NEAR-LIVING ARCHITECTURE

WORK IN PROGRESS FROM THE HYLOZOIC GROUND COLLABORATION 2011-2013

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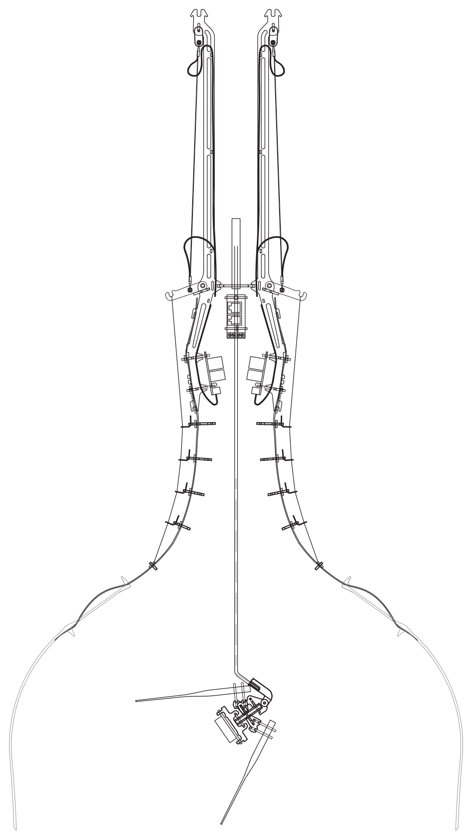


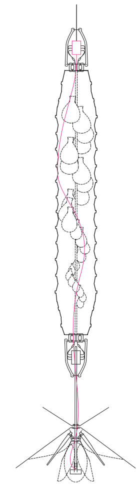
Introduction

> If architecture aspires at times to be a framing structure that comes between ourselves as human bodies incarnate and a wider universe, providing a way of establishing our place in that larger world, then it would seem appropriate that architects today begin to develop structures that articulate what we currently understand that universe to be. Hylozoic Ground is, beyond an exquisite moment of modern rococo, an attempt to construct such a veil of emplacement.
>
> Aaron Betsky
> Architect Magazine, 2010

Can architecture feel, and know, and respond to their occupants? Might buildings begin, in primitive ways, to come alive? The Hylozoic Series brings together researchers and industry collaborators from Canada, USA, and Europe in an interdisciplinary research cluster attempting to develop a potent new kind of architecture. The group is devoted to developing new technologies and new aesthetics for responsive, adaptive building systems. Building on early steps that have integrated lightweight digitally fabricated structures, interactive mechanisms and sensor networks within new building structures, the group is now developing functions that pursue empathic feelings and that contain self-renewing metabolisms. This book gathers together working papers for this increasingly ambitious collaboration.

'Hylozoism' refers to the philosophy that all matter has life. The Hylozoic Series builds upon this ancient conception by designing synthetic organic environments. A new generation of interactive technologies is rapidly emerging within contemporary architecture. Machine learning, emotional computational systems and synthetic biology reactions are at the very early stages of integration within these systems. These environments raise fundamental questions: how might we visualize the dynamics of open, evolving systems? How might new models emulating living systems and ecologies be translated into effective tools for design? New kinds of language are needed that provide critical terms of reference for discussing precise qualities of complex systems. New technical systems are needed that provide flexibility and resilience in handling conditions lying far from equilibrium. Accompanying this specialized language and technology, the group is developing new methods that can equip next generations of interdisciplinary researchers with effective design tools. Creative possibility is encouraged by following many cycles of simulation, testing and physical building.

The hybrid working methods demonstrated here involve many parallel cycles of conception, modeling, full-scale prototyping and performance analysis. The group combines both rigorous applied research and free-ranging speculation. Collaborators combine paradigms of organization and interaction that include diffusive form-language from industrial design, distributed networks and meshed arrays from mechatronics, and protocell chemical reaction design from synthetic biology. These conceptions are being used for the purpose of forming coherent, durable, functional public-scale architectural prototypes. Interdependence of specific systems and systems uncertainty characterize this pursuit.



1 Column from Aurora Simons,Edminton 2012

EVOLVING CONCEPTIONS OF ARCHITECTURE

A new generation of interactive architecture is rapidly appearing. Surging critical interest is evident in kinetic and interactive projects this past decade, building on debates from 1960s cybernetic theory and exemplified by widely recognized built projects such as dECOi's "Aegis Hyposurface"[2]. Rooted in technical innovations, these emerging projects often employ distributed communication and control systems, lightweight actuators and sensors integrated within component-based envelope systems.[3] Supported by design methods involving cycles of dynamic visualization and simulation[4], enhanced by new design tools employing generative and parametric software[5], critical voices proclaim expanded qualities of a new 'instrumental' architecture validated under broadly-defined 'performance'.[6,7] The qualities focused by voices such as Kolarevic[9], McCullough[10], Leach[11], and Spiller[12] imply an increasing consensus of key immanent, dynamic, and open qualities in this emerging work, following canonical sources on digital environments such as Negroponte's Aspects of Living in an Architecture Machine[13] and Being Digital [14], and McCullough's 1995 work, Digital Ground. This cluster of sources revolve around theories of interactional design that are marked by a striking optimism about the expanded powers of performance-based architecture.

2 Spiller, Neil, *Digital Architecture Now: A Global Survey of Emerging Talent*, Thames & Hudson, 2009.

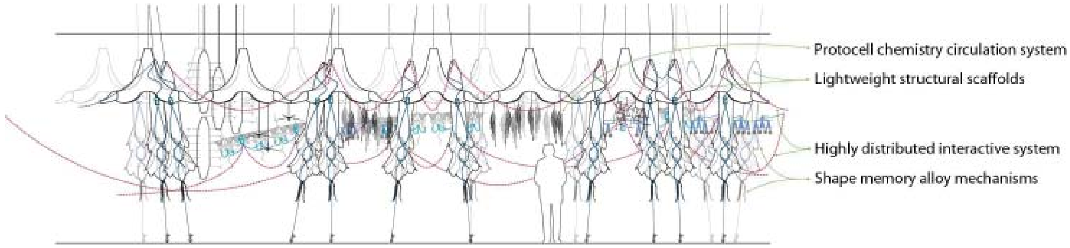
3 Fox, Michael; Kemp, Miles, *Interactive Architecture*, Princeton Architectural Press, 2009.

4 Ibid.

5 Bullivant, Lucy, *Responsive Environments: architecture, art and design*, Victoria and Albert Museum, 2006.

6 Hensel, Michael Ed.; Menges, Achim Ed., *Versatility and Vicissitude: Performance in Morpho-Ecological Design*, Wiley, 2008.

7 Kolarevic, Branko; Malkawi, Ali, *Performative Architecture: Beyond Instrumentality*, Routledge/Taylor and Francis, 2004.



8 Schematic organization of Hylozoic Ground, Venice Biennale for Architecture, 2010

However, while Hylozoic Series research aligns with many aspects of this new performance based architecture, the contributions of the partnership also shows critical restraint. The critical issues raised by this progress merit considerable debate. New paradigms are implied where humanity is seen as a participant in the complex negotiations between nature, culture and technology,[15, 16] or as architectural theorist Detlef Mertins puts it "the tangled web of creatures and environments within which humanity lives a promiscuous life."[17] In this reformed conception, humanity is entangled with natural and artificial processes by occupying a liminal rather than central position.

METHOD

Research is structured in five parallel streams:

- Meshwork and Component Design Systems
- Complex-Systems Simulation, Modeling and Interaction Design
- Living Chemistry Systems
- Cognitive and Brain Research
- Knowledge Integration and Pedagogy

Each of these stream move in multiple cycles through three phases:

- Development of tools and cross-disciplinary working methods.
- Material experimentation accompanied by built prototypes. Through this process, research is channeled into fabrication and accompanying issues of scale and material creation are addressed.
- Adaptation of prototypes into full-scale environments and observing public occupation. Cultural institutions are acting as collaborators presenting public exhibitions as test facilities that support ongoing study and development of this work.

9 Kolarevic, Branko, *Exploring Architecture of Change*, Acadia 09, Chicago, Illinois October, 2009.

10 McCullough, Malcolm, *Digital Ground: Architecture, Pervasive Computing, and Environmental Knowing*, MIT Press, Massachusetts, September, 2005.

11 Leach, Neil, Ed. *Digital Cities AD: Architectural Design*, Wiley, 2009.

12 Spiller, Neil, *Digital Architecture Now: A Global Survey of Emerging Talent*, Thames & Hudson, 2009; Spiller, Neil, *Reflexive Architecture* (Architectural Design) Academy, 2002.

13 Negroponte, Nicholas, Aspects of Living in an Architecture Machine, *Design Participation : Proceeding Design Research Society Conference*. September, 1971. pp. 63-67.

14 Negroponte, Nicholas, 1995, *Being Digital*, Vintage Books, 2000.

15 Pepperell, Robert, T*he Posthuman Conception of Consciousness*: *A 10-Point Guide,* Intellect Books, 2000.

16 Sloterdijk, Peter, *God's Zeal: The Battle of the Three Monotheisms*, Polity Pr., 2009.

17 Beesley, Philip, *Hylozoic Ground: Liminal Responsive Architecture*, Riverside Architectural Press, 2010.

MESHWORK AND COMPONENT DESIGN SYSTEMS

Lightweight structures and component systems are organized in textile-based geometric systems employing massively repeating lightweight modular scaffold components. Collaborators draw upon crafts of digital prototyping, industrial design and multi-scaled architectural craft. The designs of these structures provide resiliency, durability, and capacity for kinetics. The research focuses on material, chemical and kinetic component integration.

COMPLEX-SYSTEMS SIMULATION, MODELING AND INTERACTION DESIGN

Partners with expertise in robotics, mechatronics, and digital visualization are developing responsive and empathic functions by developing performance and control systems, by modeling interaction between occupant and space to improve interaction design, and by developing design tools for visualizing and synthesizing interactive performance behaviours. Four parallel research clusters each carry responsibility for key systems:

1. Affective movement recognition/generation examines intelligent systems, applying the core question: can we generate devices and motion paths for affective communication in support of empathic relationships in near-living architecture?
2. Real-time algorithms for maximizing engagement: how might a near-living architecture learn from its interactions with occupants in order to maximize occupant engagement, and thus the effectiveness of the relationship, in real-time?
3. Electronic and mechanical design focuses on control of distributed arrays of actuators in layered heterogeneous technical systems employing massively distributed sound, light, kinetic, air and fluid systems actuation supported by arrayed sensor networks.
4. Development modeling and interaction design includes pattern analysis to understand correlations between occupant and space.

LIVING CHEMISTRY SYSTEMS

Protocell artificial biology systems show qualities of near-living systems composed from fluid-based inorganic chemistries. These systems are capable of processing gas and fluid-based environmental elements, and are at the early stages of integration within experimental architectural facades and canopies.

COGNITIVE AND BRAIN RESEARCH

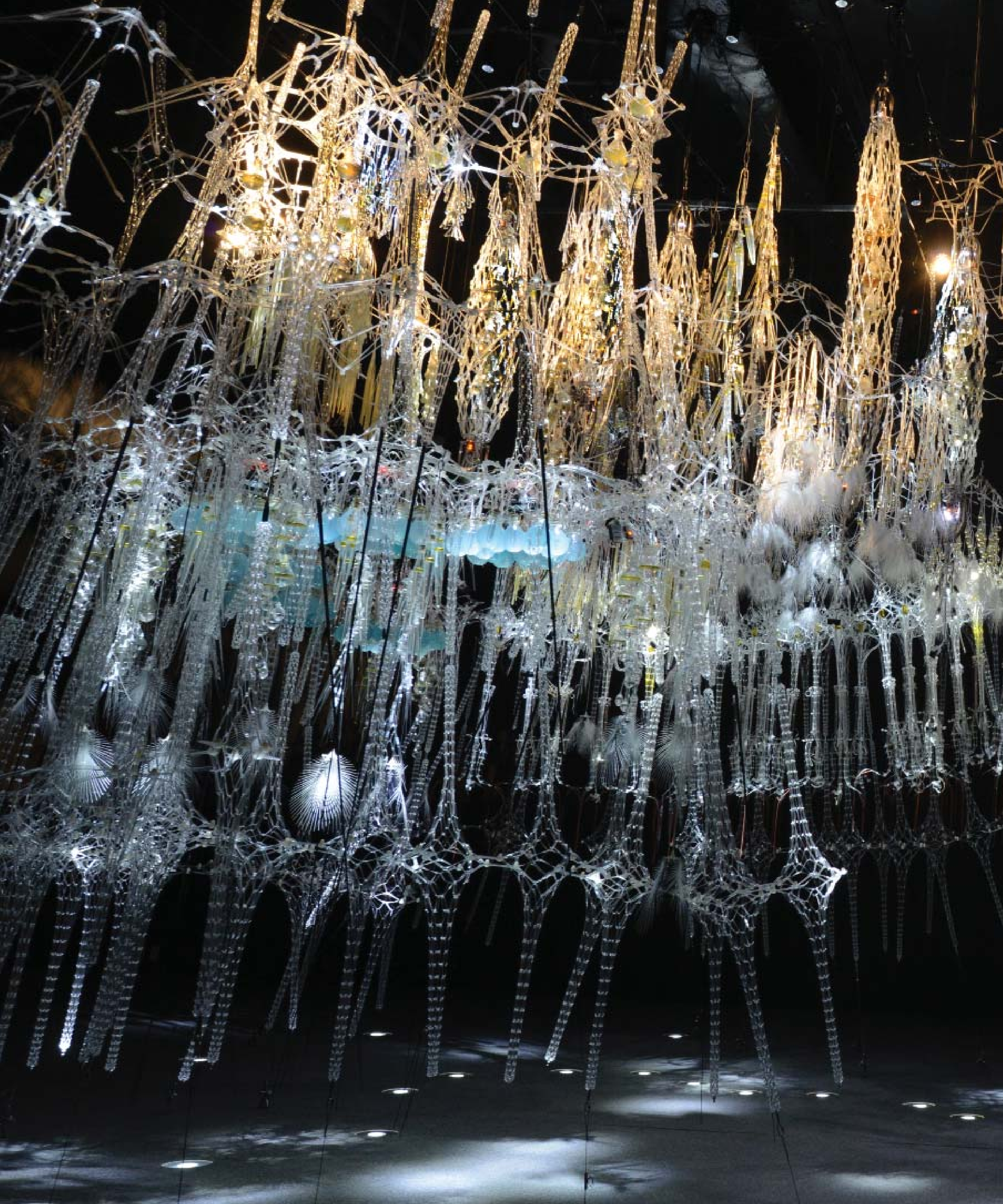
Research in this stream explores the cognitive and emotional response of occupants in actuated environments, drawing from empathic systems developed in the Complex-Systems Simulation stream described earlier. The research in this stream expands upon movement study to explore the experience of occupants within interactive environments.

