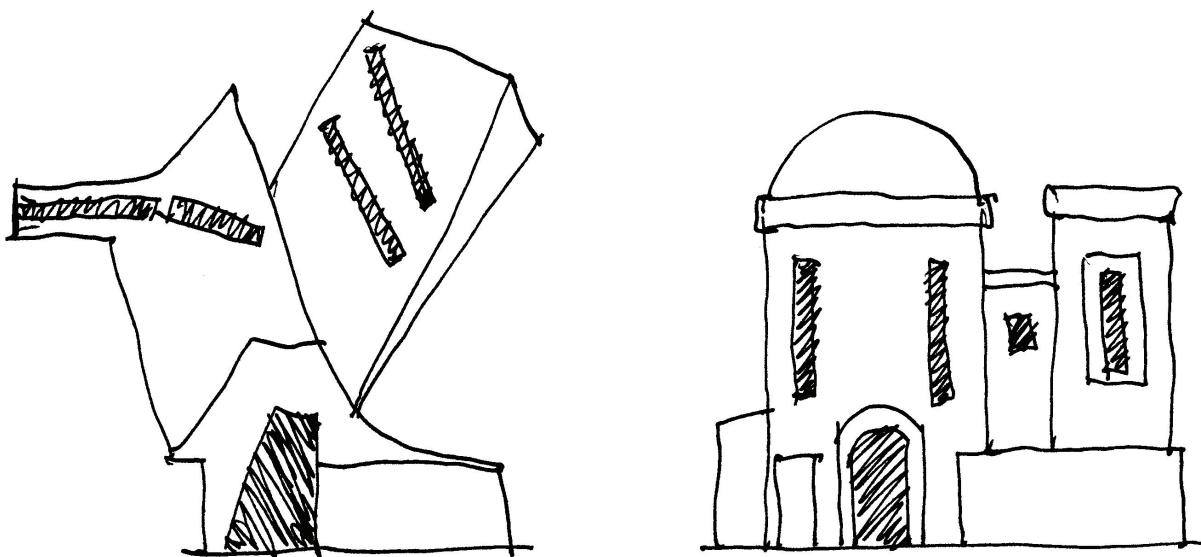

Figure 10. LEFT: disorganized complexity injected into a design for stylistic effect conflicts with the system's forces. RIGHT: design that evolves from adapting to the system's forces generates organized complexity.

Image credits
All line drawings are by the author.

Notes
(Further Reading from the Author's Books)

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2. Nikos Salingaros, "Kolmogorov-Chaitin Complexity," *Meandering Through Mathematics,* September 2012. Reprinted as Chapter 9 of *Unified Architectural Theory,* Sustasis Press, 2013.

3. Nikos Salingaros, "Documenting a Form Language and Estimating Its Complexity," Chapter 37 of *Unified Architectural Theory,* Sustasis Press, 2013.

4. Nikos Salingaros, "Life and Complexity in Architecture from a Thermodynamic Analogy," Chapter 5 of *A Theory of Architecture,* Sustasis Press, 2006.

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6. Nikos Salingaros, "Symmetries and the Value of Ornament," Lecture 9 of *Algorithmic Sustainable Design: Twelve Lectures on Architecture,* Sustasis Press, 2010. Online video lecture <http://zeta.math.utsa.edu/~yxk833/algorithmic.html>

7. Nikos Salingaros, "Biophilia", Chapters 16 & 17 of *Unified Architectural Theory,* Sustasis Press, 2013.

8. Nikos Salingaros, "Organized Complexity and a Model That Estimates Life in Architecture", Chapter 21 of *Unified Architectural Theory,* Sustasis Press, 2013.

9. Nikos Salingaros, "Hierarchical Cooperation in Architecture", Chapter 3 of *A Theory of Architecture,* Sustasis Press, 2006.

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12. Nikos Salingaros, "Alexander's Fifteen Fundamental Properties," Chapter 19 of *Unified Architectural Theory,* Sustasis Press, 2013.

13. Nikos Salingaros, "Universal Morphological Rules," Lecture 6 of *Algorithmic Sustainable Design: Twelve Lectures on Architecture,* Sustasis Press, 2010. Online video lecture <http://zeta.math.utsa.edu/~yxk833/algorithmic.html>

14. Nikos Salingaros, "The Laws of Architecture From a Physicist's Perspective,, Chapter 1 of *A Theory of Architecture,* Sustasis Press, 2006.