How might architecture address issues of ecology and sustainability so that buildings behave more like organisms in their built environments?

Applications of Insights from Biology and Mathematics to the Design of Material Structures

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For the past 12 years, Jenny Sabin Studio and the Sabin Lab (based at Cornell University's College of Architecture, Art, and Planning) have engaged in work at the forefront of a new direction for 21st century architectural research practice—one that investigates the intersections of architecture and science, and applies insights and theories from biology and computation to the design of material structures that are adaptive, interactive, and resilient.[1]

This paper describes multidirectional and multidisciplinary investigations shaping the future trajectories of these material innovations and technologies for architecture. The work aims to advance materials research and digital fabrication across disciplines to effect pragmatic change in the economical, ecological, and cultural production of contemporary architecture.

Background

Buildings account for nearly 40 percent of CO_2 emissions in the United States, with the remainder primarily from the industrial and transportation

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Portions of this paper have been adapted from Sabin (2015).

[1] See Sabin and Jones (2017), a book on design research across disciplines through the lens of LabStudio, cofounded by Sabin, an architectural designer, and Jones, a molecular and cell biologist.

sectors.[2] Most contemporary sustainable approaches to reduce these emissions offer technological solutions through sanctioned rating systems such as LEED, a rating system launched by the US Green Building Council for both new construction and renovations of existing buildings. While these measures adequately address resource consumption in buildings, they do not address the systemic ecology of the built environment over the long term.

What are ways to rethink conceptual approaches to sustainability in architecture? What design research models are available to address these questions and thus shape future innovations and applications in architecture?

Recent Pioneering Research

Forward-thinking research in building materials includes that of Matthias Kohler's group at ETH Zürich.[3] In the group's work with industrial robots Kohler coined the term *digital materiality*, which enables real-time feedback with material constraints through robotic digital fabrication processes. His more recently coined term, *computational contextualism*, refers to how sensors operate to integrate environmental feedback in a robust design process for the built environment.

Ronald Rael and Virginia San Fratello of Emerging Objects (www.emergingobjects.com) claim that all materials start as powder or end in dust. Their 3D-printed work integrates bits of data and particles of light to transform this dust into nonstandard objects and products for future building blocks, challenging the status quo of rapid prototyping by designing the material itself.

Researchers such as Rob Shepherd and Maria Paz Gutierrez explore architecture applications in programmable matter and materials science. Shepherd's work on actuators, sensors, displays, and additive manufacturing protocols for soft wearable robots underscores the importance of iterative complex feedback between material and mechanical design in the development of these techniques and wearables.

In parallel, the work of the BIOMS group (Bio Input onto Material Systems), directed by Gutierrez at the University of California, Berkeley, takes direct inspiration from skins found in nature. Repurposing the textile as an important architectural element, the BIOMS multifunctional membrane features an integrative sensor and actuator system that not only is designed to answer to many functions through what Gutierrez calls the "synergistic optimization of heat, light, and humidity transfer" but also is a closed loop system.[4] It therefore does not require energy input through mechanical actuators, sensors, and a mainframe.

Biology and computation can inform the design of material structures that are adaptive, interactive, and resilient.

And through select research projects at the Institute for Computational Design and Construction at the University of Stuttgart, Achim Menges argues that technological innovation across multiple disciplines suggests that design computation is no longer limited to the binary world of the digital, but is now interfacing with the complex realm of the physical. How is this innovative and forward-thinking work leveraged and funded?

Federal Support for Innovation

In 2010 the National Science Foundation (NSF), under the Emerging Frontiers for Research Innovation (EFRI) Science in Energy and Environmental Design (SEED) umbrella, solicited proposals for transdisciplinary research teams to engage the problem of sustainability in terms of building energy use and its impacts on the built environment.