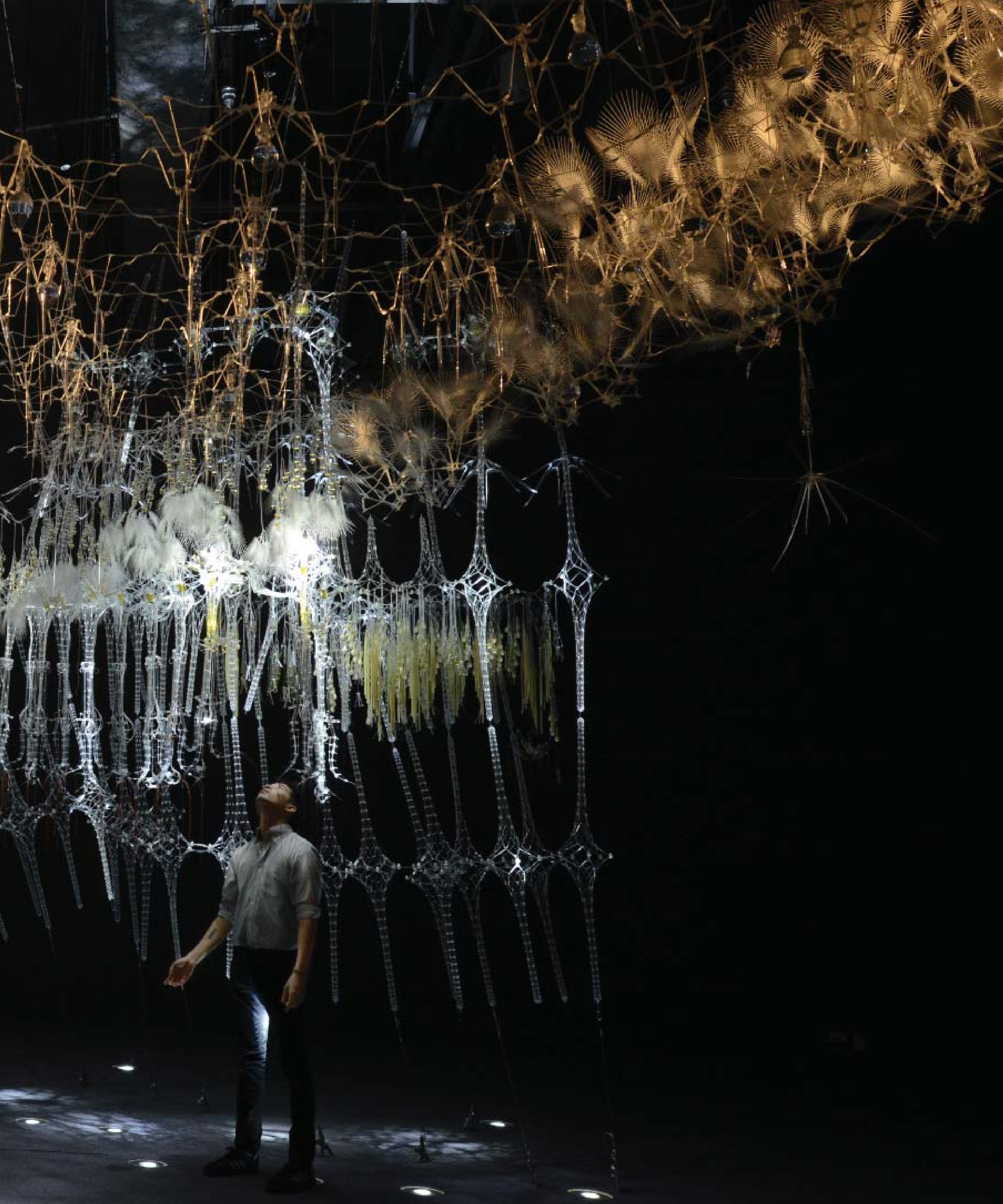
KNOWLEDGE INTEGRATION AND PEDAGOGY

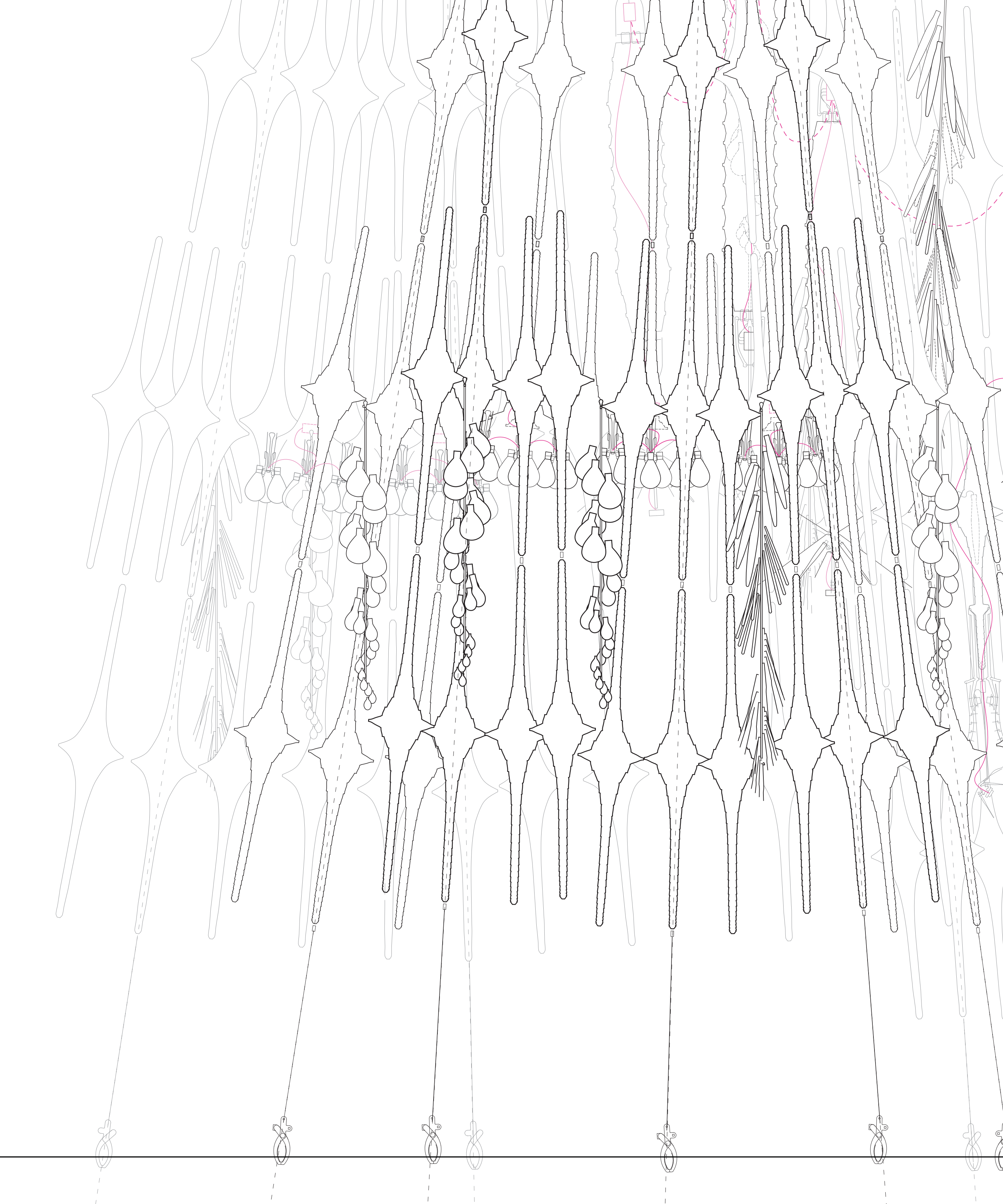
Two parallel streams focus on curriculum development and interdisciplinary working methods. The first stream works with specialized curriculum to train students from kindergarten to grade 12 in critical thinking and innovation skills required to address complex problems. The research integrates current STEM education (Science, Technology, Engineering and Mathematics) with art creating hybrid STEAM (Science, Technology, Engineering, Art and Mathematics)-education models. In addition to developing critical thinking, group work, and design skills, the workshops reinforce connections with creativity and the arts. The second parallel stream is developing working methods for interdisciplinary research supporting collaborative process among partners.

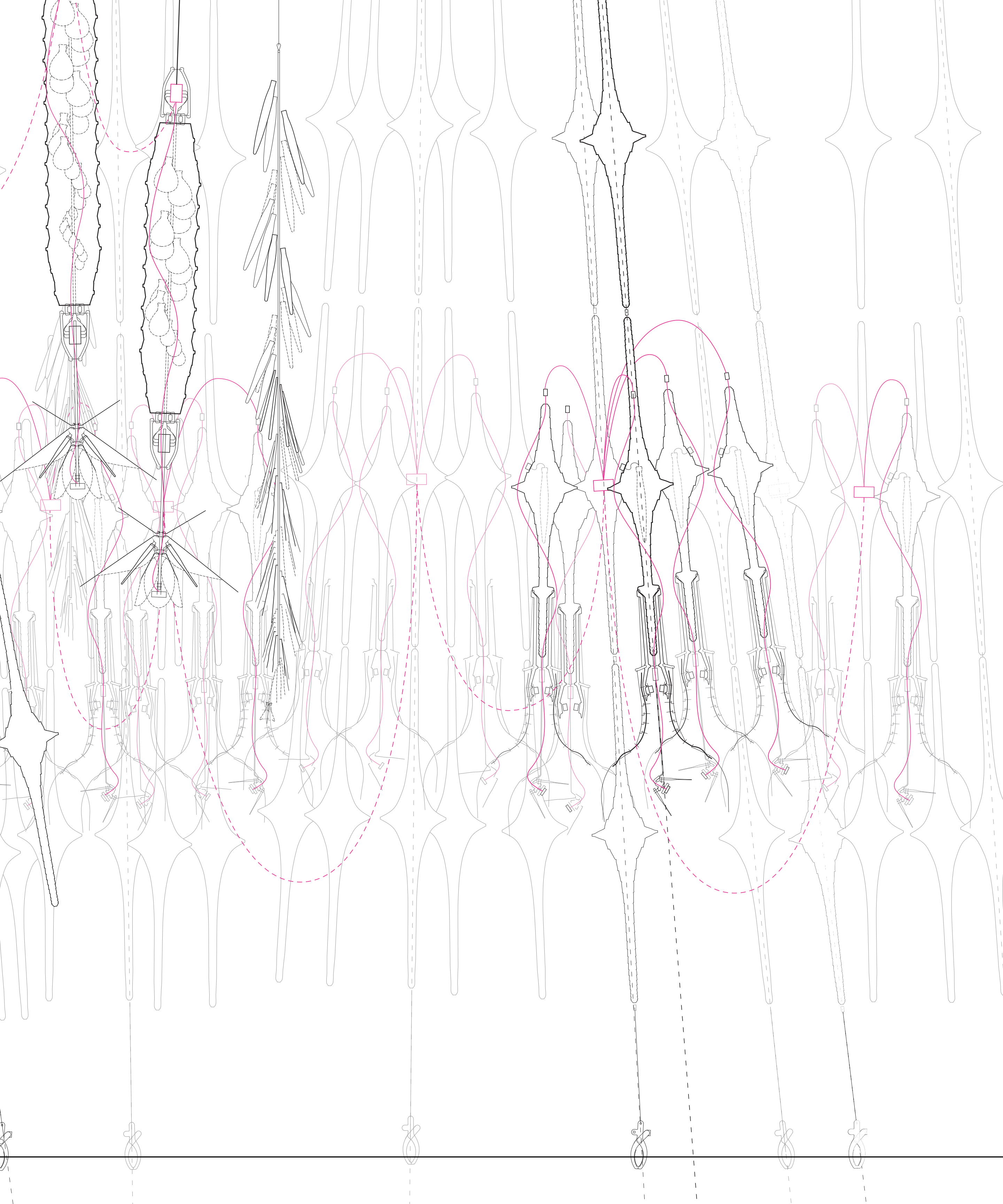
IMPACT

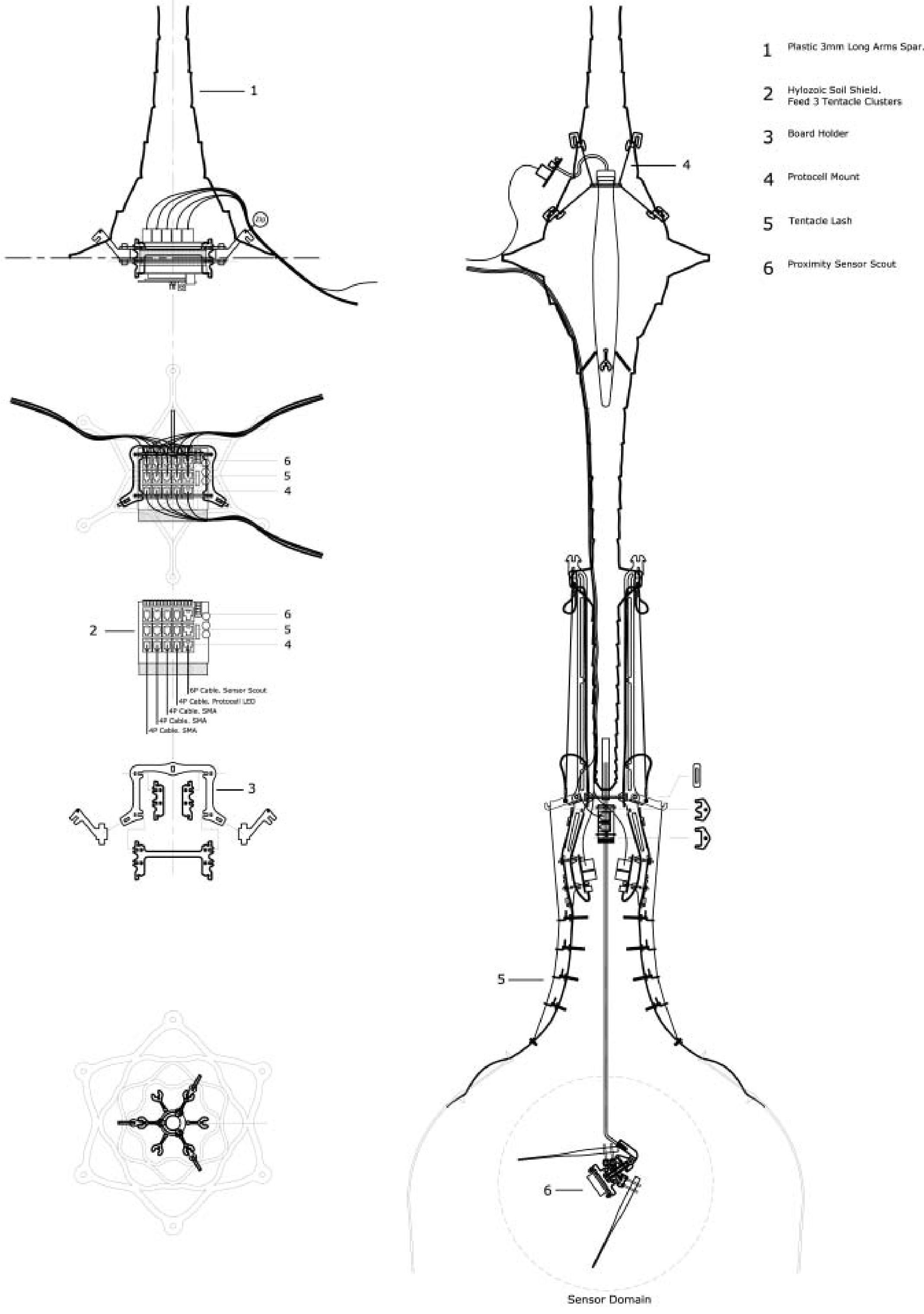
New design paradigms offer diffusive form-languages and highly distributed and iterative prototype development. New generations of young students and professional designers can be equipped with concepts that can position them for responsible, creative participation in synthesis and stewardship of the built environment. The technologies being developed in this collaboration have applications in sustainable architecture. Contributing to critical discussion, this work pursues mutual relations between synthetic constructions and the natural world.







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6P Cable. Sensor Scout
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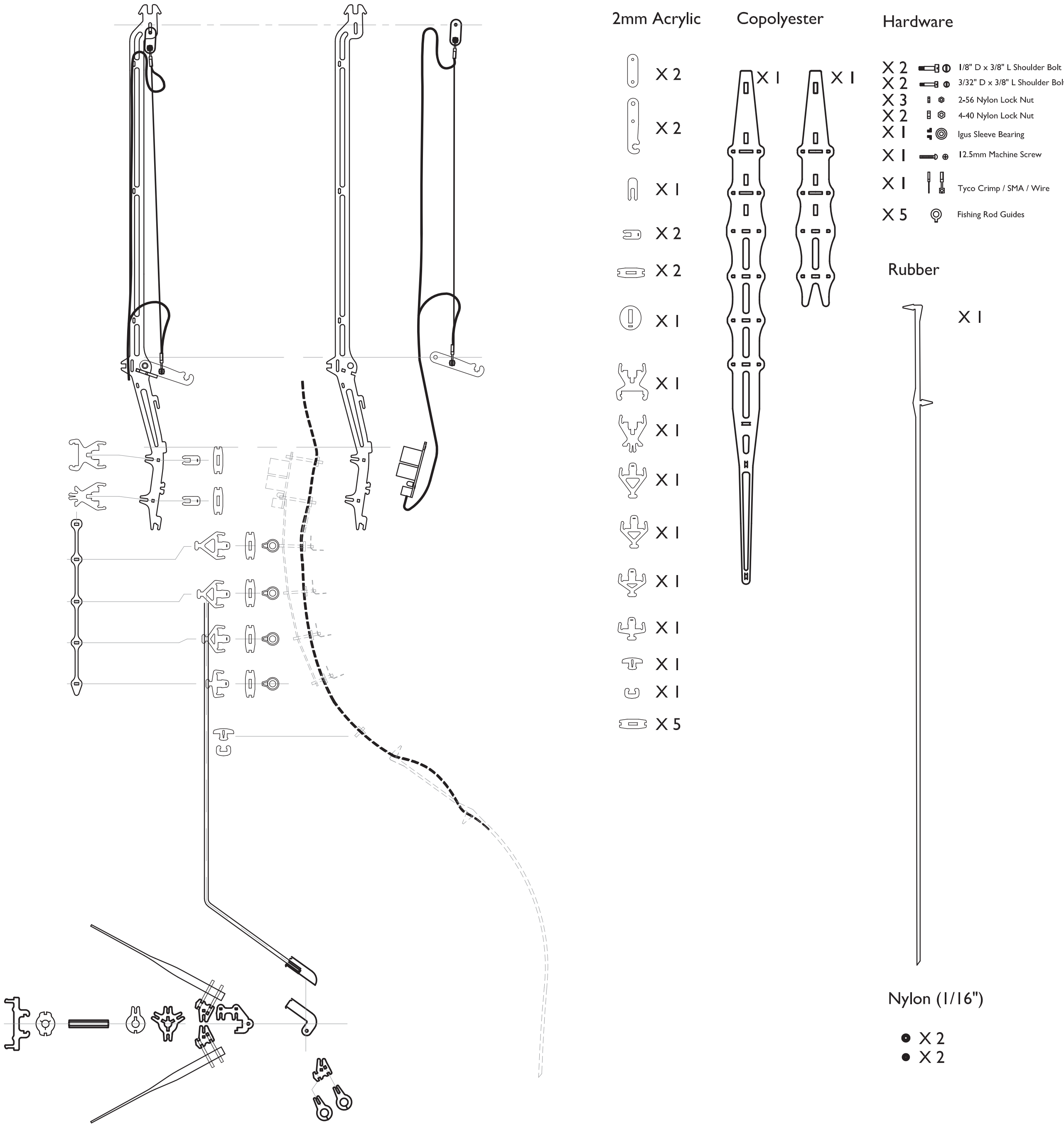
Sensor Domain
1 Plastic 3mm Long Arms Spar.
2 Hylozoic Soil Shield. Feed 3 Tentacle Clusters
3 Board Holder
4 Protocell Mount
5 Tentacle Lash
6 Proximity Sensor Scout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Hardware
X 2 1/8" D x 3/8" L Shoulder Bolt
X 2 3/32" D x 3/8" L Shoulder Bolt
X 3 2-56 Nylon Lock Nut
X 2 4-40 Nylon Lock Nut
X 1 Igus Sleeve Bearing
X 1 12.5mm Machine Screw
X 1 Tyco Crimp / SMA / Wire
X 5 Fishing Rod Guides
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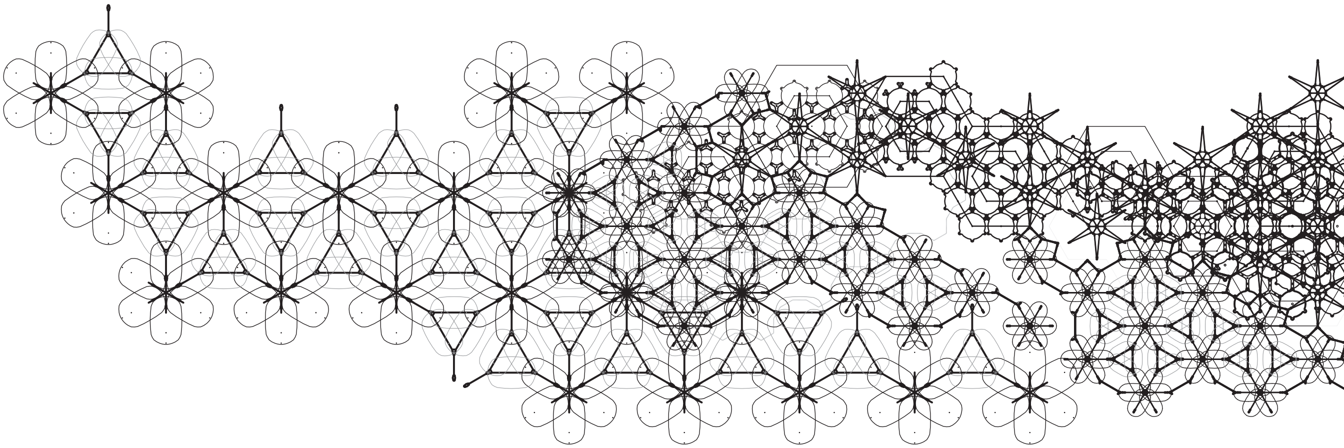

