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# Digital Morphogenesis and Computational Architectures

## Abstract

This paper examines methods in which digital media is employed not as a representational tool for visualization but as a generative tool for the derivation of form and its transformation - the digital morphogenesis. It explores the possibilities for the "finding of form," which the emergence of various digitally based generative techniques seem to bring about. It surveys the digital generative processes - the computational architectures - based on concepts such as topological space, isomorphic surfaces, kinematics and dynamics, keyshape animation, parametric design, and genetic algorithms.

## Resumo

*Este trabalho analisa métodos nos quais a mídia digital não é empregada como uma forma de representação, mas como geradora de derivações da forma e de suas transformações - a morfogênese digital. Exploram-se as possibilidades para a "busca da forma", alavancada pelo aparecimento de várias técnicas baseadas na criação digital. Esse trabalho pesquisa o processo de geração digital - as arquiteturas computacionais - baseado em conceitos como espaço topológico, superfícies isomórficas, cinemática e dinâmica, animações "keyshape", design paramétrico e algoritmos genéticos.*

## 1. Introduction

As digital infrastructures are being inscribed into cities and buildings, new forms and methods of spatial organizations are emerging (Mitchell 1995). Technological architectures are being replaced by computational architectures of topological, non-Euclidean geometric space, kinetic and dynamic systems, and genetic algorithms. According to Peter Zellner (1999), "architecture is recasting itself, becoming in part an experimental investigation of topological geometries, partly a computational orchestration of robotic material production and partly a generative, kinematic sculpting of space."

The Information Age, like the Industrial Age before it, is therefore not only challenging what we are designing but also how we design. The generative and creative potential of digital media is opening up new emergent dimensions in architecture. As seen by Bart Lootsma (Zellner 1999), "instead of trying to validate conventional architectural thinking in a different realm, our strategy today should be to infiltrate architecture with other media and disciplines to produce a new crossbreed."

## 2. Computational Architectures

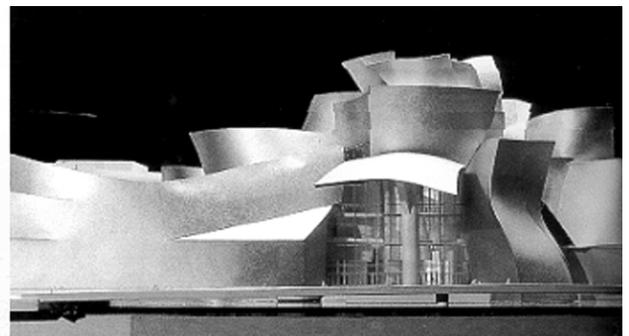
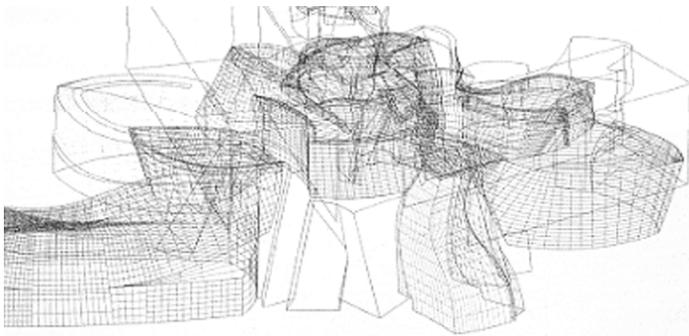
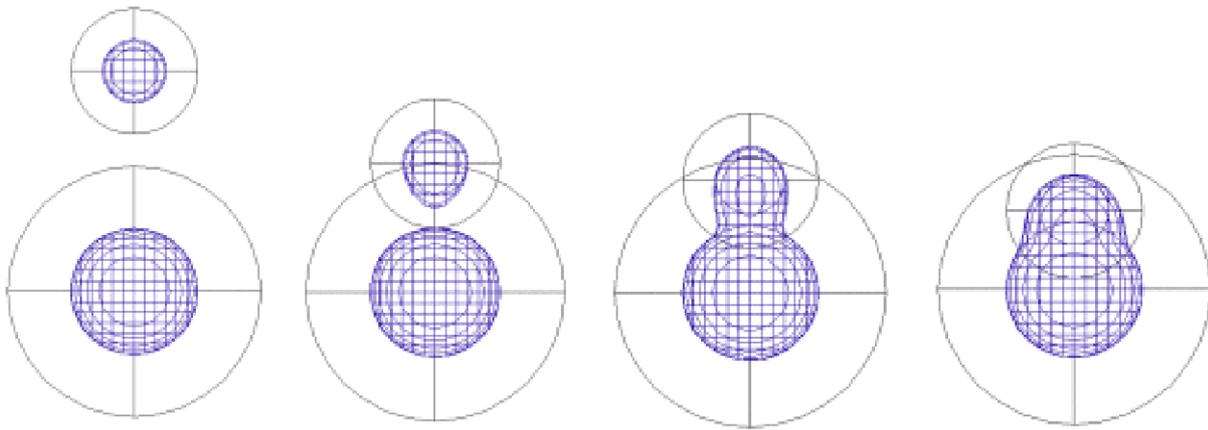