In an unprecedented occurrence, applicant teams were to include architects and, importantly, AIA licensure was not required. This opened up opportunities for both licensed architects and architectural designers engaged in practice and core academic design research to apply with collaborative teams across academia, practice, and industry. Successful project proposals required a radical departure from traditional research and design models in architecture and science, with a move toward

[2] See "Benefits of Green Building," https://www.usgbc.org/articles/green-building-facts.

[3] As discussed at the Matter Design Computation Symposium: The Art of Building from Nano to Macro, Cornell AAP Preston Thomas Memorial Lecture Series, March 10–11, 2017.

[4] As stated in an unpublished text, "Multifunctional Building Membrane: Self-Active Cells, Not Blocks," M.P. Gutierrez (BIOMS director/lead) with L.P. Lee (BioPoets director), the UC Berkeley BIOMS team (C. Irby, K. Sobolski, P. Hernandez, D. Campbell, P. Suen), and B. Kim (BioPoets team).

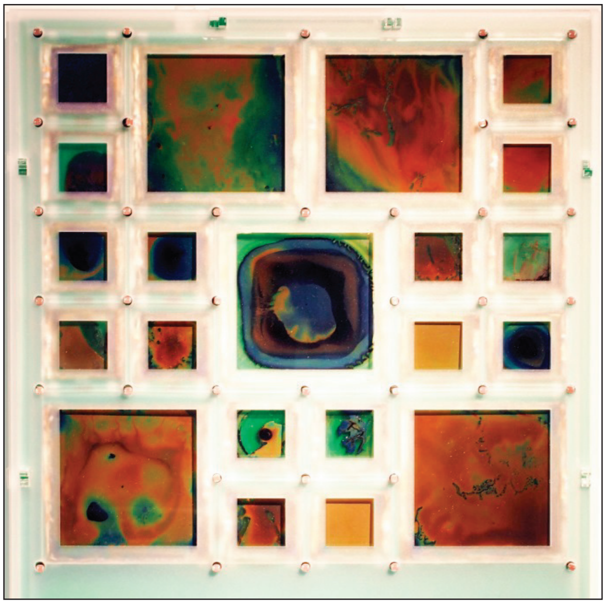

FIGURE 1 eSkin interactive prototype. Indium tin oxide (ITO)–treated glass cells with voltage-controlled nanoparticle solution, housed on a custom-built PCB substrate and controlled locally via ambient sensing nodes. © Sabin Design Lab, Cornell University; Shu Yang Group, University of Pennsylvania; Jan Van der Spiegel and Nader Engheta, University of Pennsylvania.

hybrid, transdisciplinary concepts and new models for collaboration.

Drawing on Nature to Inform Architecture

In the Sabin Lab we ask: How might architecture address issues of ecology and sustainability so that buildings behave more like organisms in their built environments? We are interested in studying the human body for design models that give rise to new ways of thinking about adaptation, change, and performance in architecture.

Our expertise and interests focus on the study of natural and artificial ecology and design, especially in the realm of nonlinear biological systems and programmable materials that use minimum energy with maximum effect. Seminal points of reference for the work include matrix biology, materials science, bioengineering, and mathematics through the filter of crafts-based media such as textiles and ceramics, with advanced digital fabrication protocols including robotic fabrication and 3D printing.

Our collaborative work looks to nature, specifically cellular biology, for an analogous deep organicity of interrelated parts, material components, and building ecology. Generative design techniques emerge with direct references to natural systems such as cellular networking behavior and models of structural color found in the wings of the blue *Morpho* butterfly or the feathers of hummingbirds. We do not simply mimic these exquisite systems and structures, but instead focus on modeling and simulating behavior and processes through custom tools and methods that translate flexibility, adaptation, growth, and complexity into applied architectural prototypes and adaptive materials systems. Our work offers novel possibilities for redefining architecture in terms of ecological design and digital fabrication.