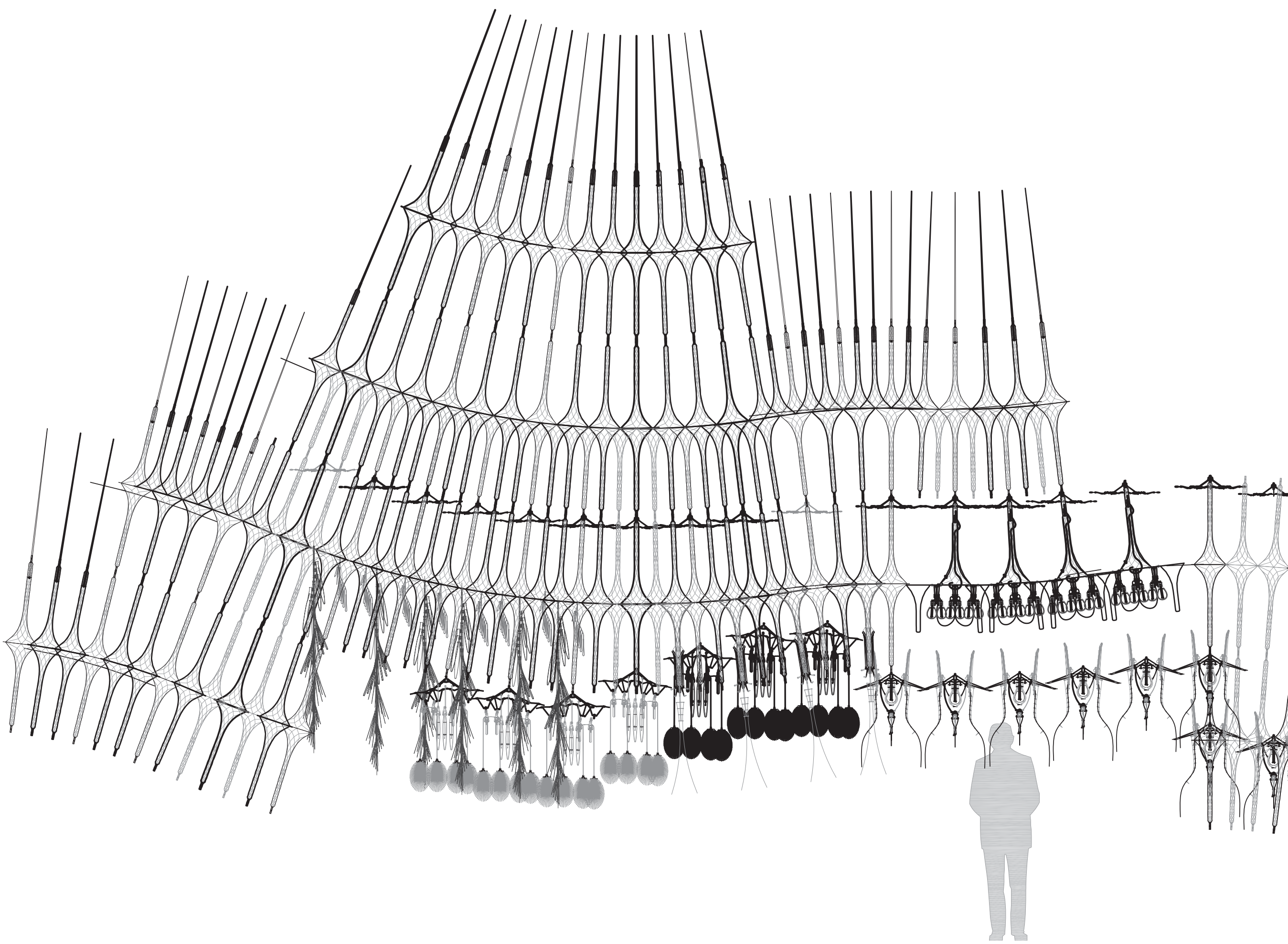

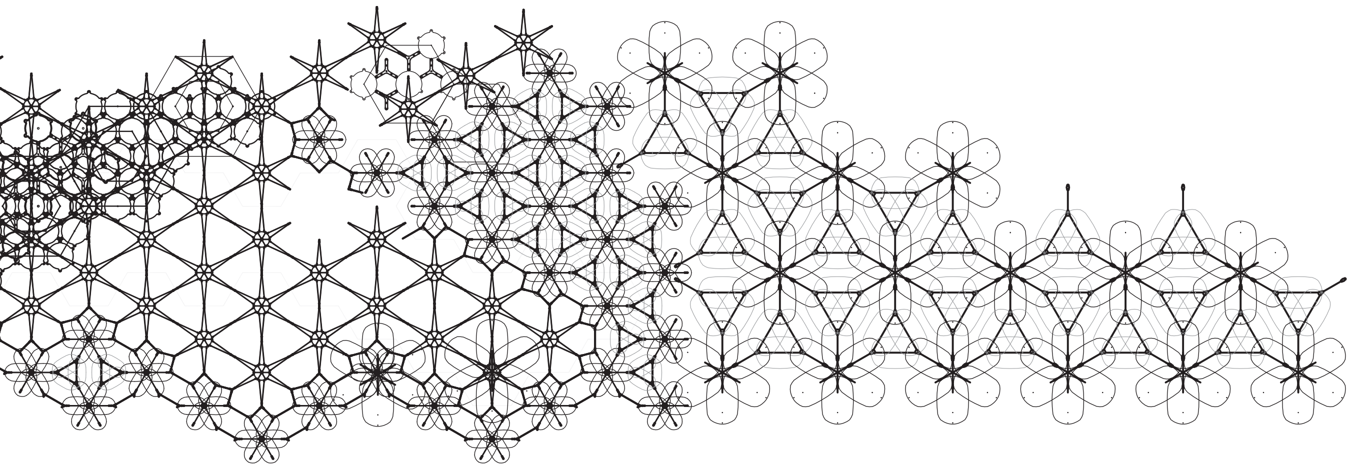

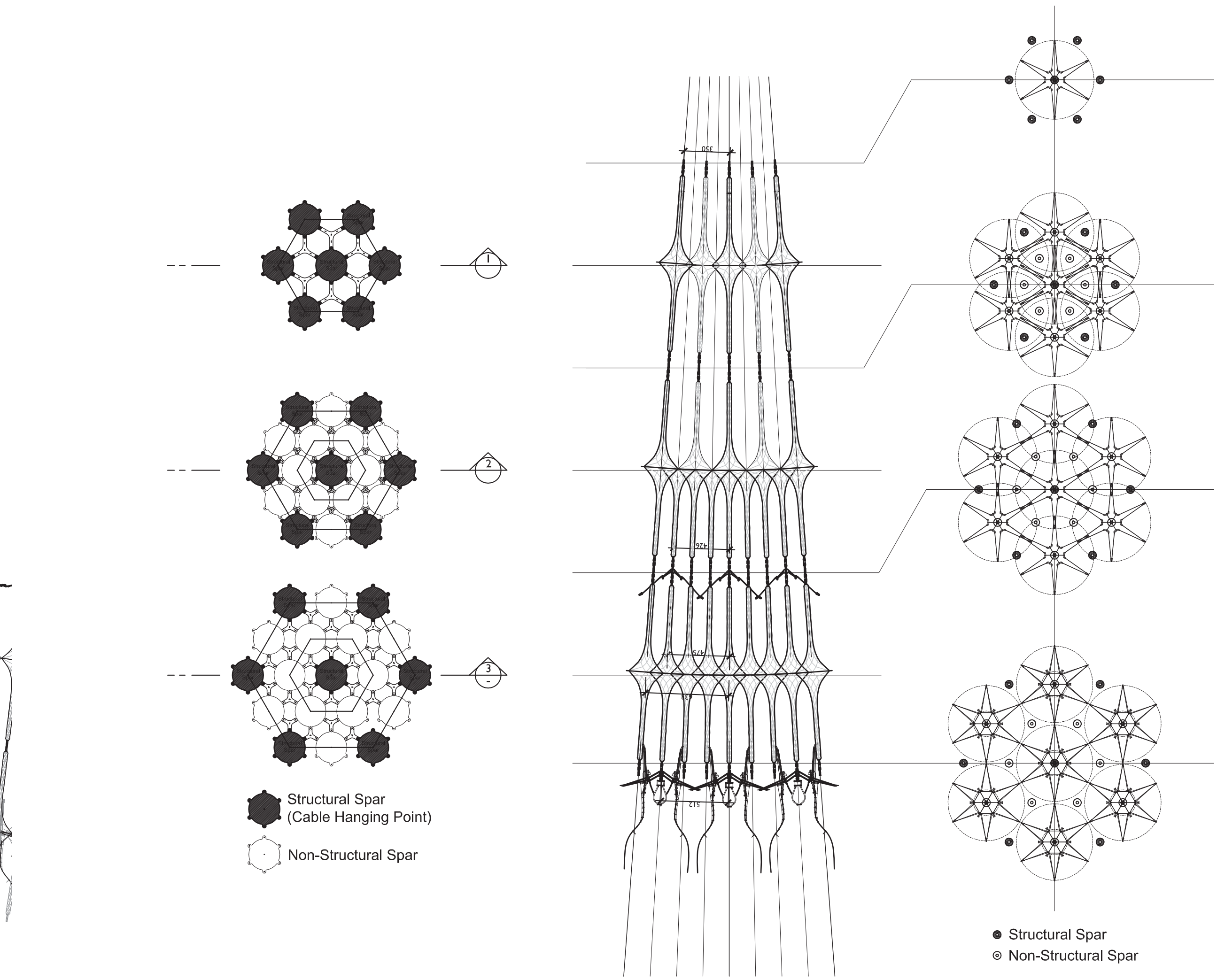

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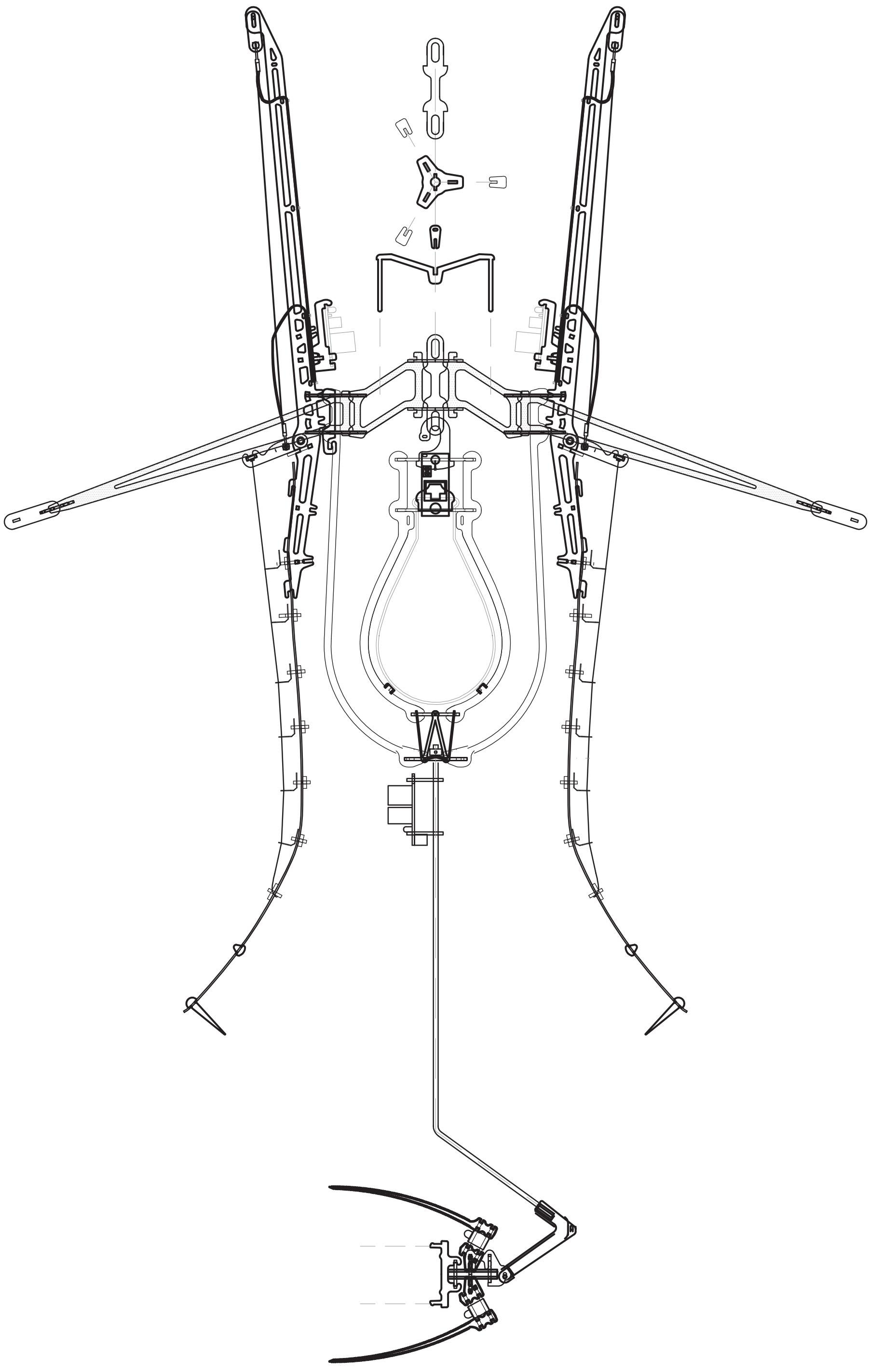
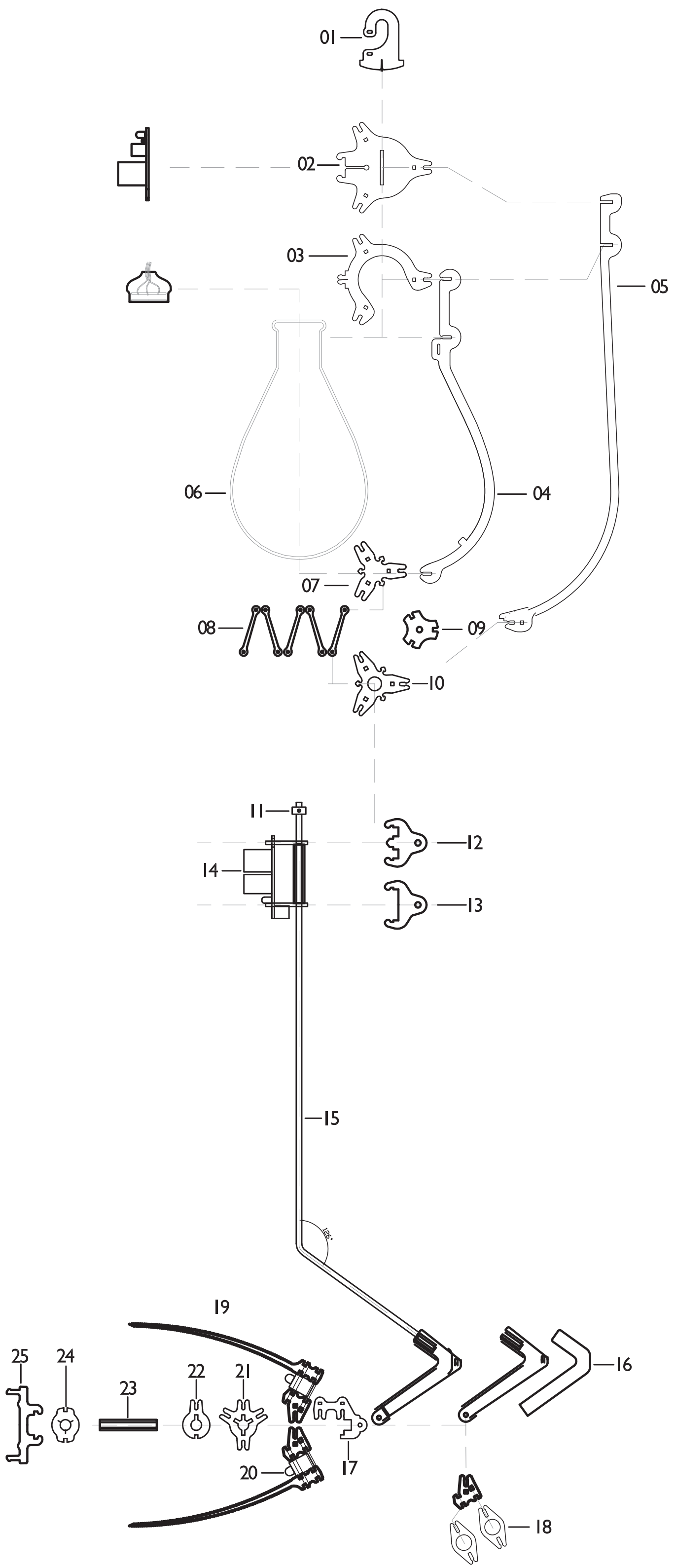
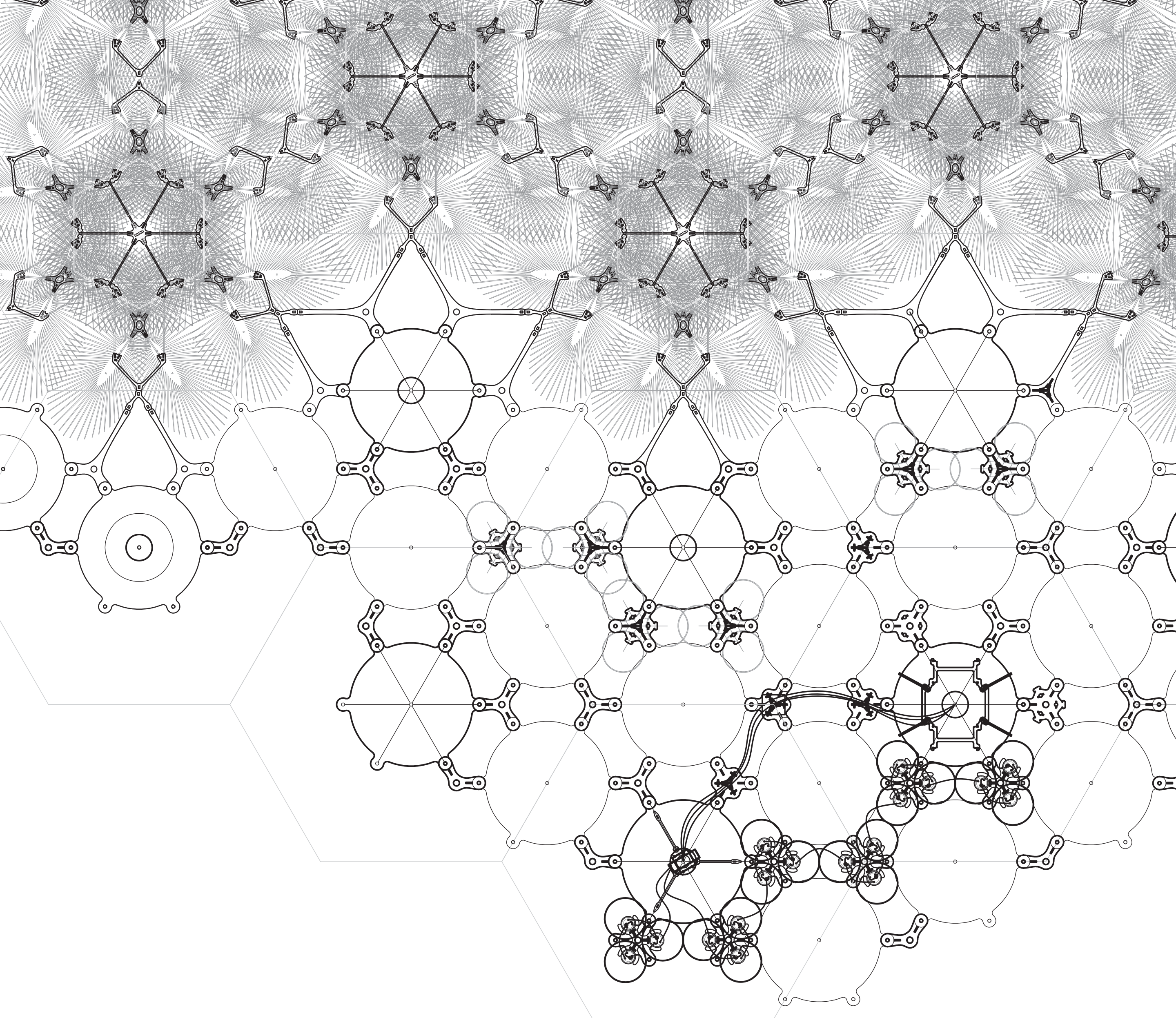




01	2 mm. Protocell Cage Hook
02	2 mm. Protocell Top Plate
03	2 mm. 250ml Flask Collar
04	2 mm. Protocell Rib
05	2 mm. Sensor Scout Long Rib
06	250ml Glass Flask (Long Neck)
07	2 mm. Protocell bottom connection plate
08	1.4mm white translucent Silicon strips
09	1.5 Red Silicone Plate.
10	2 mm. Sensor Scout Ribs bottom connection plate
11	1/8" Shaft Collar
12	2 mm. Sensor board top plate
13	2 mm. Sensor board Bottom plate
14	Sensor Interface Board
15	1/8" Aluminum Rod
16	2mm. Plastic rigid elbow
17	2mm. Pivoting Piece + Miniature Hardware
18	2 mm. LED & Spine Holder
19	Serrated Sensor spine
20	LED Light (X3)
21	2 mm. Four way Sensor Plate
22	2 mm. One way Sensor Plate
23	1/4" Plastic Tube
24	2 mm. tube Holder
25	2 mm. Sensor Holder
25	Medium Range Proximity Sensor



Diffusive Prototyping

Philip Beesley

I want to describe a particular kind of form language rooted intimately within our bodies[1]. I will try to articulate traces of subtle phenomena seeking emplacement, measured by intense mutual relationships of exchange with surrounding environments. The qualities that I will describe are characterized by punctuated oscillation. They use the paradigm of dissipative structures and diffusion as a fundamental guide for their design and their forms. This form language will be used to describe architectural projects that I will claim have living qualities. This personal involvement results in shifting boundaries that fluctuate between hard facts and hopeful fictions for exploring the future.

