An Energy Centric Approach to Architecture

Abstracting the material to co-rationalize design and performance

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This paper begins by exploring matter as an aggregated system of energy transactions and modulations. With this in mind, it examines the notion of energy driven form finding as a design methodology that can simultaneously negotiate physical, environmental and fabrication considerations. The digital workspace enables this notion of form finding to re-establish itself in the world of architecture through a range of analytic tools that algorithmically encode real world physics. Simulating the spatial and energetic characteristics of reality enables virtual “form generation models that recognize the laws of physics and are able to create ‘minimum’ surfaces for compression, bending [and] tension” (Cook 2004). The language of energy, common in engineering and materials science, enables a renewed trans-disciplinary dialogue that addresses significant historic disjunctions such as the professional divide between architects and engineers. Design becomes a science of exploring abstracted energy states to discover a suitable resonance with which to tune the built environment.

A case study of one particular method of energy driven form finding is presented. Bi-directional Evolutionary Structural Optimization (BESO) is a generative engineering technique developed at RMIT University. It appropriates natural growth strategies to determine optimum forms that respond to structural criteria by reorganizing their topology. This dynamic topology response enables structural optimization to become an integrated component of design exploration. A sequence of investigations illustrates the flexibility and trans-disciplinary benefits of this approach. Using BESO as a tool for design rather than purely for structural optimization fuses the creative approach of the architect with the pragmatic approach of the engineer, enabling outcomes that neither profession could develop in isolation. The BESO case study alludes to future design processes that will facilitate a coherent unfolding of design logic comparable to morphogenesis.
1 Introduction
Negotiating design and performance with engineering and fabrication has been one of the central topics of contemporary architectural discourse. Driving this discussion is a growing awareness of ecology and sustainability, as global warming, rising fuel prices and renewable resources become central concerns of an increasingly energy conscious society and resource driven economy. Searching for solutions has revived interest in the synthesis of natural forms as a model for architectural design.

To engage the principles of natural systems for use beyond the metaphor, we are first required to distill phenomena such as self-organization to isolated systems that can be described and modeled. To translate the complex and emergent processes of morphogenesis into abstract models for use in architecture, we require a thorough understanding of the universal principles that order natural formations. What governs the arrangement of matter as structure and form and how can we codify these rules into feasible design models?

2 Matter, Structure and Form.
2.1 WHAT IS MATTER?
The search for a fundamental building block that constitutes the physical world has occupied philosophers and scientists alike. It would seem that understanding the physical is part way toward grasping the metaphysical and thus an attractive realm of inquiry for the curious human mind striving to comprehend its own being. String theory is a promising branch of theoretical physics that aims to describe a mathematically complete model of the universe. It draws from quantum mechanics to posit a theoretical explanation for the wave-particle duality, which suggests that all matter and energy exhibits both wave and particle properties. String theory argues that the materials, forms and forces of our reality, whether organic or inorganic, quantifiable or phenomenological are entirely comprised of discrete one-dimensional units. The properties of these fundamental units or ‘strings’ are governed by oscillations induced by tension and kinetic energy. Strings can vibrate in different modes. The resonating frequency or vibrational mode of a string determines the physical characteristics, features and attributes it manifests; for instance whether the string becomes an electron, proton, gluon etc. Viewed through this lens, matter is a cohesively operating network of discrete energy-states, synthesized by “modifications, perturbations, changes of tension or energy and nothing else” (Bergson 1896). Its innumerable permutations are all aggregates of the same fundamental building block differing only in levels of organization and order. Matter is defined and determined by energy.

2.2 FORCE AND ACTION
To describe the way in which strings move through space and time, string theory is formulated in terms of force and action. The calculations are fundamentally based on Lagrangian mechanics, which demonstrates that an object subjected to external influences (force) will follow a path that minimizes a certain quantity, its action.

Naturally occurring structures exhibit adaptive mechanisms and an elastic elegance that can be attributed largely to this same property, described in the 1740’s by French mathematician Pierre-Louis Maupertius as the principle of least action. Maupertius’ proof demonstrates in all natural phenomena, a quantity called action tends to be minimized. In other words, “the evolution of any dynamic system will always follow the path of least work” (Alexander 2004). In 1917 D’Arcy Thompson raised awareness of the integral connection between dynamic systems and exogenous forces stating, “The form of any particle of matter, whether it be living or dead, and the changes in form which are apparent in its movement and in its growth, may in all cases be described as due to the action of force” (Thompson 1917). The notion that force and action govern the ordering of matter, and thus structure and form, is consistent with the idea that matter itself is a manifestation of discrete energy-states operating cohesively as a fundamentally integrated system. Force and action are vital features of the energetic continuum that shapes our universe.