Figure 1. Topological architecture: Gehry's Guggenheim Museum in Bilbao.



Figur 2. Isomorphic surfaces.

Computational architectures refer to the computationally based processes of form origination and transformations - the digital morphogenesis. Several computational architectures are identified based on the underlying concepts such as topological space (topological architecture), isomorphic surfaces (isomorphic architecture), motion kinematics and dynamics (animate architecture), keyshape animation (metamorphic architecture), parametric design (parametric architecture), and genetic algorithms (evolutionary architecture), as discussed in the following sections.

## 2.1 Topological architecture

Greg Lynn's essay (1993) on "architectural curvilinearity" is one of the first examples of the new topological approach to design that moves away from the then dominant deconstructivist "logic of conflict and contradiction" to develop a "more fluid logic of connectivity," manifested by continuous, highly curvilinear surfaces (figure 1).

The defining element of the topological architecture is its departure from the Euclidean geometry of discrete volumes represented in Cartesian space, and the extensive use of topological, "rubber-sheet" geometry of continuous curves and surfaces, mathematically described as NURBS - Non-Uniform Rational B-Spline curves and surfaces. In the topological space, geometry is represented not by implicit equations, but by parametric functions, which describe a range of possibilities (Piegl and Tiller 1997).

The shape of a NURBS curve or surface is controlled by manipulating the location of control points, weights, and knots. NURBS make the heterogeneous, yet coherent forms of the topological space computationally possible. By changing the location of control points, weights, and knots, any number of different curves and surfaces could be produced.

## 2.2 Isomorphic architecture

Isomorphic surfaces represent another point of departure from the Euclidean geometry and the Cartesian space. Blobs or metaballs, as isomorphic surfaces are sometimes called, are amorphous objects constructed as composite assemblages of mutually inflecting parametric objects with internal forces of mass and attraction. They exercise fields or regions of influence, which could be additive (positive) or subtractive (negative). The geometry is constructed by computing a surface at which the composite field has the same intensity - hence the name - isomorphic surfaces (figure 2).

Isomorphic surfaces open up yet another formal universe where forms may undergo variations giving rise to new possibilities. Objects interact with each other instead of just occupying space; they become connected through logic where the whole is always open to variation as new blobs (fields of influence) are added or new relations made, creating new possibilities. The surface boundary of the whole (the isomorphic surface) shifts or moves as fields of influence vary in their location and intensity. In that way, objects begin to operate in a dynamic rather than a static geography.

## 2.3 Animate architectures

Greg Lynn (1999) was one of the first architects to utilize animation software not as a medium of representation, but of form generation. According to Lynn, the prevalent "cinematic model" of motion in architecture eliminates the force and motion from the

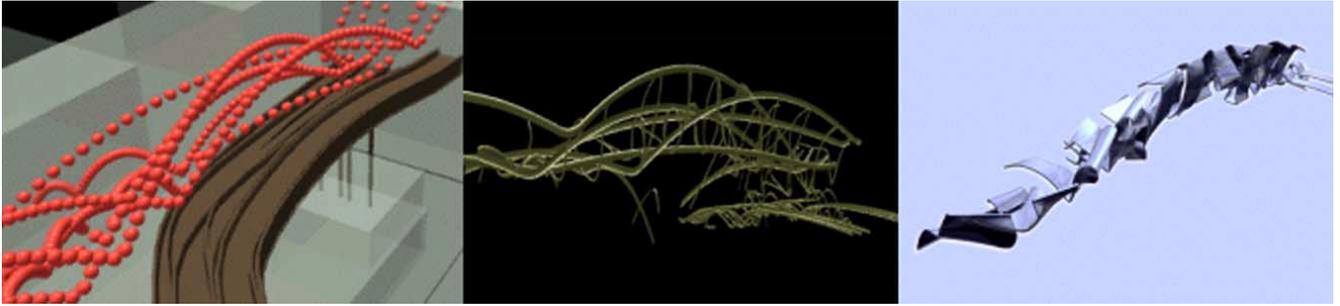


Figure 3. Animate architecture: Lynn's Port Authority Bus Terminal in New York.

articulation of form and reintroduces them later, after the fact of design, through concepts and techniques of “optical procession.” In contrast, argues Lynn, “animate design is defined by the co-presence of motion and force at the moment of formal conception.” Force, as an initial condition, becomes “the cause of both motion and particular inflections of a form.” According to Lynn, “while motion implies movement and action, animation implies evolution of a form and its shaping forces.”