For twenty-five hundred years, Western artists and designers have been speaking about emulating life[2]. The imagery and forms from this tradition show potent hope for inanimate forms of craft and art coming alive. Yet the speech and evocations of visual art and architecture have often treated 'life' as a kind of boundary, defined by separation and distance from human craft. The symbolism that evokes life has been maintained by distinguishing human artifice from the viable organisms of nature[3]. The discipline of architecture seems to have been especially emphatic in maintaining this divide. Architecture seems a counterform to nature[4], staying deliberately distinct from the living world, preferring instead the role of a stripped stage that supports the living world by means of clear restraint. Perhaps that kind of separation has a moral kind of imperative, avoiding trespass. Indeed, if we think about atrocities this past century, then there would be a very good reason to make a clean, empty place where we could be free, where a clear sanctuary could support nuanced interactions that rebuild humanity.

1 This essay was presented at Alive International Symposium on Adaptive Architecture, Computer Aided Architectural Design, ETH Zurich, March 2013.

2 Youngs, A. M. (2000). The fine art of creating life. *Leonardo*, *33*(5), 377-380.

3 Crist, C. P., & Roundtree, K. (2006). Humanity in the web of life. *Environmental Ethics, 28*(2), 185-200.

4 Hagan, S. (2001). *Taking shape: a new contract between architecture and nature*. Routledge.

facing page

5 Plan of Organic Battery cluster

Yet the distinct progress of science and technology in recent decades invites a change to this strategy of restraint. The achievement of comprehensive information within the human genome project[6], the accomplishment of potent learning functions in computational controls[7], and the increasing fluency in programming physical materials and projecting complex-system ecological modeling can conspire to demonstrate that living systems no longer need be maintained as a sacrament separate from human intervention[8]. The ability to see our traces and to understand dimensions of the impact with which we thread forms an ethical key to this change. With that sensitivity it becomes possible to speak about full-blooded fertile involvement for designers. The shift offers a symmetrical opposite to the kind of deliberately empty, existentialist freedom that has defined generations of preceding architecture[9]. Emerging from the distancing functions of reverence into a new phase of highly involved stewardship, living systems can now occupy the space of architectural design.

In this discussion I will make comments about emplacement in pursuit of a fundamental relationship with the environment rooted in diffusive form. I will describe subtle phenomena that evoke expanded physiologies, embodying the forms of diffusion and dissipative forms. Building from these qualities, projects will be described that approach living qualities. I argue for a particular kind of form language employing diffusive and dissipative forms. This morphology stands distinctly against the prevailing modern preference for stripped, minimal stages offering freedom. The language I argue for instead pursues culpable involvement. An undulating, quasiperiodic metabolism is evoked by this series of projects. Rather than a polarized working method that follows only a 'top-down' or 'bottom-up' method, the edges of this working method oscillate. The deliberate ambivalence of this approach can yield qualities where things convulse and stutter in emerging vitality.

The entire world is never stable. In poignant contrast to the architectural tradition framed by 'firmitas', today's environment seems distant from the stable hold of natural cycles. Instead of the eternity of nature, we are surrounded by turbulence. What kind of design methods might contribute to such instability? It would be tempting to follow optimums within natural form finding that they are exemplified by the space of a rain drop. If Plato were teaching today's designers he might say that the elegant reductions of primary geometry provide keys to architecture[10] by using the minimum possible envelope

6 Collins, F. S., Morgan, M., & Patrinos, A. (2003). The Human Genome Project: lessons from large-scale biology. *Science, 300*(5617), 286-290.

7 Eliasmith, C., & Anderson, C. H. (2004). *Neural engineering: Computation, representation, and dynamics in neurobiological systems.* MIT Press.

8 Grimm, V., Revilla, E., Berger, U., Jeltsch, F., Mooij, W. M., Railsback, S. F., ... & DeAngelis, D. L. (2005). Pattern-oriented modeling of agent-based complex systems: lessons from ecology. *Science, 310*(5750), 987-991.

9 Markus, T. A. (2013). *Buildings and power: Freedom and control in the origin of modern building types.* Routledge.

10 Skinner, S. (2009). *Sacred geometry: deciphering the code.* Sterling Publishing Company, Inc..

and the maximum possible territory enclosing interior territory. Yet the reductive form language that guides such efficiency is a kind of machine for resisting interaction as well. There can be no less surface for interaction than that of a sphere. The reductive form-languages of spheres and crystals achieve maximum possible territory and maximum possible inertia by minimizing their exposure to their surroundings[11]. Such a form can be effective in a cold climate that requires retention of energy. It can also be effective if you want to destroy as much as possible with embodied energy of ballistics. However, cooling requires the opposite. The opposite of a spherical raindrop appears in the form of snowflakes. Snowflakes epitomize dissipation; the operation harvests the internal heat by optimizing release through an efflorescence of exchange. Such a form offers a strategy for a diffusive architecture in which surfaces are devoted to the maximum possible intensity and resonance with their surroundings[12].

11 Chernov, A. A. (2001). Crystal growth science between the centuries. *Journal of Materials Science: Materials in Electronics, 12*(8), 437-449.

12 Wallisser, T. (2009). Other geometries in architecture: bubbles, knots and minimal surfaces. In *Mathknow* (pp. 91-111). Springer Milan.

The form-languages pursued in this discussion can contribute to a lexicon, a system for design. This search for fertile, generative language can be informed by theories of growth in the parallel discipline of human psychology. A traditional sequence of growing from infancy might follow the mid-20th century American psychologist Abraham Maslow's ladder of self-actualization[13]. Maslow's series of developmental stages follows a sequence of growth. As a very young person you lose things, get hurt and take responsibility. You move into agency and increasing freedom, able to handle separation and opposition. In such a sequence a goal is set up that moves distinctly from a diffuse, turbulent beginning into the destination of a clear, isolated and bounded whole. Artists might use similar terms to Maslow, I think, when they speak about relationships in their visual compositions, they often speak of 'figures' and 'grounds', and it seems to me that clear, bounded figures are almost always pursued as goals, emerging out of dark and uncertain grounds.

13 Maslow, A. H., Frager, R., & Cox, R. (1970). *Motivation and personality* (Vol. 2). J. Fadiman, & C. McReynolds (Eds.). New York: Harper & Row.

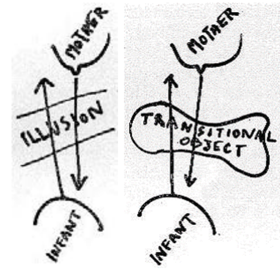
Donald W. Winnicott theorized the emergence of the infant psyche at the same time as Maslow, but his way of seeing our environment seems distinct from Maslow's prevailing views of growth and development. Similar to Maslow, Winnicott looked closely at the states that came before a person knows they are a person and before they know their name. He talks about objects and physical things as having a key relationship with living bodies and with emerging consciousness[14]. Winnicott describes Transitional Objects –

14 Winnicott, D. W. (2012). *The family and individual development*. Routledge.

blankets, stuffed animals, favourite objects that as a child you would carry as a constant. In those early times such things can be said to be coterminous with your body and with your mind. I do, dimly, remember my own 'blanky'. Perhaps I was almost fused with it when I was a tiny boy. Winnicott says some extraordinary things about trying to deliberately extend and delay the growth out of such an ambiguous state[15].

Rather than something being cut, pulled, and firmed up, the developing form language encourages quite slow and gentle condensation, allowing self-determined forms to crystallize out of a continuum. Far from responsible, wilful use of tools and manipulation of objects, he evokes a continuum that seems to offer delicious, delirious potential. In such a sensitive state there is a sense of being connected still.

From objects, Winnicott goes on to conceive of Transitional Fields[16], suggesting that cultural expressions could function in similar ways to objects handled by a pre-conscious infant, and implying in turn that public identity can emerge in ways that seem directly analogous to the emergence of individual consciousness. Winnicott says "The transitional objects and transitional phenomena belong to the realm of illusion which is at the basis of initiation of experience… the task of reality-acceptance is never completed, that no human being is free from the strain of relating inner and outer reality, and that relief from this strain is provided by an intermediate area of experience which is not challenged (arts, religion, etc.). This intermediate area is in direct continuity with the play area of the small child who is 'lost' in play." Illusions become prima materiae in such an exchange. To me, Winnicott gives confidence in the continuity of the world. He offers a potent response to the lingering question of how words and language might contribute to the generation of collective experience.

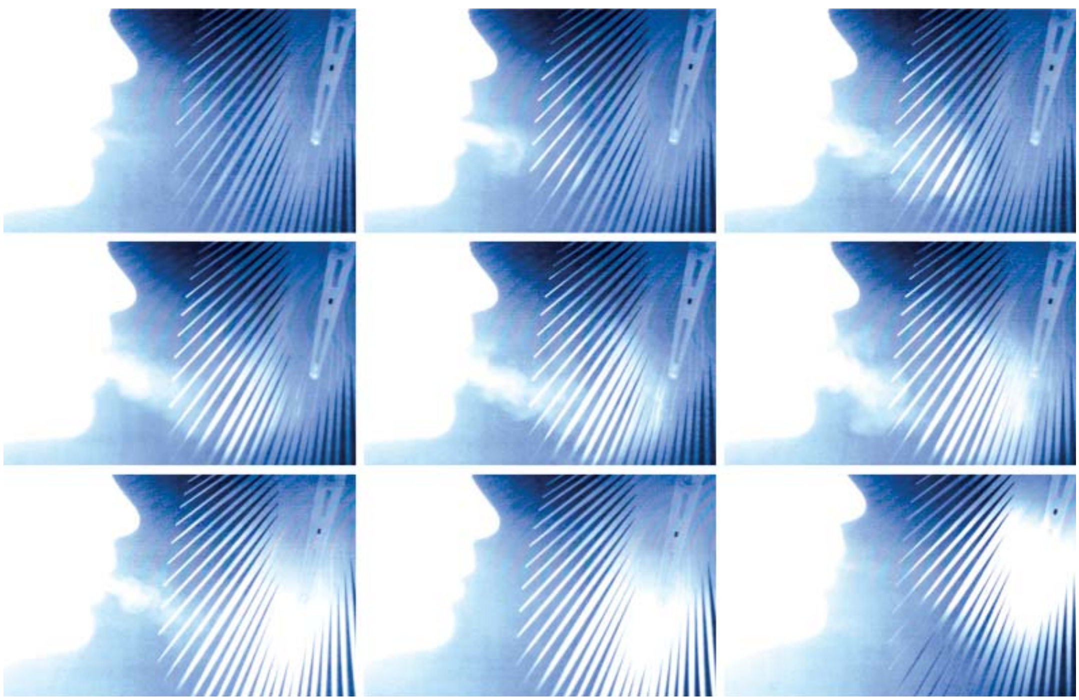


15 Donald Winnicott's hand drawings illustrate the mediating role that transitional objects can play for the emerging consciousness of an infant.

16 Winnicott, D. W. (1953). (1953). International Journal of Psycho-Analysis, 34: 89-97 Transitional Objects and Transitional Phenomena—A Study of the First Not-Me Possession. *International Journal of Psycho-Analysis, 34*, 89-97.

17 Cyclical exchanges of heat between a human figure and a polymer frond are recorded through thermal imaging.

We can look carefully and see the traces that we make. In my own work, I have started examining thermodynamics to seek a tangible exchange for the reality of an expanded physiology. Layers of exchange wrap around each of us. You can see the translucency of the heat as it propagates out through the polymer tines of the digitally fabricated frond in the image presented here[17]. Asking as the subject being photographed in that image, I ask if I am pushing that heat-energy outward or whether the surrounding milieu of vapours is pulling energy out of me. Perhaps both of those states intermingle. If we look at the cycle, heat exchanges reveal themselves at first as obvious: I emit heat; the world receives my energy. The imagery presented here is aided by increased precision in which notch filters are tuned in order to reveal a flux of carbon dioxide in the air as it carries a thermal plume into this frond. We can see it propagate and then bleed into the mass and be pulled into the middle. However, certainty in a one-way flow fades when the later stages of this sequence of images appear[18]. In the final images of the cycle, we can see that the temperature of the tines of the frond nearest my face recorded in dark tones show levels that are distinctly lower that when the cycle began.



18 Revealing subtle dynamics within an ambient environment, an 'ingestion' of heat-energy occurs as temperatures within polymer tine details travel inward, implied by the darker tones of its outer edges.

The ambient environment is not only receiving my action, but is also actively pulling heat from me. The surrounding air has pulled that energy outward, perhaps literally ingesting part of me.

I believe that the hardened boundaries exemplified by Plato's world of spheres and reductive forms might be replaced by form-languages that pursue intense involvement and exchange[19]. I make footprints in the world, but not as an individual figure leaving things about for them to dissolve into nothing. Rather, there's an active sense of the environment recoiling in multiple cycles. This implies a mutual kind of relationship. In turn, it suggests a craft of designing with materials conceived as filters that can expand our influence and expand the influence of the world on us, in an oscillating register: catching, harvesting, pulling and pushing. While personal boundaries can readily be found as functions of central systems--brain, and spine, and hearts define cores that we know well- parallel to those cores lie bundles of ganglia in our elbows or in our sternum and pineal[20]. Neural matter is riddled throughout our bodies, making a great shambling kind of network. Much of our consciousness is bound up in loops and reflexes, which happen at the outer edges of cognition. Such a model working internally could be expanded outward. In such a layered space, we could build up a deeply layered, deeply fissure set of relationships in which there are multiple sensitive boundaries. We might be able to build up in a sense of fertility reconstructing a kind of a soil and ground. We could measure values within that constructed ground by measuring resonance.

19 Ferrari, G. R. (Ed.). (2007). *The Cambridge Companion to Plato's Republic*. Cambridge University Press.

20 Gazzaniga, M. S. (Ed.). (2004). *The Cognitive Neurosciences.* MIT press.

The projects that my collaborators and I have been making pursue the construction of a synthetic new kind of soil. The projects have moved through several stages. Structures tend to be lightweight and ephemeral. One stage has concentrated on geometry and on periodic structures, looking at the kind of resilience that comes from textile matrices, in turn moving toward quasiperiodic systems in which things shift and multiply and effloresce, producing resonance. A further stage of development has involved construction of diffusive metabolisms in which protocell chemistries can start to set up exchanges and material flux, raising the possibility of renewing skins of material. Weaving those together, active agents within this work lead to questions that ask what geometries define our own personal worlds.

Hylozoic Ground, installed within the Canadian pavilion at the 2010 Venice Biennale for Architecture, was organized by a hyperbolic waffle structure that could be pulled and pushed into continuous doubly-curved shell surfaces.

The structural scaffold was clothed with layers of mechanisms. Kinetic components were grouped together, making tribal organizations of multiple clusters that would speak to each other and listen. In turn, these clusters would be organized in larger familial groups that spoke in quasi localized ways. Ripples of reaction and counter-reaction flow in this exchange. The behaviour is only partially predictable, but it is by no means random. It is the result of a tissue like aggregation of multiple gestures.

The hyperbolic scaffold is a resilient network made of tetrahedral structures, clothed with hanging filters which pass gentle convective plumes of ear and filter the environment. Electro-acoustic 'cricket' fields of polymer are shown in an image accompanying this writing[22]. Each one of the elements is powered by a miniature shape memory alloy actuator. In concert, the mechanisms

21 Touch-sensitive shape-memory alloy actuated cricket mechanism within Hylozoic Ground, 2010 Venice Biennale for Architecture.

22 Upward view, Epiphyte Chamber, Aleph Project, Museum of Modern and Contemporary Art, Seoul, 2013.

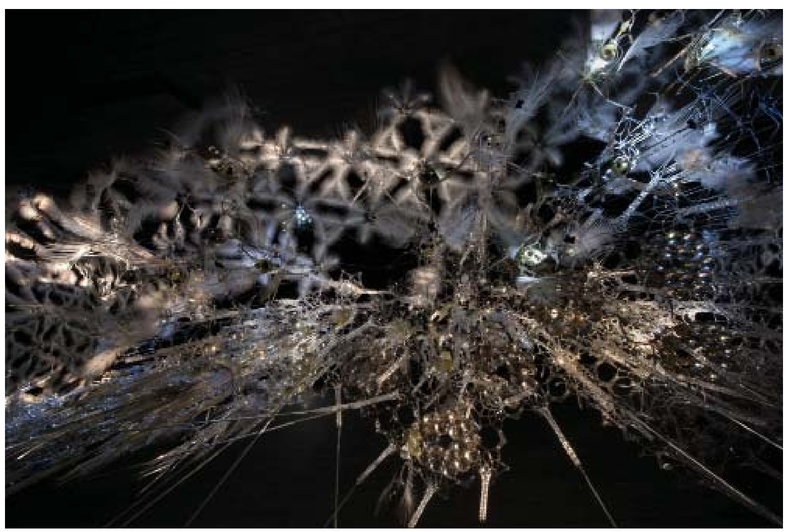
ripple out and resonate. They chirp as you come close, stimulated by touch. Protocell fields of glass flasks cycle water from the Venice canal and contribute cleaning and refreshment. These do not achieve high, efficient functions. Instead they offer a sketch of possibility.

Recent work expands into larger fields in which plumes of breathing vessels hover above and vibrations ripple through the entire field[22]. Multiple vibrations shiver through it, activated by direct-current miniature motors fitted with offset weights that create oscillating motion. Communications move out into rippling fields. Protocell environments start to work as a kind of a soil. Inside the flasks are slowly evolving reactions. Saturation is built up in layers using custom glass work that create suspended fluid reticulums. A copper compound blooms out under osmotic 'pumping' through an aqueous solution of potassium ferric cyanide, making walnut-like reticulated structures. Intensely multiplied small elements work together chained through vessels, imparting a blooming fertility. Humidity and scent are exuded. Small glands are wrapped around with traps. The elements with their humidity and with their scent gather, trap and start to harvest themselves. The sensation is on one hand, of being bathed but on the other of being eaten.

Our work pursues the beginnings for public emplacement. Large membranes made tangible rooms for gathering in a recent installation for Toronto's Luminato festival at Brookfield Place Galleria. The hanging layers of the Brookfield Place sculpture were programmed for slightly convulsive breathing motions, working to amplify the large flows of public movement that occurred each day. A whispering field of stories overhead were cued by arrays of proximity sensors. A breathing field employed approximately one hundred bladders, breathing and harvesting in response to people standing below. Such installations tend to be organized along two axes that work in parallel. Working laterally, the spaces are framed to support collective experience; the realm of the public common. Along with the mediation of who we are together, a vertical axes is used that frames personal physiology, encouraging perception of a fundament below and aerial dimensions reaching far above. This expanded emplacement reaches beyond social boundaries toward multiple dimensions.

Changing scale in recent work is a collaboration in fashion, starting to contribute to the sense of an expanded physiology in literal ways. Iris Van Herpen's studio offers a radical intimacy where the skin is only one boundary amongst many. Using simple fissured forms configured like leaky heart valves, hovering leaf-like layers very slightly push and pump in the gentlest of ways. They encouraging plumes of air to rise around you in a three dimensional lace made of silicon and impact resistant acrylic[23]. They make a live performance as they harvest your own energy and ripple around you. Layers lying immediately outside human bodies are organized in octaves of potential exploration, moving into turbulence. Musculature could be considered a mask, and an active fire-like metabolism can be sensed radiating through human skin. A corollary can be seen in a building composed of multiple layers. Traces are pulling at you. You become aware of the impact of your own tread in the world.