2.3 RESONANCE AND ORDER
An expressive visual example of the energetic ordering of matter is found in the field known as Cymatics, which is the study of standing waves. Galileo Galilei first noted these phe-
nomena in Dialogue Concerning the Two Chief World Systems. He observed when scraping a chisel across a brass plate, a sound could be produced that caused geometric order to appear in the brass filings on the plate. In 1680, Robert Hooke noted the appearance of nodal patterns when he ran a bow across a glass plate covered in flour. A century later, Ernst Chladni repeated and expanded on Hooke’s experiments before publishing Discoveries in the Theory of Sound, in which he discusses a method for visualizing the various modes of vibration in a mechanical surface.

Chladni documents a way of visualizing the resonance of particular material systems and in doing so, illustrates an important phenomenon; resonance has the ability to define a whole set of unique spatial patterns corresponding to the fundamental and its higher harmonics. Much like string theory where the vibrational mode of a string determines its physical characteristics, the emergent patterns defined by resonance are not rigid, but conform to an elastic template that can infinitely transform to negotiate changing conditions. Resonance in a material system defines optimal topology – genotype – rather than topography – phenotype.

The patterns in Figure 1 are a selection of still images from a video found by the author on YouTube. They illustrate the phase changes of a material system being ordered by resonance. The experiment is carried out with a steel plate connected to a tone generator. Sound produced by the tone generator resonates through the steel plate and introduces an energetic fluctuation into the material system – in this case rice – which responds naturally by self-organizing toward least action. The waveform under the images represents both a time axis and a steady increase in pitch. Increasing the frequency of oscillations drives the system toward a more tightly defined level of organization, suggesting that higher harmonic modes are directly linked to increased organizational complexity. An important observation is that coherent form is a global trait of each phase.

Standing waves demonstrate the concept of matter ordered according to force and action. Both organic and inorganic materials respond to external forces by restructuring to channel them evenly and with a minimum of work. Standing waves visually encode paths of least resistance. The question for architects is whether we can utilize this phenomenon to drive an ecological approach to design. Is it possible to tune architecture into an optimal
state by deploying generative digital processes that incorporate the physical forces and constraints of our energy centric reality?

3 Energy Centric Design Principles

3.1 LOCAL CHANGE, GLOBAL CONSEQUENCE—THE EPIGENETIC LANDSCAPE

The self-organization phenomena associated with Cymatics are related to non-linear thermodynamics and the dissipative structures described by Nobel laureate Ilya Prigogine. Prigogine proposes that thermodynamic systems in equilibrium are an exception rather than a rule. He argues that self-organizing matter operates in an open system of energy exchange that maintains a steady state far from equilibrium, such that a slight local energetic fluctuation can be amplified to have substantial global effects (Frazer 1995). In contrast to a system in equilibrium requiring large amounts of energy to change its state, the energy sensitive nature of dissipative structures means that self-organizing formations can quickly and efficiently adapt to changes in their environments.

In his essay Landscapes of Change, Sanford Kwinter eloquently discusses the morphological ordering of matter by energetic forces and offers metaphors for the kinds of systems and processes designers can look to engage. Kwinter draws attention to biologist and philosopher Conrad Waddington’s metaphor for biological development. Waddington’s diagram of the epigenetic landscape (Figure 2) is used as a visual analogy to describe an intimately connected architectural design process that operates in a responsive and fundamentally cohesive manner. Designers are urged to engage processes that correspond to
this flexible landscape of dynamic equilibrium in which a local change is “relayed throughout the system ... to affect, in turn, conditions all across the event surface”. Where “global behavior is an emergent property unpredicted by local rules” (Frazer 1995). Architects are challenged to explore “a unique field of unfolding ... in which forms exist only in evolution or equilibrium, that is, as event-generated diagrams” (Kwinter 1992).

Kwinter makes a strong argument for a morphogenetic approach to design, however the reader is left wondering how these concepts might manifest as practical architectural design processes. What kinds of design tools incorporate principles of self-organization, evolution and equilibrium?