Research to Create Adaptive Building Skins

Since the start in fall 2010 of our NSF SEED project, Energy Minimization via Multi-Scalar Architectures: From Cell Contractility to Sensing Materials to Adaptive Building Skins, my colleague Andrew Lucia and I (as co-PI) have led a team of architects, graduate architecture students, and researchers in the investigation of biologically informed design. We use the visualization of complex datasets, digital fabrication, and the production of experimental material systems for prototype speculations of adaptive building skins, designated eSkin, at the macrobuilding scale (figure 1). The full team, led by principal investigator Shu Yang, is engaged in rigorous scientific research at the core of ecological building materials and design.

The work described here is a subset of ongoing transdisciplinary research spanning cell biology, materials science, electrical and systems engineering, and architecture. The eSkin project applies these disciplines to the design and engineering of responsive materials and sensors (Sabin et al. 2014), operating on a multiyear research plan in three phases:

1. production of catalogues of visualization and simulation tools to discover new behaviors in geometry and matter;
2. exploration of the material and ecological potentials of these tools using experimental structures and material systems created through digital fabrication; and
3. generation of scientifically based, design-oriented applications in contemporary architecture practice for adaptive building skins and material assemblies.

The goal of the eSkin project is to explore materiality from nano to macro scales based on an understanding of nonlinear, dynamic human cell behaviors on geometrically defined substrates. To achieve this, human smooth muscle cells are plated on polymer substrates at a micro scale. Sensors and imagers are being designed and engineered to capture material and environmental changes based on manipulations by the cells, such as changes in color, transparency, polarity, and pattern (Lee et al. 2014; Li et al. 2012).

In recent eSkin prototypes, the team is exploring dynamic switching between opaque, transparent, and highly colorful components assembled in a single full-scale prototypical building façade unit (figure 1). Specifically, the team is working with structural color, where physical structures in the form of particles interact with light to produce a particular color.

Silica colloidal nanoparticles dispersed in an organic medium (solvent) are sandwiched between two transparent conductively treated indium tin oxide (ITO) pieces of glass, housed in an assembly of 3 laser-cut plexiglass frames. The light reflected from the ordered structure (depending on the particle size, distance, and reflective index contrast between the silica nanoparticles and the organic medium) is of a specific wavelength.

When a voltage is applied to the particulate solution, the surface charge of the particles is altered, changing both the distance between the particles and the color. At each intersection between the color cells, a sensor based on shifts in light intensity levels actuates voltage change between the adjacent color cells. Thus when a finger, hand, or figure passes by a sensor, a detected shift in light intensity triggers a small voltage shift across the ITO component, reorganizing the distribution of particles in the solution, ultimately affecting the reflected appearance of color from the nanoparticle solution (Sabin et al. 2014; Sabin and Jones 2017).

The relevance of this particular prototype and the eSkin project to megatall buildings is primarily in building façade design. For example, in many glass-clad megatall buildings, a glazing treatment known as ceramic frit patterning is used to minimize solar heat gain and energy loss without obstructing the occupants' view. These treatments are effective but permanently static.

We envision and have demonstrated a strategy for dynamic and adaptive building skin treatments that behave similarly to a standard frit pattern, but change throughout the day and night and in response to extreme shifts in climate and local environment. We propose to integrate eSkin in either existing building façade construction to enhance energy saving or in new megatall building façade design.

Conclusion

Through the eSkin project, insights into how cells can modify their immediate extracellular microenvironment are investigated and applied to the design and engineering of highly aesthetic passive materials, sensors, and imagers that will be integrated in responsive building skins. Such skins will enable buildings to adapt to external changes in temperature and internal solar heat gains to better regulate energy consumption and loss.

Our project addresses energy minimization at multiple scales of architecture by working toward challenging goals such as those put forward by the US DOE.[5] We hope that our interdisciplinary work will not only redefine research and design through collaboration but also address social, environmental, and technological dimensions that ultimately enhance building design and the built environment.

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[5] See https://www.energy.gov/eere/buildings/commercial-buildings-integration-0.