In summary, this work has been guided by opposing Plato's idea of a sphere, of the kind of skin that might claim to be efficient, that might claim to be responsible by reducing consumption and yet, somehow, which speaks much more potently of mortality than of a kind of a fertility. Spheres can speak of a violence and of a claim. Instead of the optimal, reductive forms of raindrops, I've suggested that snowflakes offer potent form-language that could guide emerging architecture. New projects from my studio are deeply layered and are founded in intimacy and touch. These works invite practice where we can see our traces. We can start to design in a way that can pull and harvest and resonate. The diffusive, dissipative form-language described here offers a strategy for constructing fertile new architecture.



23 Upward view of Epiphyte Spring, Zhejiang Museum of Art, Hangzhou, 2013. Recent textile-like forms imply intimate, diffusive boundaries within enclosing space.

Potent Matter: The Dynamic Chemistries of Hylozoic Ground

Rachel Armstrong

> And growing still in stature, the huge Cliff
> Rose up between me and the stars, and still,
> With measur'd motion, like a living thing,
> Strode after me...
>
> William Wordsworth
> The Prelude, Book 1: Childhood and School-time

Architecture may be considered as the ontology, epistemology and pedagogy of the production of space. Its territory extends way beyond the construction of buildings, the shaping of social and private spaces, acts as a screen for our desires, a stage for wars, provides context to our new technologies, becomes a site where myriads of material relationships are forged, a sanctuary for secrets, a theatre for our triumphs and may constrain, or nurture us. Yet in the late 20th century architecture has become equated with the construction of monuments to industrialization. The colossal phallic Burj Khalifa tower, Qatar's vulval 2022 World Cup Stadium design and the futuristic Infinite Loop Apple Headquarters, speak of artifice having conquered the natural world in imposing its will upon matter by realizing its striking mathematically-derived forms upon native landscapes. Through industrial construction technologies, oneiric structures can now be conjured by subduing matter to our geometric command, as it if was no more trivial than writing an algorithm for a virtual reality program.

IN DEFENSE OF MATTER

Modern paradigms that underpin industrial production processes are a *"revolution operating on matter"*[1], which propose that it can be reduced to bundles of brute substances that are merely fit to be consumed by machines. Yet, according to Maurice Merleau-Ponty, the 'flesh of the world' is composed of more than the naïve summation of fundamental qualities but through an

1 Brown, S.D. 2002. Michel Serres: Science, translation and the logic of the parasite' *Theory, Culture & Society*, 19(3), pp.1-27.

facing page

2 Radiant Soil, Paris, 2013.

awakening in our bodies[3]. Indeed, the effects of many contributing agencies produce the material realm. Yet, while a whole spectrum of philosophical perspectives speculate on the nature of matter, each perspective becomes a simplification or abstraction of what matter 'actually' is. For example, the material realm is more than the consequences of Bruno Latour's interacting actants[4], or Henri Bergson's "self-existing images" [5] and nor is it simply the consequence of language. Indeed, no single, reduced view of the material realm can provide a complete view of its character. Rather our experience of matter is shaped by deeply entangled relationships and emergent properties that result from complex interactions, which Karen Barad and Donna Haraway propose are diffractions of matter that continually interfere with each other to produce unique, emergent patterns[6] that may underpin material creativity[7]. Indeed, the true complexity of the material realm can only ever be partially observed within different existence spheres, such as language, phenomenology and realism.

So, in our Heraclitean reality – a world in continual flux – matter is a lively and complex force to be reckoned with. A 21st century theory of matter requires a new conceptual operating system for matter that is based on an appreciation of the properties of non-equilibrium. My research explores how assemblage[8] theory may provide a dynamic, complex understanding of the material realm without presuming that all effects are completely understood. The term assemblage is currently a philosophical concept that refers to platforms where specific groupings of actants form heterogeneous bodies that produce material encounters and even hypothetical entities that are porous, transitional and mutable. It is likely that the entire range of experiences with assemblages have not been discovered, or even invented yet, perhaps in a similar manner to how Jean Marie-Lehn's supra-molecular chemistry[9] has enabled us to synthetize new substances for the first time in the history of the universe.

Yet, to truly begin to apprehend the nature of 21st century matter, it requires a direct conversation with the material realm so that it may reveal further findings about its contrary character to inform our observations of it through experimental data, cultural theory and thought experiment. My research has therefore uniquely operationalized the concept of assemblages in a material context, so that it may be explored and interrogated as a real model of a philosophical proposition and to engage the voice of the material realm through the language of chemistry so that it may inform the experiments, potentially in surprising ways.

3 Merleau-Ponty, M. 1993. Eye and mind. In the Merleau-Pony aesthetics reader, Philosophy and painting, ed. G.A. Johnson. Evanston: Northwestern University Press, pp. 121-149.

4 Latour, B. 2005. *Reassembling the Social: An Introduction to Actor-Network-Theory*. Oxford: Oxford University Press.

5 Bergson, H. 2004. Matter and memory, Mineola, New York: *Dover philosophical classics*.

6 Barad, K. 2007. *Meeting the Universe Halfway: Quantum Physics and the Entanglement of Matter and Meaning*. Durham: Duke University Press.

7 Prigogine, I. 1997. *The End of Certainty: Time, Chaos and the New Laws of Nature*. 1st edition. New York: The Free Press.

8 Deleuze, G. and Guattari, F. 1979. *Thousand Plateaus: Capitalism and schizophrenia* (Athlone Contemporary European Thinkers). London: The Athlone Press.

9 Lehn, J.M. 1988. Perspectives in Supramolecular Chemistry-From Molecular Recognition towards Molecular Information Processing and Self-Organization. *Angewandte Chemie International Edition*, 27 (11): 89–121.

Indeed, 21st century matter possesses a subversive character that is lively and partly co-authors our experience of reality[10, 11]. Yet, we lack the conceptual toolset to see, describe or properly handle the full spectrum of its creative potential. 21st century design practices therefore require new approaches since now we have access to apparatus through which can manipulate quantum phenomena. Therefore we may now be more directly involved in the re-ordering, transformation, or annihilation of matter in ways that were previously unattainable. Even without access to specific apparatus, 21st century objects can also negotiate quantum field theory, where they can be suddenly brought into being and extinguished, navigate wormholes, respond to dark matter and exhibit 'quantum tunneling'. In other words, we can now appreciate that matter may act in ways that seemingly defy intuition, or even Newton's classical laws of material conservation. Indeed, a 21st century theory of matter completely contradicts notions of homogeneous atomism whereby every substance is made of correctly ordered fundamental particles. Yet modern physics has demonstrated the existence of a diverse range of primitive material fragments that exist so briefly they have to be 'made' in giant technologies such as the Large Hadron Collider (LHC). This structure - the largest Swiss watch ever made - accelerates plasma beams to near the speed of light, and then smashes them into each other to produce a heterogeneous range of primitive particles. In this rarefied context, we are seeing matter in evolution, which does not directly relate to an everyday philosophy of objects but nonetheless highlights the strange nature of matter and the encounters that shape our understanding of it.

10 Barad, K. 2007. *Meeting the Universe Halfway: Quantum Physics and the Entanglement of Matter and Meaning.* Durham: Duke University Press.

11 Bennett, J. 2010. *Vibrant matter: A political ecology of things.* Durham: Duke University Press.

Indeed, Gaston Bachelard's heurestical notion proposes that there is no simple substance - only complex objects, which can be built by theories and experiments that are iteratively improved upon[12]. Yet, 21st century materiality appreciates that objects are more than complex entities but also highly dynamic structures. Indeed, at the subatomic level, all substances are vibrating and behave discontinuously across scales. It is not clear, for example, why gold is a red, active substance in colloidal form at the nanoscale and a largely inert material with a characteristic hue at the macroscale. So, when matter is dynamic, it behaves according to the laws of non-equilibrium systems. While some objects are encountered at relative equilibrium at the macroscale, such as a table, London Bridge, or the metallic shell of an aeroplane, at the quantum scale they will nonetheless behave as far from equilibrium systems, although this will not be directly observed.

12 Bachelard, G. 1994. *The poetics of space: The classic look at how we experience intimate places.* Beacon Press: Boston.

A 21st century phenomenology requires engagement with the incompletely characterized, innate potency and strangeness of the material realm. This emanates from multiplicities and existential paradoxes, such as in quantum physics where matter appears to behave as both particle and wave[13]. These observations are entangled with notions of complexification that raise the possibility of continual convergence between different modalities despite modern insistence that aspects of reality are discrete. Indeed, a 21st century philosophy of objects appreciates that the physical world is composed of chimaeras and inconstant substances. They exhibit recognizable qualities that are not absolutes, but they are sufficiently persistent for them to be identifiable. However, with time these qualities may change. These potential permutations confer the material realm with its formidable presence and straddle the grotesque and sublime. Indeed, a 21st century theory of objects is socially relevant and empowers them with political agency so they may claim (co)authorship in the production of our living spaces by producing effects that impact on human activities, such as the noxious chemicals secreted by decomposing garbage tips or sudden power outages of national electricity grid systems[14]. We may also view this empowerment as part of our own agency in the world so that we, as material expressions, may also inhabit a physical realm that it is not reduced, abstracted or disconnected. Rather, we may understand that our own physical being in the world, of being a body, may influence our experience of reality in ways that surprise us, such as in recovering from a serious illness, or through record-breaking achievements and acts of spontaneous creativity.

Our most potent encounters with 21st century materiality are experienced as massive, spontaneous material shifts that are dictating the context in which architecture exists. They are understood as global phenomena, such as climate change, which may be understood as observations in environmental conditions that can be attributed to specific causes, such as climbing partial pressures of carbon dioxide, greater than average rainfall, reductions in biodiversity, the march northwards of tropical diseases, or apparent shifts in the earth's magnetic poles. However, these material expressions are also associated with a cultural phenomena such as Swangeddon, where swans replaced people in the streets of Worcester when the banks of the River Severn flooded on Christmas Eve, 2013[15]. With an awareness that climate change is at least partly precipitated by anthropogenic causes, these extreme events are also no longer entirely naturalized[16], or meet our aesthetic expectations of the natural world[17].

13 Barad, K. 2007. *Meeting the Universe Halfway: Quantum Physics and the Entanglement of Matter and Meaning*. Durham: Duke University Press.

14 Bennett, J. 2010. *Vibrant matter: A political ecology of things.* Durham: Duke University Press.

15 Edmonds, L. 2013. Seven swans a-swimming! Inquisitive birds make the most of river's burst banks to go exploring. Mail Online. [online] Available at: *http://www.dailymail.co.uk/news/article-2528924/Severn-swans-swimming-Inquisitive-birds-make-rivers-burst-banks-exploring.html*. [Accessed 15 March 2014].

16 Van Mensvoort, K. and Grievink, H.J. 2012. *Next Nature: Nature Changes Along with Us*. Barcelona: Actar.

17 Morton, T. 2007. *Ecology Without Nature: Rethinking Environmental Aesthetics.* Cambridge: Harvard University Press.

To fully access this rich material potential a new toolset for working with dynamic matter is needed. My research aimed to operationalize the philosophical concepts underpinning the notion of a lively, empowered material realm at far from equilibrium states by identifying dissipative structures as an experimental model through which proposals could be practically demonstrated and tested[18]. My work also proposed to engage the voice of the material realm through the language of chemistry, so that it could inform experimental outcomes. Dissipative structures proved to be an ideal experimental model to explore dynamic materials in an architectural context, since they straddle the conceptual realms of object and process-oriented theories. They are simultaneously objects that possess structure and also embody process through a simple 'metabolism' [19] that takes energy from outside the system and transforms it into a range of lively material phenomena, whose integrity is maintained by a continual flow of atoms and energy. Dissipative structures, also known as systems, exhibit lifelike properties that can be demonstrated and tested in architectural design contexts to produce tools[20] and technical objects[21]. Specifically, dissipative structures can deal with architectural programs by applying Natural Computing techniques[22] as outlined by Bernard Tschumi, which entangle 'space, event and movement' [23]. They also possess an architectural quality according to Mark Morris' notion of *"miniature thinking"*, where the collective organization of agents with qualities unique to their scale can link the small and full-scaled worlds in an emergent, dynamic temporal relationship that invokes the fantastic and uncanny through scalar fantasy and alchemical lore[24]. From an experimental perspective, exploring the surprising properties of objects is more feasible when they are encountered at the human scale and are far from equilibrium. Using dissipative structures as a technological platform that is operationalized by assemblage theory and instrumentalized by natural computing, it is possible to work in new ways with 21st century matter to produce complex expressions of materiality that are encountered as rich ecologies, rather than the reduced formalism of machines which typifies the production of contemporary architecture[25]. Indeed, designing, building and operationalizing the *Hylozoic Ground* chemistries over the last few years has provided insights that gesture towards a 21st century theory of matter.

BACKGROUND TO THE HYLOZOIC GROUND CHEMISTRIES

When I first started working on the chemical designs for the *Hylozoic Ground* series using a range of dissipative structures, such as 'protocells', Traube cells

18 Prigogine, I. 1997. *The End of Certainty: Time, Chaos and the New Laws of Nature.* 1st edition. New York: The Free Press.

19 I am using the term 'metabolism' in this case to refer to a simple chemical reaction that prolongs the dynamic state of a lifelike material system by keeping it away from reaching effective thermodynamic equilibrium (Schrödinger, 1944), rather than invoking the biological concept of a complex network of biochemical interactions that maintain the processes underpinning life.

20 Heidegger, M. 1993. The Question Concerning Technology. In William Lovitt and David Farrell Krell eds. Martin Heidegger, *Basic Writings. Revised and expanded edition*, pp. 287-311.

21 Massumi, B. 2012. 'Technical mentality' revisited: Brian Massumi on Gilbert Simondon. In: A. De Boever, A. Murray, J. Roffe and A. Woodward eds. Gilbert Simondon: *Being and technology.* Edinburgh: Edinburgh University Press, pp. 19-36.

22 Natural computing is a set of unconventional computing practices that engage with the computational properties of the material realm by applying spatial programs to shape events, and is discussed in more depth in a separate section in this essay.

Denning P. J. 2007. Computing is a natural science. *Communications of the ACM*, 50(7), pp. 13-18.

23 Tschumi, B. 2012. Architecture concepts: Red is not a colour. *Rizzoli international publications*.

24 Morris, M. 2011. Dream a little dream. *Architectural Design*, 81(2), pp.44-49.

25 Le Corbusier. C.E. 2007. *Toward an architecture.* Los Angeles: Getty Research Institute.

and various chemical organs, they were conceived and designed as functional objects that had the potential to couple with an existing system through process-enabled encounters, or simple metabolisms. While the objects themselves possessed unconventional properties - in that they were lively and were compelled to connect with other bodies within specific windows of opportunity - they were nonetheless produced through what is best described as an 'artisan chemical practice.' A range of different chemistries was developed for the *Hylozoic Ground* installation, each with a unique character. In 1892 Otto Bütschli first described simple oil in water mixtures that are powered by a saponification process and take the form of programmable lifelike droplets[26]. When these so-called Bütschli droplets are observed with the naked eye, they show striking lifelike qualities. For example, they are able to move around their environments, sense their surroundings, interact with each other and synthetize solid matter. Another species of active chemistries based on banding chemical structures described by Raphael Liesegang, called Liesegang Ring Plates, were produced, taking the form of activated gels through which partially solution coloured salts moved through the matrix under the influence of gravity that marked time as chemical clocks, through the diffusion and precipitation of reactive chemical complexes. Another dynamic chemical species, originally described by Moritz Traube in 1867, known as Traube cells, underwent a striking transformation of colour, volume and shape from blue diamond shaped crystals into swelling brown seaweed-like membranous fronds. Each population of dynamic chemistries was constructed using a hand held pipette and mounted carefully within special housing. For example, the Bütschli droplets were suspended at an oil interface for maximum visibility from underneath in hand-blown spherical flasks that acted as lenses through which the droplet populations were magnified and bathed in a radiant halo. The ambition was to develop systems with weak technological functions that could be coupled with the cybernetic network of interacting bodies. The outputs were initially imagined as similar to the organic vinegar and lemon batteries that Beesley had already been working with in the *Sargasso* installation; a geotextile meshwork created with Mette Ramsgarde Thompsen for the COP15 exhibition at the Royal Danish Academy in 2009.

26 Armstrong, R. and Hanczyc, M.M. 2013. Bütschli dynamic droplet system. *Artificial Life Journal*, 19(3-4), pp. 331-346.

Indeed, the initial pedagogy of the dynamic chemistries was therefore centred on an investigation of their epistemologies, typologies and functions. This included applied encounters such as troubleshooting for missing key ingredients where ingredients that could be used in a domestic setting, such as glycerine and food colouring, were substituted into the preparation and created a different portfolio of outcomes[27]. As the *Hylozoic Series* evolved through many sites and configurations, the nature of production of the dynamic chemistries also changed. Rather than being produced by artisans, they were translated into robust recipes that could be repeatedly executed by non-scientific collaborators. Gradually, the systems of production of these procedures also changed and could take place through an increasingly remote and distributed process that depended on the orchestrated actions of many dedicated contributors. With the international proliferation of different organ species within the various manifestations of the *Hylozoic Series* and also in discrete installations in group shows, including the 'kitchen protocells' made for the 'On Architecture' group show in Belgrade[28], the dynamic chemistries have begun to play a very different role in design philosophy. They have taken on a greater status than merely connectable 'objects', or soft technologies, but provide a tool for structural coupling between specific geographies of objects. They therefore provide access to a lively, interconnected material realm in which we are all immersed. This is not simply an attitude or an intellectual stance on the nature of reality, but a physical engagement with a set of principles that dynamic chemistries can help reveal, and actively interrogate. This suggests that at far from equilibrium states, chemistries may help us investigate aspects of the material realm in ways that mechanisms cannot.

CHEMISTRY AS TECHNOLOGY

Simondon proposes 'technical objects' fall into two types: Cartesian and cybernetic[29]. I propose that chemical technologies constitute a new category, or technical ordering, and are not simply soft machines (complete solutions) or cybernetic systems (adaptive) as they can transform their materiality. However, chemical technologies are not detached technologies but may horizontally couple with mechanical or cybernetic assemblages. Dynamic chemistries possess some of the properties of living systems and therefore, like biotechnologies, may invent unexpected outcomes in the course of their becoming or discover new operations to achieve these goals. Even in the most conventional sense dynamic chemistries are not simply 'objects'. In physical terms they are 'dissipative structures', which are highly ordered material systems that are produced when matter is at far from equilibrium[30]. Dynamic chemistries are produced by self-assembly within chemical networks like the Bütschli system[31] when one group of substances, such as olive oil, is added to another, such as a strong alkaline solution.

27 Modifications to the Bütschli system using domestic ingredients led to a separate practice of 'kitchen protocells' by constructing a field of interaction based on the dynamic properties of water, rather than on the saponification reaction that underpins the original preparation. An interface for the exchange of water was created by layering olive oil over glycerine and then adding food colourant to the system. The droplets temporarily rested at the interface between the two chemical fields before collapsing as water was drawn from the food colourant by the hygroscopic properties of the glycerine, leaving visible trails of matter that could be read as a 3D painting.
Armstrong, R. 2014. *Vibrant architecture: How 'vibrant matter' may raise the status of the material world in architectural design practice and be recognized as a codesigner of our living spaces.* Unpublished PhD thesis. University College London.

28 On Architecture, 10 December 2013. Gallery of Science and Technology, Serbian Academy of Sciences and Arts, Belgrade. [online] Available at: *http://www.strand.rs/architecture/program.html.* [Accessed 18 January 2014].

29 Massumi, B. 2012. 'Technical mentality' revisited: Brian Massumi on Gilbert Simondon. In: A. De Boever, A. Murray, J. Roffe and A. Woodward eds. Gilbert Simondon: *Being and technology.* Edinburgh: Edinburgh University Press, pp. 19-36.