In his projects, Lynn utilizes an entire repertoire of motion-based modeling techniques, such as keyframe animation, forward and inverse kinematics, dynamics (force fields) and particle emission. Kinematics is used in animation in its true mechanical meaning: to study the motion of an object or a hierarchical system of objects without consideration given to its mass or the forces acting on it. As motion is applied, transformations are propagated downward the hierarchy in forward kinematics, and upward through hierarchy in inverse kinematics. In some of Lynn's projects, such as the House Prototype in Long Island, skeletons with a global envelope are deformed using inverse kinematics under the influence of various site induced forces.

In contrast to kinematics, the dynamic simulation takes into consideration the effects of forces on the motion of an object or a system of objects, especially of forces that do not originate within the system itself. Physical properties of objects, such as mass (density), elasticity, static and kinetic friction (or roughness), are defined. Forces of gravity, wind, or vortex are applied, collision detection and obstacles (deflectors) are specified, and dynamic simulation computed. Greg Lynn's design of a protective roof and a lighting scheme for the bus terminal in New York (figure 3) offers a very effective example of using particle systems to visualize the gradient fields of “attraction” present on the site, created by the forces associated with the movement and flow of pedestrians, cars, and buses on the site.

## 2.4 Metamorphic architecture



Figure 4. Parametric architecture: Marcos Novak's “algorithmic spectaculars.”

Metamorphic generation of form includes several techniques such as keyshape animation, deformations of the modeling space around the model using a bounding box (lattice deformation), a spline curve, or one of the coordinate system axis or planes, and path animation, which deforms an object as it moves along a selected path.

In keyshape animation, changes in the geometry are recorded as keyframes (keyshapes) and the software then computes the in-between states. In deformations of the modeling space, object shapes conform to the changes in geometry of the modeling space.

## 2.5 Parametric architecture

In parametric design, it is the parameters of a particular design that are declared, not its shape. By assigning different values to the parameters, different objects or configurations can be easily created. Equations can be used to describe the relationships between objects, thus defining an associative geometry, i.e., the “constituent geometry that is mutually linked” (Burry 1999). That way, interdependencies between objects can be established, and objects’ behavior under transformations defined. As observed by Burry (1999), “the ability to define, determine and reconfigure geometrical relationships is of particular value.”

Parametric design often entails a procedural, algorithmic description of geometry. In his “algorithmic spectaculars” (Figure 4), i.e., algorithmic explorations of “tectonic production” using Mathematica software, Marcos Novak (1996) constructs “mathematical models and generative procedures that are constrained by numerous variables initially unrelated to any pragmatic concerns ... Each variable or process is a ‘slot’ into which an external influence can be mapped, either statically or dynamically.” In his explorations, Novak is “concerned less with the manipulation of objects and more with the manipulation of relations, fields, higher dimensions, and eventually the curvature of space itself.” The implication is that the parametric design doesn’t necessarily predicate stable forms. As demonstrated by Burry (1999), one can devise a paramorph - an unstable spatial and topological description of form with stable characteristics.

## 2.6 Evolutionary architecture

Evolutionary architecture proposes the evolutionary model of nature as the generating process for architectural form (Frazer 1995). In this approach to design, according to Frazer, “architectural concepts are expressed as generative rules so that their evolution and development can be accelerated and tested by the use of computer models. Concepts are described in a genetic language which produces a code script of instructions for form-generation. Computer models are used to simulate the development of prototypical forms which are then evaluated on the basis of their performance in a simulated environment. Very large numbers of evolutionary steps can be generated in a short space of time and the emergent forms are often unexpected.”