3.2 ENERGY DRIVEN FORM FINDING

In 1995, John Frazer published An Evolutionary Architecture, proposing a bold new direction for architecture and design in general by transcending the metaphors offered by Winter. Frazer’s strategy makes use of computing to model physical, material and environmental characteristics. Through a simulated process of self-organization and evolution, architecture becomes “the expression of an equilibrium between the endogenous development of the architectural concept and the exogenous influences exerted by [its] environment” (Frazer 1995). Evolutionary architecture is defined by a set of designer rules, a
The genetic code that responds to external forces by self-organizing into optimal ‘minimum’ form. In contrast to designing a singular explicit response, the architect defines an implicit generative system capable of producing infinite variations. The search space expands as a result and transforms form making into form finding.

The work of Frazer et al. at the Architectural Association is a precursor to an energy centric design approach. An Evolutionary Architecture emphasizes the role that nature can play as a model for architecture and the importance of abstracting physical, environmental and material characteristics into a digital language that can be used to drive architectural design. The particular notion of form finding that is described enables simultaneous global resolution of external forces by emulating nature’s efficient, energy driven ordering processes. By deploying “form generation models that recognize the laws of physics and are able to create ‘minimum’ surfaces for compression and bending [and] tension” (Cook 2004), design becomes a dynamic process infused with the precarious sensitivity of life itself.

### 3.3 Trans-Disciplinary Logic

To engage with energy driven design processes, of critical importance is the ability to assign physical, environmental and material properties within a digital environment. So how do we induce energetic fluctuations into otherwise inert digital geometries? The answer lies within the tools of other disciplines such as engineering. For example, common finite element analysis utilizes algorithms that emulate physical quantities such as forces and material properties. By exploiting these kinds of tools, architects can encode the verifiable quantities of the physical world as design drivers.

This trans-disciplinary logic emphasizes a co-rational approach to design and liberates architecture from its visual preoccupation. Cecil Balmond has remarked, “I felt architects’ imaginations were restricted because they never entered the abstract fully. And they were limited by the visual” (Turnbull 2004). We are at the precipice of a significant transformation as the language of architecture aligns with science and engineering via an abstracted vocabulary of energy transaction and modulation. This shift calls into question the traditional architect-engineer relationship by replacing the distanced interaction of the past century with a renewed synergetic collaboration that proliferates design outcomes neither profession could develop in isolation.

### 4 Case Study

#### 4.1 An Introduction to Bi-Directional Evolutionary Structural Optimization

The Axiom of Uniform Stress is a phrase coined by Professor Claus Mattheck, whose research into tree growth has demonstrated that uniform stress is a common structural
characteristic of naturally occurring self-optimizing structures (Mattheck 2008). Nature is a master of elegance and material efficiency, the value of Mattheck’s insight transcends the metaphor and is readily transferable to design and engineering.

In 1992 Professors Mike Xie and Grant Steven proposed Evolutionary Structural Optimization (ESO), an algorithm that incrementally evolves constrained geometry toward an optimal structural solution (Xie and Steven 1992). Finite element analysis is used to identify the least stressed material and the ESO algorithm aims to remove redundant elements, consequently driving the geometry toward uniform stress, discarding material while maintaining stiffness of the structure. The original concept was extended to include the addition of material to high stress regions and was aptly named Bi-directional Evolutionary Structural Optimization (BESO). A number of analogous tools have since been developed in research practices around the world. Claus Mattheck has implemented his own evolutionary algorithm for structural optimization called Soft-Kill Option (SKO), Philippe Morel from EZCT Architecture and Design Research has developed an equivalent code for use with Mathematica, and Ole Sigmund et al. maintain a series of comparable web-based applets, broadly named Topology Optimization (TopOpt). Japanese structural engineer Mutsuro Sasaki is another key proponent of this technique, having deployed a similar methodology called Extended Evolutionary Structural Optimization (EESO) to co-rationally design the Qatar convention centre. Sasaki notes that evolutionary structural optimization uses “the principles of evolution and self-organization of living creatures, adapted from an engineering standpoint, to generate rational structural shapes within a computer” (Sasaki 2007).

The inputs needed for a BESO model are basic parameters assembled from contextual analysis and design intent. These parameters are distilled into a virtual model consisting of preliminary geometry, load cases, boundary conditions and design elements such as materials, voids and fixed regions. The nature of finite element analysis as a fundamentally energy driven procedure means that for a given set of criteria, BESO will generate optimal and rational structures using the most efficient distribution of material possible.