30 Prigogine, I. 1997. *The End of Certainty: Time, Chaos and the New Laws of Nature.* 1st edition. New York: The Free Press.

31 Bütschli, O. 1892. *Untersuchungen ueber microscopische Schaume und das Protoplasma,* Leipzig.

The chemical field spontaneously spreads out and breaks up into millimeter scale droplets that can move around their environment, sense it, produce microstructures and interact with each other. Owing to the strong forces that exist between these sets of substances, they are *a priori* empowered objects and do not depend on an external energy source to animate them like machines do, so their interactions directly articulate existing sets of relationships.

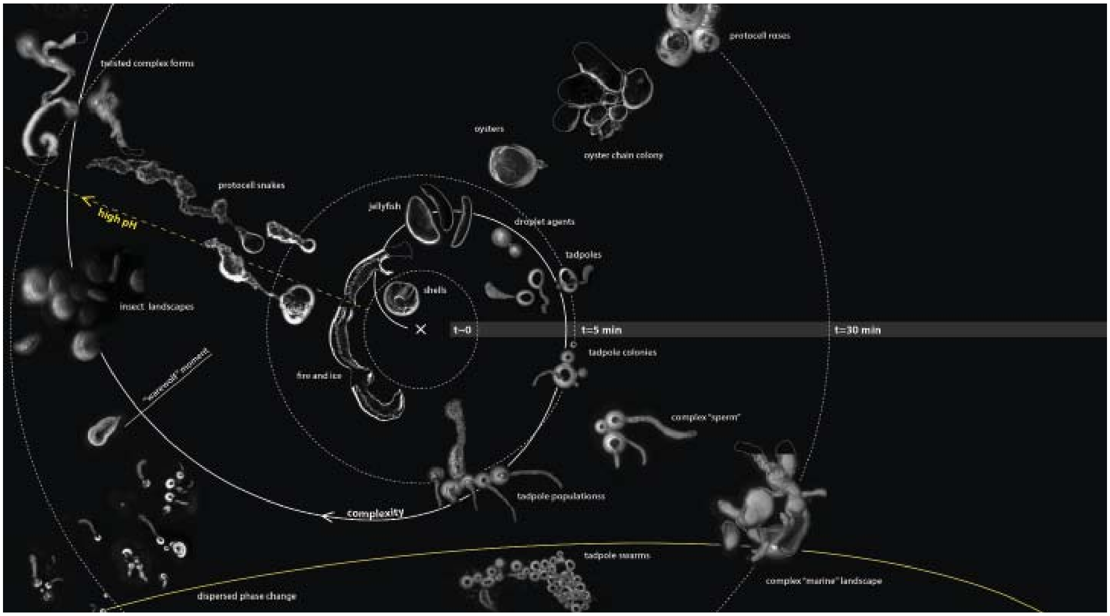
Dynamic droplets achieve their outcomes by inserting time and space into matter through spontaneous movement produced by the mass flow of molecules in the system, which evades the decay towards equilibrium. This is consistent with biological systems that are highly reticular and are spatially and temporally organized, such as the endoplasmic reticulum, which constitutes a site in which biochemical processes are spatially distributed throughout the body of the cell. Within this interior labyrinth, a host of metabolic processes are catalyzed and transformed to create a chain reaction of self-perpetuating chemical flow, where the output of one reaction becomes the beginning of another. In this way, living systems maintain their operational integrity as transformers since not all their chemical relationships are simultaneously active or in the same place and are therefore separated in time and space.

It is important to note that these exchanges are literal. They are not imagined, represented or translated in any way. They constitute a virtual field of possibilities that can evolve and resolve in different ways through matter. Yet because they are ultimately real, their actual outcomes can only embody one possibility from a range of possible material expressions. I mapped the field of potentiality of the Bütschli system by recording the structural and behavioural performance of over 300 Bütschli droplet experiments using a Nikon Eclipse TE2000-S inverted microscope with Photometrics Cascade II 512 camera and in-house software, using the outcomes to design a cartographic system based on oceanic ontologies[32], which was drawn by Simone Ferracina[33].

The diagram reflects the potential activity of Bütschli droplets on an oil field, which may be considered as a stage, or architectural site, in which the interactions between droplets are 'actors' -the architectural program. Interactions generate events and leave physical traces on an ever-changing stage that operates beyond abstractions and directly records the site details as a generative, dynamic system, which Matt Lee describes as an 'oceanic ontology' [34]. The site details are organized on the diagram within concentric circles, which represent an exponentially increasing series of time intervals, where novelty and

32 Lee, M. 2011. Oceanic ontology and problematic thought, NOOK Book/Barnes and Noble. [online] Available at: *http://www.barnesandnoble.com/w/oceanic-ontology-and-problematic-thought-matt-lee/1105805765*. [Accessed 19 April 2013].

34 Lee, M. 2011. Oceanic ontology and problematic thought, NOOK Book/Barnes and Noble. [online] Available at: *http://www.barnesandnoble.com/w/oceanic-ontology-and-problematic-thought-matt-lee/1105805765*. [Accessed 19 April 2013].



33 Protocell Topology diagram

event frequency rapidly decrease with time. Complexity within the system is represented as a tightly curled spiral around the origin of the reaction. This provides an instrument through which the relationships between the Bütschli forms and their progeny may be grouped according to design preferences. While it is useful to find modes of recognition to navigate oceanic ontologies such as the Bütschli system, their expressions are probabilistic, complex, dynamic and highly contextualized resisting traditional classification systems. Indeed, they are consistent with Latour's notion of 'post-epistemological' phenomena[35].

35 Latour, B. 2013. Once out of nature: Natural religion as a pleonasm. Gifford lec ture series, University of Edinburgh. [online] Available at: *http://www.youtube.com/ watch?v=MC3E6vdQEzk*. [Accessed 7 July 2013].

Dynamic chemistries therefore embody the transformation of an object, specifically a dissipative structure, within a silent network of material systems, which are conjured when assemblages are brought into proximity with each other. These bodies may be engaged in acts of design as a technology of assemblages that offers its own disclosures and methods of production. When these systems are deployed as spatial programs they bring forth events from a technological fabric that has been so naturalized it has receded into the background of our daily lives and is now completely invisible to us. This technology is, of course, Nature, or as Bruno Latour prefers, OOWWAAB (Out Of Which We Are All Born)[36].

36 Ibid.

The *Hylozoic Ground* dynamic chemistries offer an evolving experimental platform that visualizes and shapes the material connectivity, novelty and transformation that already take place within natural systems and couples them with artificial systems. Dynamic chemistries enable the manipulation of these very simple ecological networks through the hardware of dynamic chemical objects and software of metabolism. However, dynamic chemistries also enable the deliberate modification of these networks, and while the underlying metabolic systems are sufficiently robust to accommodate local disturbances, the redistribution of chemical flows within these networks may eventually produce new kinds of Nature - entangled material expression of culture, ecology and technology [37]. As these exchanges become naturalized, their visibility withdraws from design practice and creates a primordial material matrix that is bursting with creativity. Indeed, this murky process underpins the material complexification and diversity that shapes the proto-ecologies of evolutionary change. Yet Nature is not neutral and deeply contextualizes which specific life forms may persist within a system through a process of Natural Selection. Such survival pressures arise from an existential sea of deeply entangled, mutable, unspecified entities. As their operations are observed, the transitional objects become increasingly ambiguous as their boundaries are being continually formed and reformed by complex networks of entangled interactions and the cultural forms of editing that attribute meaning to these configurations[38, 39]. Where some persist, others transform and many wither.

While proto-ecologies may be regarded as open fields of unevenly distributed assemblages, boundaries are still forged between them. Peter Sloterdijk proposes that these spaces are patrolled by a kind of 'immunology' of space[40], where certain structures are allowed to flourish and others are actively destroyed to allow the continued existence and evolution of the established system. Yet in a nonhuman world, boundary interactions are not exclusive to the behaviour of populations like flocks of migrating birds, schools of dolphins, or dynamic droplet assemblages, but also exist as strong and weak forces between objects, including gravity, electromagnetism, and strong and weak nuclear forces. These produce a host of interactions, including attractions, repulsions, amplifications and extinctions, which may be observed at the interface of trembling dynamic droplets, migrating Liesegang ring bands or blooming Traube cell membranes. Matter has its own immunology and object-technics, whose rules of interaction are forged by molecular bonds and physical forces that arise from many different agencies, some of which are human but many of them are not. While

37 Van Mensvoort, K. and Grievink, H.J. 2012. *Next Nature: Nature Changes Along with Us*. Barcelona: Actar.

38 Barad, K. 2007. *Meeting the Universe Halfway: Quantum Physics and the Entanglement of Matter and Meaning*. Durham: Duke University Press.

39 Bennett, J. 2010. *Vibrant matter: A political ecology of things*. Durham: Duke University Press.

40 Sloterdijk, P and Hoban, W. 2011. Bubbles: Spheres I - Microspherology: *Spheres Volume I: Microspherology: 1* (Semiotext(e) / Foreign Agents). MIT Press: Cambridge.

from a phenomenological perspective objects appear to resist and exceed their interactions, the *Hylozoic Ground* chemistries demonstrate that object bodies constantly throb with interaction at interfaces, where assemblages overlap with and are infused by the medium in which they exist. In the *Hylozoic Ground* installation, the various assemblages were designed in ways to reveal their relentless material exchanges through striking phenomena, such as the production of brightly coloured carbonate shells in the presence of carbon dioxide.

METHODS OF NATURAL COMPUTING

Since it is possible to shape the interactions of dynamic chemistries to achieve design outcomes, they may be regarded as arising in the shadowy realm between the 'born and the made' [41]. They possess natural qualities, technological capabilities and also computational abilities. Indeed, natural computing may be thought of as the design choreography of space, event and movement through matter, where the notion of an alternative kind of computation and technological platform has far reaching effects from cultural and environmental perspectives. The main goal of this field is to develop programmable, lifelike systems using a spectrum of platforms to better understand and reflect the properties of complex phenomena, such as adaptation, learning, evolution, growth, development and robustness. I will aim to draw together some of these threads as an entanglement of speculative writing, real world laboratory experiments, philosophical discourses and descriptions of project work while raising the possibility of working directly with Nature itself as a technology.

41 Kelly, K. 2010. *What technology wants*. New York: Viking.

Modern computing harnesses the properties of a particular kind of technology that uses mathematical abstractions and mechanical systems to build models of the world. Today, digital computers are such an integral part of our lives that we are harvesting vast amounts of data as if, the World Economic Forum observes, it was *'the new oil'*[42]. Yet digital computing has limits. It is not materially embodied but a symbolic expression of mathematics, and while it has enabled us to reflect on the shape of our thoughts to degrees that were formerly inaccessible, it does not enable us to directly materialize them. Instead, it relies on physical transformers, such as 3D printers that work indirectly to abstract and reinterpret possible material outputs, re-transposing them into a range of possible forms.

42 World Economic Forum on Europe and Central Asia, 9 June 2011. Personal Data: The "New Oil" of the 21st century, *World Economic Forum*. [online] Available at: *http://www.weforum.org/sessions/summary/personal-data-new-oil-21st-century*.

Mathematician Francoise Chatelin observes that if digital computing becomes entrenched as the only computing platform available to us, then it extinguishes the philosophy of mathematics since we cannot evolve concepts including number theory, which has the potential to bring us new symbols that possess meaning that extends way over and above the binary significations of the digital realm. By keeping the relationship between the philosophy of mathematics and computing very much alive, we may be able to find ways of realising forms of computing that directly couple with natural systems[43].

Nevertheless, the digital realm does not inevitably stand apart from the natural world. Rocco and Bainbridge advocate the facilitated convergence of the digital realm with other media by using advanced technologies, such as nanotechnology, biology, information and cognition. They propose that this NBIC singularity has the potential to create new production platforms with radical new benefits for humanity and the economy[44].

Natural computing offers a potential site for NBIC convergence by orchestrating the properties of matter and therefore inseparably entangles information and materiality so that hardware and software are tightly coupled. Currently, natural computing embraces broad, overlapping and multi-disciplinary practices, including digital modelling of biological systems, unconventional computing, synthetic biology, complexity chemistry and some aspects of robotics. Researchers include Martin Hanczyc at the Southern University of Denmark[45], Lee Cronin at the University of Glasgow[46], Klaus-Peter Zauner at the University of Southampton[47], Gabriel Villar at the University of Oxford[48], and Andy Adamatzky at the University of West England[49].

Owing to its embodiment and its parallel processing abilities, natural computing outputs embrace a different spectrum of possibilities to those of machines. Over the course of human development, we have used living things in a technological context and manipulated them accordingly, from guiding the metabolic activities of horses as transport systems, to harnessing the genetics of different laboratory workhorses that underpin the emerging science of synthetic biology such as yeast, *Escherichia Coli* and *Mycobacteria* genitalium.

But natural computing operates at a much lower level than biology. It does not require a centralized coding system like DNA but works through distributed methods. It is based in the common language of all natural systems, which are shaped by physics and chemistry. Natural computing's operating system is instructed by the actions of assemblages, which articulate a reality in continual flux and actively build networks without the need for an external energy source. However, although I have operationalized assemblages as dynamic chemical system for

43 Chatelin, F. 2012. *Qualitative Computing: A Computational Journey into Nonlinearity*. World Scientific Publishing Company: Singapore.

44 Roco, M.C. and Bainbridge, W.S. 2003. Converging Technologies for Improving Human Performance, Nanotechnology, Biotechnology, Information technology and Cognitive science. *NSF/DOC-sponsored report*. Dordrecht: Springer.

45 Hanczyc, M.M. Toyota, T. Ikegami, T. Packard, N.H. and Sugawara, T. 2007. Fatty acid chemistry at the oil-water interface: Self-propelled oil droplets. *Journal of the American Chemical Society*, 129(30), pp. 9386 – 9391.

46 Cronin, L. Krasnogor, N. Davis, B.G. Alexander, C. Robertson, N. Steinke, J.H.G. Schroeder, S.L.M. Khlobystov, A.N. Cooper, G. Gardner, P.M. Siepmann, P. Whitaker, B.J. and Marsh, D. 2006. The imitation game—a computational chemical approach to recognizing life. *Nature Biotechnology*, 24, pp. 1203-1206.

47 Palmer, J. 11 January 2010. Chemical computer that mimics neurons to be created. *BBC News*. Available at: *http://news.bbc.co.uk/1/hi/8452196.stm*

48 Villar, G. Graham, A.D. and Bayley, H. 2013. A tissue-like printed material. *Science*, 340(6128), pp. 48-52.

49 Adamatzky, A. Bull, L. De Lacy Costello, B. Stepney, S. and Teuscher, C. eds. 2007. *Unconventional computing.* Beckington, UK: Luniver Press.

the *Hylozoic Ground* as a demonstrator for a new kind of production platform that reversibly couples with a range of material systems, they are not formally recognized as a technology. Nevertheless, they are relevant to design and engineering practices since they offer the potential to construct spatial programs and realize them in different ways to machine-based programs.

The operating principles of machines and assemblages are compared in the following table:

	MACHINE	ASSEMBLAGE
COMPONENT	Object	Agent
ORDER	Series	Parallel
POWER STRUCTURE	Hierarchical system	Non-hierarchical
FUNCTIONAL SYSTEM	Machine	Assemblage
ENERGY	Extrinsic	Intrinsic and extrinsic - spontaneous operations may be prolonged with resource supply
CONTROL	Hard	Soft
PREDICTABILITY	Deterministic	Probabilistic
TRANSFORMATION	Binary - on/off	Variable states. generally conservative but may behave unpredictably and collapse or transform at tipping points

However, working with the assemblages that form the operating system of natural computing as a technological platform is challenging as they require new toolsets to operate, record and evaluate their impacts. They are very different to object-centered systems as they are sensitive to and forge connections with the environment. For example, natural computing techniques shape the interactions of assemblages so that they can carry out sustained interactions like growth and repair. They may also be directed towards accomplishing human-centered goals. For example, assemblage technology may fix dissolved carbon dioxide into a material form to produce self-assembling mineral structures, which was achieved in the 'proto-pearl' flasks in the *Hylozoic Ground* installation.

Most of the experiments that I have conducted using natural computing have been applied to the Bütschli system. Natural computing's outputs are consistent with the performance of non-equilibrium systems, which may be described by the laws of complexity. Unlike the inert objects that constitute a machine, the actants that comprise assemblages possess their own agency and result in a range of phenomena, such as emergence. Therefore, technological opportunities exist to directly and dynamically manipulate materials at far from equilibrium states in complex ways by developing spatial chemical programs. Yet natural computing is not about governing a discrete set of components but require orchestration of an entangled system of agents that interchangeably operate through emergent phenomena in various materials forms, such as fabric, software and hardware.

For example, the Bütschli system exemplifies how tightly fabric, software and hardware are coupled in natural computing processes. Bütschli droplets are produced when oil molecules, which may be thought of as a dynamic chemical program (both fabric and software), encounter alkali (both fabric and software) to produce soap-like crystals (both fabric and hardware), which form microstructures[50]. The overall performance of this system is shaped by many environmental conditions including temperature and local conditions like the movement of the droplets and the speed at which crystallization occurs.

50 Armstrong, R. and Hanczyc, M.M. 2013. Bütschli dynamic droplet system. *Artificial Life Journal*, 19(3-4), pp. 331-346.

Non-equilibrium chemistries operate through the ontology of assemblage technology that is qualitatively different than machines and consequently produce a range of unique phenomena. The hardware principles of this system are embodied in the droplet behaviour, which are not manufactured but self-assembled. Bütschli droplets self-assemble when an alkaline solution is added to an oil field, which spreads out and breask up into dynamic droplets about a millimetre in diameter.

Each droplet is an empowered object, agent, or actant, which possess an internal force that is powered by chemistry (or metabolism) and does not need an external energy source for it to exert its effects. Some of the properties are lifelike and these droplets can move around their environment, sense it and produce solids as a side effect of their metabolism. The droplets do not exist in series but work in parallel and are not organized hierarchically. They spontaneously form loose, reversible interactions, which form the basis of their assemblage operating system. Natural computing systems, therefore, inherently possess robustness, flexibility and the capacity to deal with external events.

Perhaps surprisingly, the technology is relatively conservative and is predictable within limits, except when tipping points in the system are reached. In the case of Bütschli droplets, populations may simultaneously change their shape and behaviour. The details of this process are still not fully understood. The technological principles of natural computing may be demonstrated in Bütschli droplets by changing the internal and external chemistry of the system. If mineral solutions are added to Bütschli droplets they can produce insoluble crystals in the presence of dissolved carbon dioxide. Populations of Bütschli droplets will also rapidly move toward a source of alcohol in their environment, which is likely to be caused by the reduction in surface tension by the solvent, although this has not been formally established.

However, for natural computing to be genuinely useful as a technology it needs to be readily applied at the human scale. While Bütschli droplet agents normally assemble at the microscale, it is possible to make them larger by slowing down their internal chemistry and engineering them to several centimetres.

When the droplets are placed within a constrained space, the chemical patterns that govern their interactions may be revealed as a consequence of the spatial restriction. An installation designed for the Synth-Ethic group show at the Bio fiction festival held at the Natural History Museum in Vienna in April 2011 introduced a two centimetre diameter spatial constraint to a modified preparation of the Bütschli system, which provoked the appearance of Turing Bands. This phenomenon is produced by diffusion and reaction patterns by chemical systems and is described by Alan Turing in his 'The Chemical Basis of Morphogenesis' paper[51]. Turing proposed that biological processes, such as gastrulation, animal skin patterns and specifically 'dappling', could be explained by this physical and chemical process. Today, these effects are attributed to the actions of information molecules such as RNA. However, since the lifelike properties of the Bütschli system are chemical, Turing's theory is actually responsible for the sinusoidal patterns produced in the system.