The key concept behind evolutionary architecture is that of the genetic algorithm, “a class of highly parallel evolutionary, adaptive search procedures,” as defined by Frazer. Their key characteristic is a “a string-like structure equivalent to the chromosomes of nature,” to which the rules of reproduction, gene crossover, and mutation are applied. Various parameters are encoded into the “a string-like structure” and their values changed during the generative process. A number of similar forms, “pseudo-organisms,” are generated, which are then selected from the generated populations based on predefined “fitness” criteria. The selected “organisms,” and the corresponding parameter values, are then crossbred, with the accompanying “gene crossovers” and “mutations”, thus passing beneficial and survival-enhancing traits to new generations. Optimum solutions are obtained by small incremental changes over several generations.

In the process of genetic coding, the central issue is the modeling of the inner logic rather than external form. Other equally important issues are the definition of often ill-defined and conflicting criteria and how the defined criteria operate for the selection of the “fittest”. Equally challenging is the issue of how the interaction of built form and its environment are transcribed into the morphological and metabolic processes.

## 3. Implications

### 3.1 Dynamics and the fields of forces

Greg Lynn’s work on “animate form” was very much inspired by D’Arcy Thompson “On Growth and Form” (1917), in which Thompson argues that the form in nature and the changes of form are due to the “action of force.” With his work on using motion dynamics to generate architectural form, Lynn has compellingly demonstrated what Nicholas Negroponte (1970) had only hinted at in his seminal work from some thirty years ago, “The Architecture Machine,” also acknowledged in Lynn’s writing:

“Physical form, according to D’Arcy Thompson, is the resolution at one instant of time of many forces that are governed by rates of change. In the urban context the complexity of these forces often surpasses human comprehension. A machine, meanwhile, could procreate forms that respond to many hereto un-manageable dynamics. Such a colleague would not be an omen of professional retirement but rather a tickler of the architect’s imagination, presenting alternatives of form possibly not visualized or not visualizable by the human designer.”

Lynn argues that “traditionally, in architecture, the abstract space of design is conceived as



Figure 5- Bernard's Cache "objectiles."

an ideal neutral space of Cartesian coordinates," but that in other design fields, "design space is conceived as an environment of force and motion rather than as a neutral vacuum." He makes an argument that "while physical form can be defined in terms of static coordinates, the virtual force of the environment in which it is designed contributes to its shape," thus making the forces present in the given context fundamental to the form making in architecture. Lynn attributes to this position the significance of a paradigm shift "from a passive space of static coordinates to an active space of interactions," which he describes as "a move from autonomous purity to contextual specificity." Instrumental to this conceptual shift is the use of digital media, such as animation software, which he uses as "tools for design rather than as devices for rendering, visualization, and imaging."

### 3.2 Emergence and the fields of indetermination

Topological space opens up a universe where essentially curvilinear forms are not stable but may undergo variations, giving rise to new possibilities, i.e., the emergent form. Designers can see forms as a result of reactions to a context of "forces" or actions, as demonstrated by Lynn's work.

There is, however, nothing automatic or deterministic in the definition of actions and reactions; they implicitly create "fields of indetermination" from which unexpected and genuinely new forms might emerge. The capacity of computational architectures to generate "new" designs is therefore highly dependent on designer's perceptual and cognitive abilities. Their generative role is accomplished through the designer's simultaneous interpretation and manipulation of a computational construct (topological surface, isomorphic field, kinetic skeleton, field of forces, parametric model, genetic algorithm, etc.) in a complex discourse that is continuously reconstituting itself - a 'self-reflexive' discourse in which graphics actively shape the designer's thinking process.

### 3.3 Mass customization

The numerically controlled production processes of the past decade, which afforded the fabrication of non-standardized repetitive components directly from digital data, introduced into architectural discourse the "mass-customization" (Mitchell 1999) and the new logics of "seriality," i.e., the local variation and differentiation in series. In process, building construction is being transformed into production of the differentiated components and their assembly on site, instead of the conventional manual techniques. This transformation of building design and construction into digitally driven production processes was famously manifested in Frank Gehry's buildings, with his Guggenheim Museum in Bilbao being the most dramatic recent example.

For Bernard Cache (1995), in parametric design "objects are no longer designed but calculated," allowing the design of complex forms with surfaces of variable curvature that would be difficult to represent using traditional drawing methods, and laying "the foundation for a nonstandard mode of production." His objectiles (figure 5) are non-standard objects, mainly furniture and paneling, which are procedurally calculated in Microstation and industrially produced with numerically controlled machines.

For Cache, it is the modification of parameters of design, often random, that allows the manufacture of different shapes in the same series, thus making the mass-customization, i.e., the industrial production of unique objects possible. In other words, it is now possible to produce "series-manufactured, mathematically coherent but differentiated objects, as well as elaborate, precise and relatively cheap one-off components," according to Peter Zellner (1999), who argues that in the process the "architecture is becoming like 'firmware,' the digital building of software space inscribed in the hardwares of construction."