4.2 BESO AND THE ARCHITECT

The BESO algorithm currently utilizes Abaqus CAE for modeling, visualization and finite element analysis. Although Abaqus includes a powerful parametric modeling environment, its cumbersome interface is not suited to the generative methodology afforded by BESO, particularly with respect to the exploratory stages of architectural design. Furthermore due to the restrictive interface, BESO users and developers have been limited to working with simple solids. A minor example of trans-disciplinary knowledge transfer is a discovery by the author that enables geometry to be imported from more familiar modeling environments using a standard IGES file format. This means freeform preliminary geometries can now be defined in less rigid environments such as Maya, 3DSMax or Rhinoceros, before having materials, loads and supports assigned in Abaqus.

To integrate architectural design considerations with BESO, it is necessary to become familiar with the behavior of the algorithm and to have at least some sense of how physical structures are likely to act under certain forces. As an architect, this takes time and patience. The emergent properties of the BESO search space enables a singular preliminary geometry to evolve into innumerable variations depending on assigned materials, the placement of supports and the magnitude of loads. The radically differing outcomes illustrated in Figure 3 serve to demonstrate the concept of dynamic topological optimization discussed earlier, and the significant consequences of a single parameter change. In this case, a new load added to the centre of the preliminary cantilever form, completely restructures the outcome. Fundamentally, design becomes energy centric, as form, function and structure mutually depend on the encoding of energy states. A moment of trans-disciplinary fusion between the architect and engineer can occur when both transcend the visual by abstracting design intent into a series of engineering parameters describing materiality, loading conditions and supports.

4.3 A PREFACE TO ENERGY CENTRIC DESIGN

In a digitally based analysis environment, assigning materials, determining loading conditions and placing supports, induces an energy differential through an otherwise neutral
geometry. This energy has a particular signature. In a sense, BESO acts as a deterministic search function to resolve the particular material formation that best achieves uniform stress and least action for a particular energy state. Similar to the harmonic resonance that guides the forms in Figure 1, BESO liberates geometry through a dynamic process that can be thought of as expressing three-dimensional paths of least action (Figure 4).

BESO is by no means the quintessential tool for architecture, but rather hints toward a multi-criteria paradigm in which design software is natively encoded with algorithms that simulate physical, environmental and fabrication constraints. A paradigm where generative design is governed by energy driven criteria and computation becomes a tool for simultaneously tuning systems toward optimal design, performance and construction.

5 Research by Design

Exploration into the design implications of evolutionary structural optimization was initiated with a standalone ESO module called Evolve97. Familiarization with this relatively basic 2D implementation revealed the key principles of structural optimization strategies and some of the characteristics displayed by the emergent forms. A similar process was undertaken to familiarize with BESO. Two recurring attributes using both Evolve97 and BESO were noted and can be seen in Figure 5. Firstly, uniformly distributed loads tend to generate periodic structures. Secondly, eccentric loading tends to form branching structures and ambiguous structural foam that could be regarded as filigree. The Evolutionary Plasticity project (Figure 6) arose from these observations.

5.1 EVOLUTIONARY PLASTICITY

Evolutionary Plasticity considers how evolutionary structural optimization can be used to generate context specific and materially efficient components for use in building and construction. This project developed alongside further familiarization of Evolve97 and BESO. It was undertaken concurrently with research into large scale rapid manufacturing methodologies that facilitate complete geometric freedom.

The brief was to create a structural column connected to a standard building grid that minimizes the amount of material used, eases visual interference and improves aesthetic. The two observations made during initial research were integral to a strategy that aimed toward macro-optimization, sub-optimization and micro-optimization of a single object. Poroity is an important feature of natural structures, thus the approach taken here focuses on discovering the means by which branching and topological reorganization could be amplified at each scale of optimization. The final form of this project was guided to maximize its strength to weight ratio. The full-scale structure could be manufactured from CAD data using a combination of 3D printed foam and a relatively new metal casting process known as ‘lost foam’ casting.
Evolutionary Plasticity revealed a number of insights relevant to designing with optimization tools. As the differing scales of optimization emerged, it became clear that there was an intrinsic link between performance and aesthetic. Does structural efficiency give rise to ornamentation, or the notion of performative ornament? Another interesting observation was the tendency toward periodic, porous and filigree structures, suggesting that multi-scale and multi-criteria optimization should be defined from the bottom up. Instead of global form being the first optimization procedure, a family of variable and physically responsive structural cells could be defined first. These could be aggregated at various scales according to physical and environmental constraints, forming an efficient, integrated and elegant macro-structure. This intimate scale of consideration has an immediate and dramatic effect on the overall coherence of architectural design and form generation.