Natural computing is therefore susceptible to many influences. Since it possesses innate agency, the platform itself has the capacity to coauthor events that are relevant to design and engineering tasks. These tasks may be further shaped by humans through these techniques and constitute a form of 'soft' control.

Chemical assemblages are probabilistic systems that are influenced by many different factors, some of which I have just discussed. They are a promising potential design platform as they have the potential to evade the traditional

51 Turing, A.M. 1952. The Chemical Basis of Morphogenesis. Philosophical *Transactions of the Royal Society of London. Series B, Biological Sciences*, 237(641), pp. 37-72.

binary divisions between various systems and modalities, such as Nature/machine, humanism/environmentalism and matter/information. In dissolving these divisions, natural computing may increase our choices in the way we design with materials and may help us to build ecologies. However, if it is to be socially relevant it needs to produce human-centred impacts.

Natural computing techniques were speculatively applied in the architectural project *Future Venice*[52], which proposed to attenuate the city from sinking into the soft delta soils on which it is founded. Programmable droplets were designed to grow an artificial limestone reef underneath the foundations, which stand on woodpiles, and could navigate the waterways using metabolic processes and natural computing techniques. Specifically, the droplets were designed to move away from the light and produce a limestone-like substance, or 'biocrete', when at rest. In the light-soaked waterways, the droplets would move towards the darkened foundations of the city and accrete around the woodpiles on which the city stands. Here, they would use dissolved minerals and carbon dioxide to accrete an artificial limestone-like structure under the foundations of the city and spread the point load. A natural version of this process already occurs along the canals and is carried out by the natural marine wildlife. It is hoped that the programmable droplets could work alongside the organisms to co-construct an architecture that is mutually beneficial to the marine ecology and the city.

52 Armstrong, R. 2012. Future Venice. In Myers, W. and Antonelli, P. eds. *Bio Design: Nature, Science, Creativity.* London: Thames & Hudson /New York: MOMA, pp.72-73.

Importantly, should the environmental conditions change and the lagoon dry out – say for example, Pietro Tiatini and his colleagues succeed in anthropogenically lifting the city by pumping seawater into its deflated aquifers, or if when the MOSES gates are raised in 2014[53] and the native ecology reaches a catastrophic tipping point - the programmable droplets would be able to re-appropriate their actions. As the waters subside, the woodpiles would be coated with a protective layer of 'biocrete' that stops them rotting when they are exposed to the air.

53 Teatini, P. Castelletto, N. Ferronato, M. Gambolati, G. and Tosi, L. 2011. *A new hydrogeologic model to predict anthropogenic uplift of Venice, Water Resources Research,* 47(12), W12507.

Indeed, natural computing processes could be applied to the whole bioregion of Venice. Developing the right kinds of metabolisms and spatial programs could give rise to tactics that generate new relationships between natural and artificial actants to become the bedrock for forging life-promoting synthetic ecologies. Natural computing could potentially become a practice of shaping overlapping spatial programs and developing design tactics that enable a constant flux between fabric, space, structure and location. The outputs of the system do not imitate Nature but operate according to shared 'low level' programming principles that are applied through horizontal couplings between different populations of assemblages.

Still, natural computing does not propose a comprehensive solution to Venice's precarious future or indeed claim to end the legacy our environmental woes. Rather, it offers a convergent platform that enriches the available opportunities by which human and nonhuman communities may jointly respond to environmental events and challenges by codesigning their shared futures through the orchestrated construction of synthetic ecologies and weaving post natural fabrics throughout our living spaces.

Potentially, these approaches could give rise to a new platform to underpin human development as an alternative technological approach to digital computing and machines, which underpin industrial processes and offer ways of performing useful work that do not damage our ecosystems at their point of attachment to Nature, but strengthen them.

THE EVOLUTION OF ECOLOGICAL DESIGN

Dynamic chemistries are soft, permeable, mutable entities with presence. They can construct relationships and can transform one group of substances into another, not as inevitability, but as an occasional, asymmetrical event. Dynamic chemistries do not mimic natural systems or conform to already aestheticized notions that inform naturalism. Yet they work synergistically with Nature by sharing its language and constructing new possibilities using the hardware of matter and the language of metabolism. Dynamic chemistries are able to construct spatial programs that work toward an ecological design method through the production of new material hybrids. Further research and development of Natural computing methods may help us deal with 'ecological surprise', the unpredictable and transformational change in one or more natural systems that can be sudden, non-linear and catastrophic[53]. Indeed, dynamic chemistries may even facilitate a material politics that may help heal the metabolic rift that opened up with the growth of the modern economy, and catalyze a transition from an industrial to an ecological age as humans that are conceived through the lens of ecology rather than through the operational system of machines.

> … yet having felt the power
> Of Nature, by the gentle agency
> Of natural objects, led me on to feel
> For passions that were not my own …
>
> Michael: A Pastoral Poem. William Wordsworth

53 Lindenmayer, D.B. Likens, G.E. Krebs, C.J. and Hobbs, R.J. 2010. Improved probability of detection of ecological "surprises". *Proceedings of the National Academy of Sciences*, 107(51) pp. 21957-21962.

Using Affect to Increase Empathy in Near-Living Architecture

Ali-Akbar Samadani, Dana Kulić & Rob Gorbet

The psychology literature reports on the human tendency to ascribe human-like social and affective attributes to non-anthropomorphic structures. In some cases, researchers report that observers even consider these structures to be engaging in social interactions with each other[1]. Our experience with the *Hylozoic Series* of sculptures supports this observation: visitors are both emotionally impacted by their visit, and ascribe definite emotional states to the environments, which they often anthropomorphize. At the Venice Biennale installation of *Hylozoic Ground* in 2010, visitors were overheard saying, "Look, it's happy!" or "It's angry", and ascribing many other emotions to the sculpture. In some cases, visitors interacted with the sculpture as if it was human, talking to it, observing it with sidelong glances, and wagging their fingers at it admonishingly.

1 F. Heider and M. Simmel, "An experimental study of apparent behavior," *American Journal of Psychology,* vol. 57, no. 2, pp. 243–259, 1944.

If we are to realize the full potential of Near-Living Architecture, along with a host of other interactive machines, such as service and companion robots and interactive games, it is important to equip them with affective communication capabilities in order to enable an engaging, entertaining and empathic human-machine interaction. The capability to automatically recognize occupants' expressions and generate actuated affective responses improves the life-like attributes of the sculptures and enhances the hylozoic[2] perception, the perception that the environment is living, by their occupants.

2 Hylozoism is the ancient belief that all matter has life.

To pave the path toward fully interactive kinetic mechanisms capable of affective communication with their occupants, it is important to first develop a sufficient understanding of how humans perceive and express affect through bodily movements, and the postural and motion cues most salient for affective expressions.

facing page

3 Radiant Soil, Paris 2013

To this end, we have been conducting experiments on different affective human movement corpora to identify salient movement features for affective expressions, employing these features in developing computational models for affective movement recognition and generation. Human movement data consists of the time-series values describing the motion of many different body joints, resulting in large-scale datasets. We employ stochastic modeling approaches to derive a more concise representation of the movements that isolate movement cues relevant to affective expressions and enable efficient and accurate affective movement, recognition and generation. In particular, our research focuses on:

1. Understanding which features of movement convey affective expressions;
2. The automatic recognition of affective expressions encoded in movements; and
3. Adapting pre-defined motion paths in order to "overlay" affective content and generate affective expressions with kinetic mechanisms.

When generating affective expression with a kinetic mechanism, several additional considerations are introduced. The mechanism kinematics and dynamics may be different from a human demonstrator and may impose constraints on the range of motion. Furthermore, the structure and physical appearance of a mover might influence the human perception of its affective expressions. For example, if a mechanism doesn't have a human appearance, we have found it may be more difficult for a viewer to ascribe the full range of human emotions to it[4]. As part of our research, we have been conducting perceptual user studies to investigate the impact of the mechanism's structure and physical appearance on the perception of its movements. This article reviews the ongoing research and current results on the computational analysis of affective movements.

4 A. Samadani, E. Kubica, R. Gorbet and D. Kulić, Perception and Generation of Affective Hand Movements, *International Journal of Social Robotics,* Vol. 5, No. 1, pp. 35 - 51, 2013.

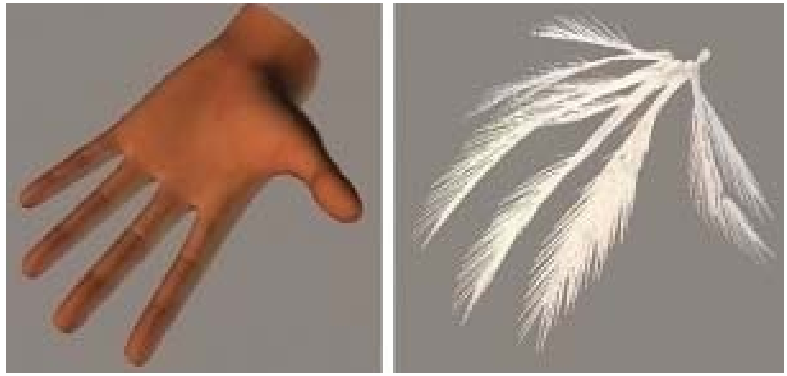
5 M. Karg, A. Samadani, R. Gorbet, K. Kuhnlenz, J. Hoey, and D. Kulic, "Body movements for affective expression: A survey of automatic recognition and generation," *IEEE Transactions on Affective Computing*, vol. 4, no. 4, pp. 341-359, Oct. 2013.

1 AFFECTIVE MOVEMENT PERCEPTION

Body movements are important observable manifestations of underlying affective states, and humans are adept at recognizing affective expressions encoded in body movements[5]. In order to develop reliable computational models for automatic affective movement recognition and generation for interactive machines and near-living architecture, it is important to understand how humans perceive affect from movements. In our work[6], we focus on the movement of human hands as the hand is an important medium for communicative gestures, and closely resembles the motion style and structure of the moving components of the Hyzoloic sculptures.

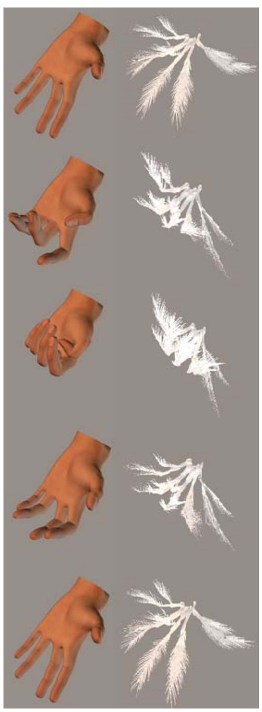
6 A. Samadani, E. Kubica, R. Gorbet and D. Kulić, Perception and Generation of Affective Hand Movements, *International Journal of Social Robotics,* Vol. 5, No. 1, pp. 35 - 51, 2013.

7 M. Karg, A. Samadani, R. Gorbet, K. Kuhnlenz, J. Hoey, and D. Kulic, "Body movements for affective expression: A survey of automatic recognition and generation," *IEEE Transactions on Affective Computing*, vol. 4, no. 4, pp. 341-359, Oct. 2013.



8 Structures used to display the affective hand movements in the user study. Anthropomorphic hand model (left), non-anthropomorphic frond like hand model.

We have tested the perception of hand movements intended to convey happiness, anger and sadness in a user study[7]. The hand movements were animated on a human-like hand model and frond-like hand model[8], and the impact of physical appearance of the mover on the perception of the movements was also studied. The frond-like structure was selected to resemble the appearance of the moving parts of the *Hylozoic Series* of near-living architectural environments.



9 Sequence of frames displaying a movement on a human-like and frond-like hand models.

Participants were able to perceive, above chance level, that there was some affective content in the movements from both the human-like and frond-like models. However, the accuracy of perception of the affective expressions varied between the structures. Participants perceived the expressions encoded in the hand movements as intended when the movements were displayed on the human-like model[9]. On the other hand, the sad movements displayed on the frond-like structure were perceived as happy movements. Furthermore, the frond-like structure displaying sad movements was frequently described as pleasant, friendly, and gentle, which also indicates the influence of the display structure on the perception of affective movements.

We have also conducted an experiment to investigate the potential role of the gender of the observer in the perception of affective movements displayed on different structures. To the best of our knowledge, there has been no previous research reporting on the role of gender and display structure on the perception of affective movements.

We found that the observer's gender significantly influenced their perception of affective movements and that the impact of the display structure and intended emotion on the perception of the affective movements differs between male and female observers[10]. For instance, male observers correctly recognized angry movements regardless of the display structure, whereas female observers associated less arousal and less-negative valence[11] to the frond-like structure displaying angry movements.

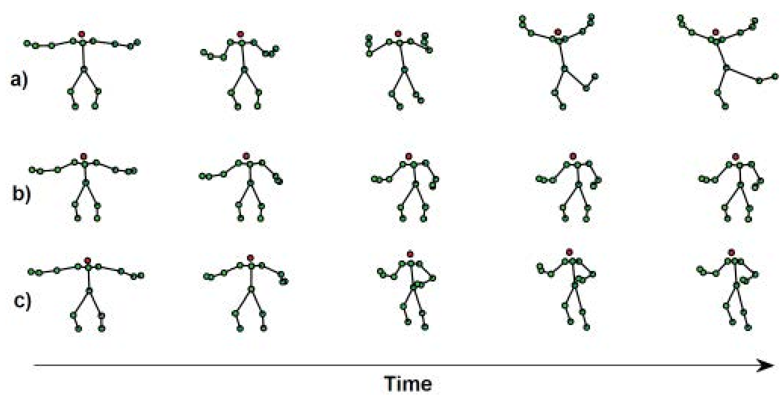
10 A. Samadani, R. Gorbet and D. Kulić, Gender differences in the Perception of Affective Movements, International *Workshop on Human Behavior Understanding*, LNCS vol. 7559, pp. 65 - 76, 2012.

2. AFFECTIVE MOVEMENT RECOGNITION

The qualitative nature of affective movement perception, along with the subconscious and individual nature of affective movement expression, pose several challenges for computational analysis of affective expressions and, particularly, for automatic recognition. Furthermore, affective movements can be highly variable in terms of intensity, timing and the flexibility of the body, even when the same demonstrator repeats a single movement multiple times (viz., stochastic variabilities).

In addition to the interpersonal and stochastic differences, an affective expression can be communicated through a number of kinematically different movements. There also exist kinematically similar movements that convey distinct affective expressions[12]. Ideally, an automatic affective movement recognition model should be able to recognize the affective movements independent of kinematic, interpersonal and stochastic variabilities.

11 In psychology, affective expressions are often represented using *categorical (discrete)* or *dimensional* models3. The most popular categorical description of affect is the *Ekman* model, which proposes anger, happiness, sadness, surprise, disgust, and fear as the six basic and universally recognized emotions. In dimensional models, affective expressions are described as points in a continuum of a low-dimensional space. For instance, the *Circumplex* model represents affective expressions in a two dimensional space defined by *arousal* and *valence*. The arousal dimension represents the level of activation, mental alertness, and physical activity, whereas the valence dimension ranges from negative (unpleasant) to positive (pleasant).



12 Movement exemplars from an affective human movement corpus[13]: (a) and (b) are two happy movements, which are kinematically different, whereas the happy movement in (b) is similar to the fearful movement in (c).

13 A. Kleinsmith, P. De Silva, and N. Bianchi-Berthouze, "Cross-cultural differences in recognizing affect from body posture," *Interacting with Computers*, vol. 18, no. 6, pp. 1371–1389, 2006. pp. 65 - 76, 2012.

14 A. Samadani, A. Ghodsi, and D. Kulić, Discriminative functional analysis of human movements, *Pattern Recognition Letters*, vol. 34, no. 15, pp. 1829 – 1839, 2013

15 A. Samadani, R. Gorbet and D. Kulić, Affective Movement Recognition based on Generative and Discriminative Stochastic Dynamic Models, IEEE *Transactions on Human-Machine Systems*, 2014, Accepted for Publication.

16 A. Samadani, A. Ghodsi, and D. Kulić, Discriminative functional analysis of human movements, *Pattern Recognition Letters*, vol. 34, no. 15, pp. 1829 – 1839, 2013

We have developed computational models that identify an abstract encoding of affective movements on which we built recognition models for distinguishing between different affective expressions[14, 15]. The abstract encoding of the movements is a dimensionally reduced movement representation in terms of a minimal set of movement features most salient for affective expressions.

In our recent work[16] we have presented an affective movement recognition approach based on stochastic dynamic models robust to temporal variabilities in the movements, capable of encoding kinematically dissimilar movements conveying the same affective expression in a single model. We have demonstrated the accuracy of the model using different affective human movement corpora with various bodily expressions of affect displayed by different demonstrators. Promising interpersonal recognition rates of 77% and 97% were achieved for full-body affective human movements (conveying anger, fear, happiness, and sadness) and hand-arm affective human movements (conveying anger, disgust, fear, happiness, sadness, and surprise), respectively. The achieved recognition performance surpasses previously reported recognition accuracy on the same movement sets. The recognition performance of the developed models could be further improved given a richer training dataset of affective movements that covers a wide range of expressions with kinematic, stochastic, and interpersonal variability.

In near-living architecture, the recognition model could help the environment to correctly perceive occupants' expressions and use these perceived expressions as a control input to mechanical actuation modules in order to generate an appropriate actuated response.

2.1 SALIENT AFFECTIVE MOVEMENT FEATURES

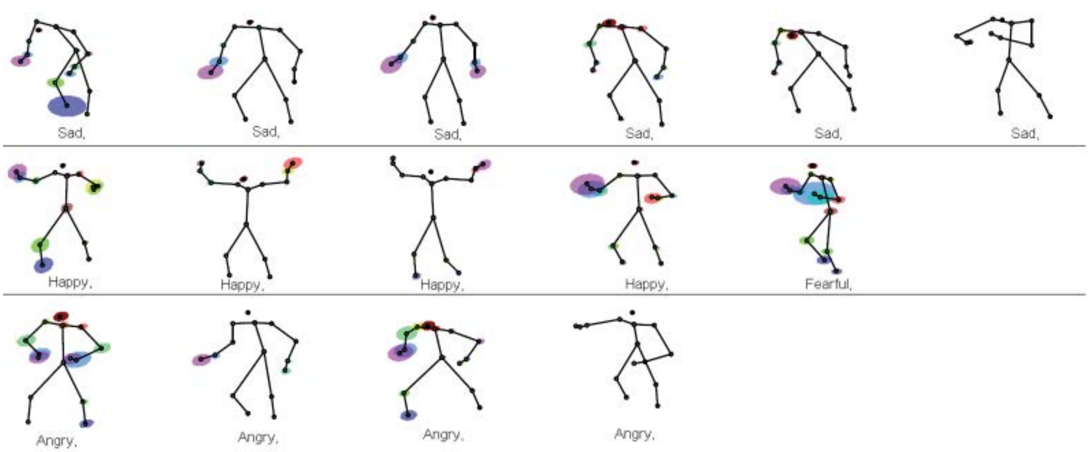
We have found that both postural and dynamic movement features are important for accurate affective movement recognition. Figure 12 demonstrates a set of salient movement features identified in our work as contributing to conveying different affective expressions. We have found that the upper body plays a key role in affective expression in full-body human movements. Our findings also indicate the important role of the human hand postures and motion for discriminating between different affective expressions.

As can be seen in Figure 17[17], there are characteristic postures salient to different affective expressions:

- Sad movements are generally characterized by a drooped head and shoulders, an overall slumped posture and a protective crouch posture;
- Happy movements are characterized by open and expansive postures, upward hand and arm movements, and advancing movements;
- Angry movements are characterized by arms akimbo postures, angled forward postures and clenching fists; and
- Fearful postures seem to show alert, retreating and cowering movements.