## References

- Burry, Mark. (1999) "Paramorph." *AD Profile 139: Hypersurface Architecture II*. London: Academy Editions.
- Cache Bernard. (1995). *Earth Moves*. Cambridge: MIT Press.
- Frazer, John. (1995). *Evolutionary Architecture*. London: Architectural Association.
- Lynn, Greg. (1993). "Architectural Curvilinearity: The Folded, the Pliant and the Supple." *AD Profile 102: Folding in Architecture*. London: Academy Editions.
- Lynn, Greg. (1998). *Animate Form*. Princeton: Princeton Architectural Press.
- Mitchell, William. (1995). *City of Bits: Space, Place, and the Infobahn*. Cambridge: MIT Press.
- Mitchell, William. (1999). *E-topia*. Cambridge, MIT Press.
- Negroponte, Nicholas. (1970). *Architecture Machine*. Cambridge: MIT Press.
- Novak, Marcos. 1998. "Transarchitectures and Hypersurfaces." *AD Profile 133: Hypersurface Architecture*. London: Academy Editions.
- Perez-Gomez, A. and L. Pelletier. (1997). *Architectural Representation and the Perspective Hinge*. Cambridge: MIT Press.
- Perrella, Stephen (ed.). (1998). *AD Profile 133: Hypersurface Architecture*. London: Academy Editions.
- Piegl, Les, and Wayne Tiller. (1997). *The NURBS Book* (2nd ed.). New York: Springer.
- Saarinen, Aline (ed.). (1968). *Eero Saarinen on His Work*. New Haven: Yale University Press.
- Thompson, D'Arcy Wentworth. (1917). *On Growth and Form*. Cambridge (UK): Cambridge University Press.
- Zellner, Peter. (1999). *Hybrid Space: New Forms in Digital Architecture*. New York: Rizzoli International Publications.

## 4. Conclusion

Computational, digital architectures are profoundly changing the processes of design (and construction), but for many architects, trained in the certainties of the Euclidean geometry, the emergence of curvilinear forms poses considerable difficulties. In the absence of an appropriate aesthetic theory, the "hypersurface" forms (Perrella 1996) often seem to be utterly esoteric and spatially difficult to comprehend, and are often dismissed with as just another architectural "fad."

It is worth reminding that it was Le Corbusier's "free plan" and "free façade" that allowed for elements of variable curvature to emerge in the modernist projects of the mid-century. Eero Saarinen (1968) attributed the reemergence of the plastic form to the advances in building technology, while acknowledging "it is the aesthetic reasons which are driving forces behind its use." Saarinen is rather cautious in his use of plastic form, implying that it has a rather limited applicability and warning that the "plastic form for its own sake, even when very virile, does not seem to come off."

Saarinen's cautious approach to plastic form is exemplary of the apparent ambivalence of the modernists towards the curvilinear, an attitude that is still widely present. While it enabled them to break the monotony of the orthogonal and the linear, it also heralded the emergence of a new unknown geometry, about which they were still not sure (Cache 1995); the modernists "knew that they had, above all, to avoid two opposite pitfalls: a dissolution into the indefinite and a return to the representation of natural form," the former manifested in "the loss of form," and the latter in "the organicist maze into which art nouveau had fallen."

The skeptical, or at least ambivalent, attitudes towards the curvilinear are often compounded by a rather blasé attitude in contemporary critical discourse towards the ways ("methods") and means ("devices") of digital form generation, which intentionally seek indeterminacy in design processes. The accidental plays a rather prominent role in establishing the "fields of indetermination" from which genuinely new forms may emerge. Perez Gomez and Pelletier (1997) argue that tendency for accidental should be accepted as a legitimate design outcome, because the computer graphics systems impose a "homogenous space" that is "inherently unable to combine different structures of reference." As Mark Burry (1999) acutely points out, "emerging critical theory... has no embarrassment in accepting, or benignly accommodating or even celebrating the accident or the error," with the implication that the "intellectual value of a perverse giving-up of authorship ('design') is neither judged with quizzicality, nor seen as a potential artistic impropriety."

In summary, the computational architectures described in this paper necessitate certain design strategies that provide for a dynamic manipulation of the designs with a high degree of indeterminacy. The existence of such strategies is not seen as a limiting factor in design -unpredictability, uncertainty, and indeterminacy are still present, as are the possibilities for the "finding of form," which the emergence of these computationally based generative techniques seem to engender intentionally.