5.2 STRANGE ATTRACTION
Strange Attractor is a pavilion for wine tasting in Southeastern Victoria, Australia. It is a project undertaken with Mesne Design Studio. The departing trajectory for the scheme is an oscillation between two discreet points. These points are the two primary attractors of the pavilion, the bar and the restaurant. To describe the energetic oscillations of guests, the Lorenz attractor was chosen as a conceptual diagram by which to organize and evoke a spatial experience of distinct but intimately connected space.

The challenge was to encode this qualitative architectural concept as a BESO model. Firstly, it was necessary to locate the attractors within a preliminary geometry defined by a response to the site and brief. Numerous approaches were explored, including defining non-design regions and concentrating supports and loads. The final strategy (Figure 7) included a combination of typical loading conditions, eccentric loading in some regions and the inclusion of two voids to locate the attractors and create the desired ‘figure eight’ circulation of the pavilion. Considering the theme of this paper, the eccentric loading conditions applied in the final BESO model can be regarded as tuning the system’s energy state with architectural design intent.

The form that finally emerged from the many iterations of the co-rational design and optimization process was a sinuous structural spine dividing the initial geometry into two distinct but intimately connected spaces. The attractors, encoded as void spaces, become integrated with the structural spine as skylights, which enlarge to form curvaceous cavern-like spaces on the interior. A point to make here is that evolutionary optimization processes cannot produce finished buildings, but rather a preliminary organizational response to set criteria. To transform this particular geometry into architecture, a secondary strategy was necessary to enclose the internal spaces while maintaining coherence of the elegant structural spine.

The solid topological form that emerged from the BESO process was analyzed to determine sub-optimization and fabrication strategies. The design team explored the idea of a three-dimensional framing system to minimize material usage and increase the strength to weight ratio of the final structure. In order to negotiate fabrication considerations, the mesh resolution of the digital model was significantly decreased to accommodate larger frame members (Figure 8). This sub-optimization strategy enabled a coherent link between the geometrically complex structural spine and its rectilinear envelope. The resulting pavilion proposal (Figure 9) has a glazed building envelope supported by triangulated framing that seamlessly negotiates the transition from surface to structural spine.

5.3 FUTURE RESEARCH
The projects outlined above are an introduction to working with BESO as an architectural design tool. A series of further investigations are planned to expand on the insight gained thus far. The bottom up, cellular design methodology mentioned in Evolutionary Plasticity will be explored with a specially coded feature in BESO that evolves three-dimensionally periodic structures. Another exploration will include the optimization of sculptural geometries that capture specific design intent and are easily generated in the fluid modeling environments familiar to architectural design.

The largest task and ultimate goal for energy driven design processes such as BESO is
to facilitate multi-criteria evolutionary optimization to dynamically reveal an optimal topological response combining design, structural and environmental criteria.

6 Conclusion
In the increasingly energy conscious and resource driven global economy, pressure to achieve more with less has had a profound impact on the direction of contemporary architectural thinking. Architects are searching for deeper resonances with the natural world and have turned to computation in an attempt to transcend the metaphor. Our search necessitates a comprehensive understanding of the fundamental properties that organize matter as structure and form. This paper argues for an energy centric approach to architectural design, which reflects the awareness that all formations of matter are complex aggregates of discrete energy-states and harnesses this understanding to benefit both the coherence of the design process and the outcomes produced.

The evolutionary approach to architecture proposed by John Frazer in 1995 is central to this discourse, however where Frazer’s discussion primarily focuses on ways of generating the genetic seeds of design, this paper emphasizes the importance of abstracting the material world into a set of encoded energy based algorithms that simulate physical and environmental conditions. The BESO case study presented herein integrates an energy driven structural optimization logic. The initial materials, loads and supports assigned in the digital model operate to define a particular energy state throughout the preliminary geometry. This energetic signature is a significant designer component of the system, inducing forces that act to define an optimal topology – a path of least action. By revealing this path, BESO enables design intent and structural performance to be simultaneously and coherently negotiated towards an optimum.

The concept of inducing energetic fluctuations into otherwise inert digital geometry closely aligns the architectural design process with the principles of morphogenesis. Architecture enters a trans-disciplinary paradigm governed by energy driven criteria and computation becomes a tool with which to tune architectural material systems toward optimal design, performance and ultimately, construction.

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8 References