With regard to the speed of movements, we found that sad movements are slow and are characterized by lingering in time, and happy and angry movements are characterized by fast motions. Fearful movements are long in duration and are characterized by frequent jitteriness and freezing postures.

Knowledge of the salient affective movement features gained from our experiments can inform the design of physical elements for the Hylozoic sculptures for a more affective interaction with their occupants, which in turn will improve our ability to enhance the occupant experience. Nevertheless, the efficacy of the identified salient features for generating affective movements displayed on Hylozoic sculptures needs to be verified through user studies.



17 The full-body postures corresponding to the salient features for different affective expressions. The colored spheres around the body joints show the importance of the movements of these joints (high velocity and jittery movements).

3. AFFECTIVE MOVEMENT GENERATION

In order to give near-living environments and interactive mechanisms in general a more affective motion language and encourage increased empathy in communication, we are developing a framework for synthetically generating movement trajectories with recognizable affective content. The research question we are interested in is: How can we modulate a specific motion trajectory to overlay a desired affective expression? It is important to exploit an abstract movement representation in the computational analysis of movements that captures both kinematic and dynamic specificities as well as expressive qualities. Such an abstract representation also enables a more computationally efficient analysis of the movements.

Our approach to affective movement generation makes use of abstract movement representations in terms of a set of high-level descriptors. For a given trajectory, this generates a novel motion trajectory that conveys a desired expression while closely resembling the given trajectory. In a previous work[18], these descriptors represented the main modes of variation in a collection of affective movements identified using a statistical feature extraction technique. We observed that movements conveying different affective expressions form distinct clusters in a low-dimensional space spanned by the identified modes of variation. The centroid of each cluster was used as the prototypical representation for the corresponding affective expression and high-dimensional movement trajectories were generated for the prototype movements using an inverse transformation defined in terms of the main modes of variation.

18 M. Karg, A. Samadani, R. Gorbet, K. Kuhnlenz, J. Hoey, and D. Kulic, "Body movements for affective expression: A survey of automatic recognition and generation," *IEEE Transactions on Affective Computing*, vol. 4, no. 4, pp. 341-359, Oct. 2013.

We verify the expressivity of the synthetically generated affective movements both objectively and subjectively. For objective verification, we test how well the generated movements are recognized using our automatic recognition models (discussed in Section 2). The expressivity of the generated movements is subjectively verified via user studies, in which participants rate the perceived expressions from animations of the generated movements. In our previous study[19], synthetically generated affective movements were recognized correctly by the recognition model, and were also perceived as intended by observers in a user study.

19 A. Samadani, E. Kubica, R. Gorbet and D. Kulić, Perception and Generation of Affective Hand Movements, *International Journal of Social Robotics,* Vol. 5, No. 1, pp. 35 - 51, 2013.

Another set of high-level descriptors exploited in our ongoing generation work comes from movement notation systems. Movement notation systems from psychology and the dance community provide a rich tool for an abstract and informative representation of the movements as compared to high-dimensional body joint trajectories commonly used in computational movement analysis.

The Laban system is a prominent movement notation system that was developed for writing and analyzing dance choreography[20]. Laban encodes both the structural characteristics and the expressive qualities of a movement using a set of semantic descriptors. The Laban system has four major descriptors: Body, Effort, Shape and Space. Body and Space describe the structural characteristics of the movement, whereas Effort and Shape are primarily concerned with the qualitative aspects of the movement. Effort encodes the use of energy along four bipolar dimensions of Weight, Time, Space and Flow with their extremes being Light/Strong, Sustained/Sudden, Indirect/ Direct and Free/Bound, respectively. Bartenieff emphasizes that emotions and their intensity can be precisely observed through the Effort components[21].

20 R. Laban and L. Ullmann, The mastery of movement. Plays, Boston, 1971.

In collaboration with a certified motion analyst (CMA), we have proposed a set of formulas for quantifying Laban descriptors and verified the efficacy of the quantification in comparison with annotations provided by the CMA for a hand-and-arm affective movement dataset. The dataset consists of different affective expressions communicated through a set of predefined hand and arm movements by a professional actor[22]. In an ongoing project, the quantified Laban descriptors are used to obtain an abstract encoding of affective movements and form the basis for a new affective movement generation approach.

21 I. Bartenieff, Effort-Shape analysis of movement: The unity of expression and function. Albert Einstein College of Medicine, Yeshiva University, 1965.

22 A. Samadani, S. Burton, R. Gorbet, and D. Kulić, “Laban effort and shape analysis of affective hand and arm movements,” *International Conference on Affective Computing and Intelligent Interaction,* 2013, pp. 343 – 348.

With respect to near-living architecture and interactive machines, the generation models can be used to modulate actuated responses of the sculptures to manifest more empathic, life-like and affective expressions. When integrating generative models into the sculptures, the affective motion parameters should be attenuated to meet the kinematic and dynamic capabilities of the actuators (range of motion and maximum velocity and/or acceleration).

4. CONCLUSIONS

We have learned from the analysis of affective movements that it is feasible to perceive and express affect via movements of non-anthropomorphic mechanisms. However, there are limitations in creating such affect-aware mechanisms. These limitations stem from appearance, kinematic and dynamic differences between the mechanisms and humans. Kinematic and dynamic differences constrain the range of motion executable by a mechanism, which along with a mechanism’s physical appearance may limit the range of expressions conveyable or in some cases may alter the perception of intended affective movements displayed by the mechanism.

There are also several reports on perceptual differences, which arise depending on whether the affective expressions are conveyed directly from a physical

23 A. Samadani, E. Kubica, R. Gorbet and D. Kulić, Perception and Generation of Affective Hand Movements, *International Journal of Social Robotics,* Vol. 5, No. 1, pp. 35 - 51, 2013.

structure (e.g., kinetic sculpture), a video or an animation[23]. Therefore, the physical structure and presentation (physical versus virtual) of display mechanism may influence the human interaction with them and merits further exploration.

We have also observed gender-specific differences in the perception of affective movements displayed on different structures, which emphasize the importance of considering the user's gender in designing affect-aware mechanisms and call for validating displayed affective movements by interactive mechanisms with both male and female users. Furthermore, research should be conducted to identify if there exist physical structures and appearances that might limit (or modulate) the communication of affective expression with male or female observers.

The occupants' culture and the context within which the sculptures are presented might also influence occupant experience. Therefore, it is important to investigate the impact of culture and context during human-machine interaction and consider them in developing interactive sculptures capable of affective expressions; expressions that best match the expectation of their occupants. Other modalities such as sound and light can be also combined with the actuated responses of the sculptures to express a wider range of expressions, which in turn help in creating a more empathic and hylozoic experience for the occupants.

On the recognition side, in order to develop recognition models that closely emulate the human perception of affective movements, the affective movement perception from differing human observers should be incorporated in developing automatic recognition models.

For the generation side, as part of our ongoing research, generation approaches are being designed that are capable of generating a wide range of movements with various affective expressions. These approaches are either example-based or model-based. Example-based approaches are data-driven and their success depends on the dense sampling of affective movements available for training the generation algorithm. Model-based approaches make use of our findings on the salient features for affective expressions to constrain a target motion trajectory with a set of motion and postural features specific to a desired expression.

By understanding what aspects of movement connote different affective states, and developing algorithms for generating corresponding motion paths, this research gives the environment the ability to communicate affective state to its occupants. This is a critical step in furthering our broad goal of imbuing near-living architecture with the ability to engage in more empathic relationships with occupants.

Anticipating Behaviours

Åsmund Izaki, Christian Derix & Lucy Helme

To design spaces for humans to thrive in, one must consider the principles of human behaviour and perception. At Aedas Computational Design & Research (CDR), we have conceptualised and applied new ideas of human-centric architecture through computational design practice over a decade, creating a *new organic architecture*[1]. With this in mind, we developed a parallel project, in collaboration with Philip Beesley Architect Inc., that would complement and interpret the *Hylozoic Series* with the purpose of communicating and predicting its spatial performance over time. The human-centric design approach had to be further expanded in order to address the embedded responsive mechanisms of *Hylozoic Veil* . Within the work, users interact with a near-living system, rather than a mute space, entering into a social relationship with their environment. New languages are needed that help articulate non-verbal interactions that consist of behavioural acts, such as movement in and through space. The social and adaptive relationships between entities can then become the primary material of design, no less physical and real than the pervasive parametric form generation found in digital design practices today.

1 Derix, Christian, and Åsmund Izaki. "Spatial Computing for the New Organic." *Architectural Design* 83.2 (2013): 42-47.

In the best case, spontaneous interactions emerge from bottom-up rules defined in a system. Examples from previous exhibitions show how psychologically complex situations arise from simple acts. For instance, when a particular visitor tried to trigger a response and felt ignored, he would turn around and give up. A delayed reaction then suddenly gave him the feeling *he* was the one being played with (rather than vice versa). In order to make these dialogues intellectually and perceptually stimulating it is important to understand how the behaviour of each agent, whether artificial or biological, is likely to play out spatially, over time. To map these relationships, we must simulate how spatial and behavioural systems mutually affect each other in the Hylozoic

facing page

2 Aerial view of Hylozoic Veil, Salt Lake City, 2011.

environments through a concept we call *co-relation*. This term is similar to the idea of correlation and dependence in statistics, that describes relationships between two sets of data, but rather than defining a causal relationship, the data sets co-exist and influence each other as fields. In fact, it bears closer relation to Hillier's conception of manifold or commutative square:

The architecture of architecture is equally based on such structures which include, for example, the mapping between human behaviour and its spatial containment, or between psycho-physiology and the environmental filter. In design the mapping structures are used as autonomic devices to solve problems. In research these mapping devices are studied in order to understand and improve them.[3]

3 Hillier, Bill, and Adrian Leaman. "How is design possible?" *Journal of Architectural and Planning Research* 3.1 (1974): 4-11.

In the Hylozoic environments the spatial organisation influences the probable movement patterns, but it is at the same time a product of way-finding principles and cognitive processes for decision-making. Similarly, the behaviour of the Hylozoic environment conditions visitors' behaviour: people learn how their actions affect the installation's response patterns, while in turn the response-rules are based on anticipating the actions of the visitors.

INTELLIGENCE IN THE STRUCTURE

According to Habraken[4], built environments are products of control distributions on different levels. In the Hylozoic system, each node controls its own behaviour at the local level, but the global result is also dependent on input from visitors and from other nodes. Even though there is a central system for coordination and communication, the Hylozoic system is cellular at the core. One way to describe it is to say that each node reads and writes space. It reads its environment through sensor values or activations from other nodes and it writes actuator outputs or activation signals to its neighbours. Sensing, actuation and communication combine into one medium. For each instance of the *Hylozoic Series*. the neighbourhood maps describing the network of communication between nodes are uniquely defined. These maps become part of the design and adaption of the system into a specific context, together with other behavioural rules that determine delay timings and recursion levels.

4 Habraken, N. John, and Jonathan Teicher, eds. *The structure of the ordinary: form and control in the built environment*. MIT press, 2000

In the work presented here we have focused on understanding global properties at the system level, in order to address fundamental architectural questions of space and occupation. Representation and visualisation of invisible qualities related to perception and affordance are used to understand the way one inhabits and relates to space, rather than literal simulations of people and their emotions. In *From Object to Field*,[5] Stan Allen suggests the "figure not as a demarcated object, but as an effect emerging from the field itself – as moments of intensity, as peaks or valleys within a continuous field". One of our visualisations developed for this project at the systemic level shows how spatial patterns of activation can form clusters, consisting of singular occurrences, or generate more continuous field conditions in line with the thoughts put forward by Allen. Responses can be generated to trigger people's curiosity to explore more secluded areas by drawing attention to these places. The Hylozoic system might be required to respond differently depending on the number of visitors in the space; a very densely crowded environment versus an almost empty space allows for different modes of interaction.

5 Allen, Stan. "From object to field: Field Conditions in Architecture and Urbanism." *Architectural Design* 127 (1997): 24-31.

The spatial layout itself - how the system is installed in a specific location - also invites a certain use-pattern. The modules can be configured in a forest-like typology where visitors primarily move through the installation on a single ground level. Alternatively, the elements can be mounted so that they are primarily observed from exterior points of views. This was the case with the *Hylozoic Veil* (2011) installation at The Leonardo in Salt Lake City, which was used as the primary case study and site for data collection. *Hylozoic Veil* was installed in a vertical atrium space, where the layout distribution suggested a vertical movement across floors, with escalators as observation. In a few places the visitors would also enter into the environment. Based on this set-up, we explored the possibility of the visitor experiencing the metabolism of the system by peeking into its internal mechanism and observing its responses to external stimuli.

EMERGENT PROPERTIES

Hillier[6] has shown that the topological structure of urban networks can determine local use patterns. A public square might only work if it is connected in a certain way to the rest of the urban fabric, or might become active through the rhythm of workplaces in adjacent neighbourhoods. These properties are emergent in the sense that local conditions in the system influence global states and other local conditions. Similarly, the Hylozoic environments' local activities propagate and affect other parts of the system.

6 Hillier, Bill. "Space is the machine: a configurational theory of architecture." (2007).

The prospect of designing with emergent systems has been an aspiration for computational design in architecture, especially in academia, for decades. In our view, bottom-up systems can be successfully applied to finding solutions and states that are otherwise difficult to create while they also have the capacity to address and meet external requirements. In philosophy, there are generally considered two types of *emergence: strong* and *weak*. In *weak emergence*, global states are reducible to lower-level rules, meaning that the resulting states and behaviours can be studied given the relevant rules and a computer, while properties of *strong emergence* are entirely irreducible and dependent on the actual relationships in the system. If one were to adopt this view, the designer would not be able to affect the system with intent since strongly emergent states could not be simulated or predicted. The designer would then be rendered incapable of any purposeful action, other than choosing an arbitrary set of simple rules with the resulting behaviours being foreign to the design process.

We believe there is much to be learnt from more systematic modelling and simulation in order to refine the spatial set up and behavioural programming based on rigorous explorations. That is the motivation behind developing a means to test and evaluate bottom-up processes according to the tacit knowledge of the designer or other stakeholders. Through simulation and modelling, some of the desirable qualities of the weak emergence of complex systems can be integrated with other strategies, such as agile development methods. The behavioural rules of the system can be refined through simulating the resultant changes. This strategy can be applied iteratively to converge to low-level rules that produce classes of systemic behaviour occurring in certain situations when visitors act according to a generic form. These are not linear static mappings of inputs at a certain time, but play out differently according to dynamic correlations between actors in the space.

PROTOTYPING SIMULATIONS

The Aedas Computational Design Research group (CDR) is responsible for developing three strands of simulations: operational diagrams, spatial field conditions and the geometric environment. This scope could only be addressed through an agile development strategy of smaller prototypes, rather than starting from a narrower problem description and required analysis. Each development worked as a sketch that could provide new information about the problem. The strand was refined through selection and evaluation of prototypes that guided the development. Through this method the prototypes would slowly converge towards useful solutions, while making sure that the simulation elements could be combined later on through user interfaces for control. Disparate concerns that first appeared to be unrelated would later on help to build up informed, layered understandings of the whole system.

From the start it was clear that a framework was needed that would allow different scenarios to be simulated, while keeping parameters open to change in real time. Initial aspects of the Hylozoic environments were encoded and modelled to prepare for simulations. The materials used as inputs were spatial descriptions, such as models and drawings, schematics of all the electronics, the Arduino code to control the sensor-actuator feedback in each microcontroller, and actual data logs of recorded events over four days at the Leonardo venue. CDR created an emulator in Java that mirrored the principles of the Arduino code to implement the same operations virtually, removing the need for reprogramming the modules to tweak the performance onsite. The virtual operations were connected to the spatial layout, specifying each type of module and its location, together with a topological diagram embedded in the neighbourhood maps.

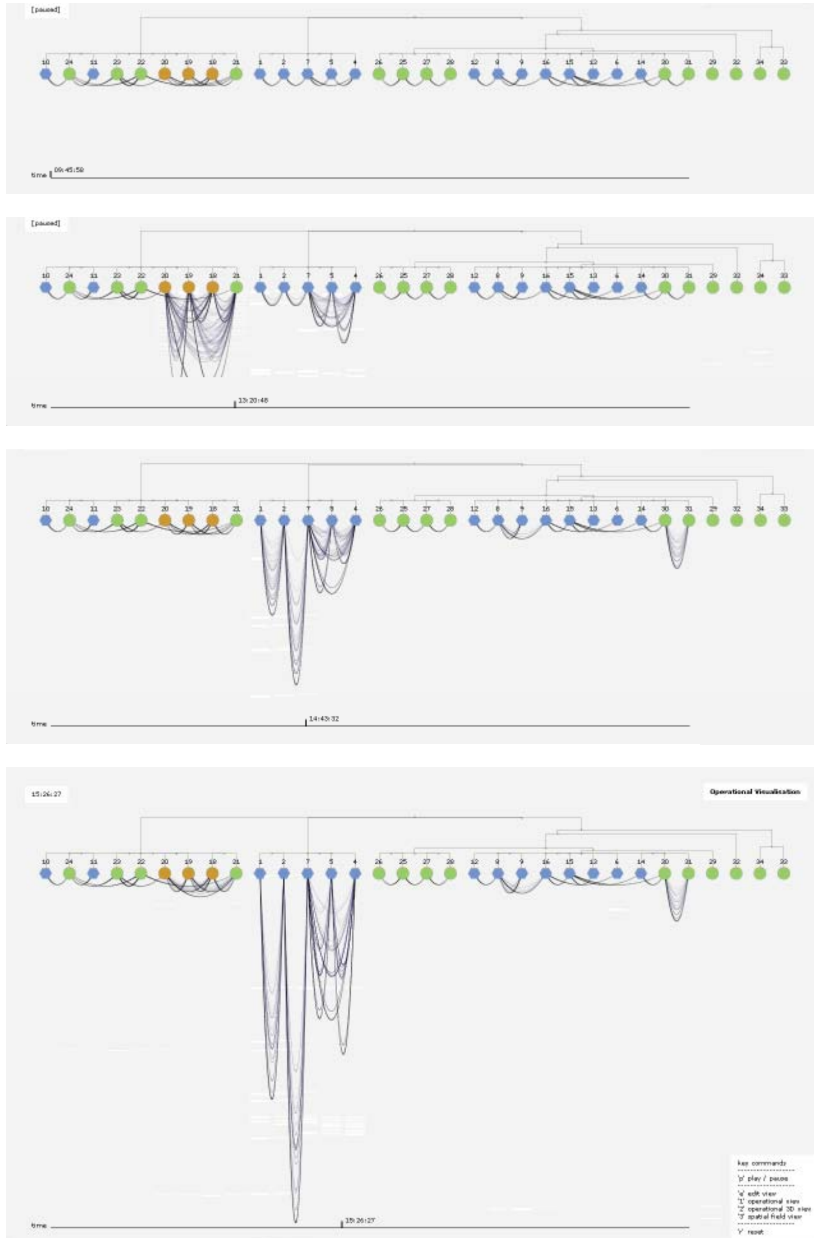
Statistical mappings helped reveal behaviour patterns of both the visitors and the Hylozoic system, through learning about historic operations and activations. Activation levels from the four day-long logs were visualised as statistical histograms to help find general trends in the occupants' behaviours, such as peak activity levels or the general distributions over time. An early operational mapping gave an impression of how behavioural dynamics played out to create temporal patterns that could be enacted visually through computational diagrams. In more refined versions, physics simulations and network models were used to find tactile expressions embodying aspects of the behaviour of the Hylozoic environments. Through other prototypes, CDR defined analogies to the coded behaviours of the Hylozoic system that could represent how it affected its environment. Methods such as vector fields and particle simulations were adapted for analysing these spatial fields.

CONVERGING MODEL

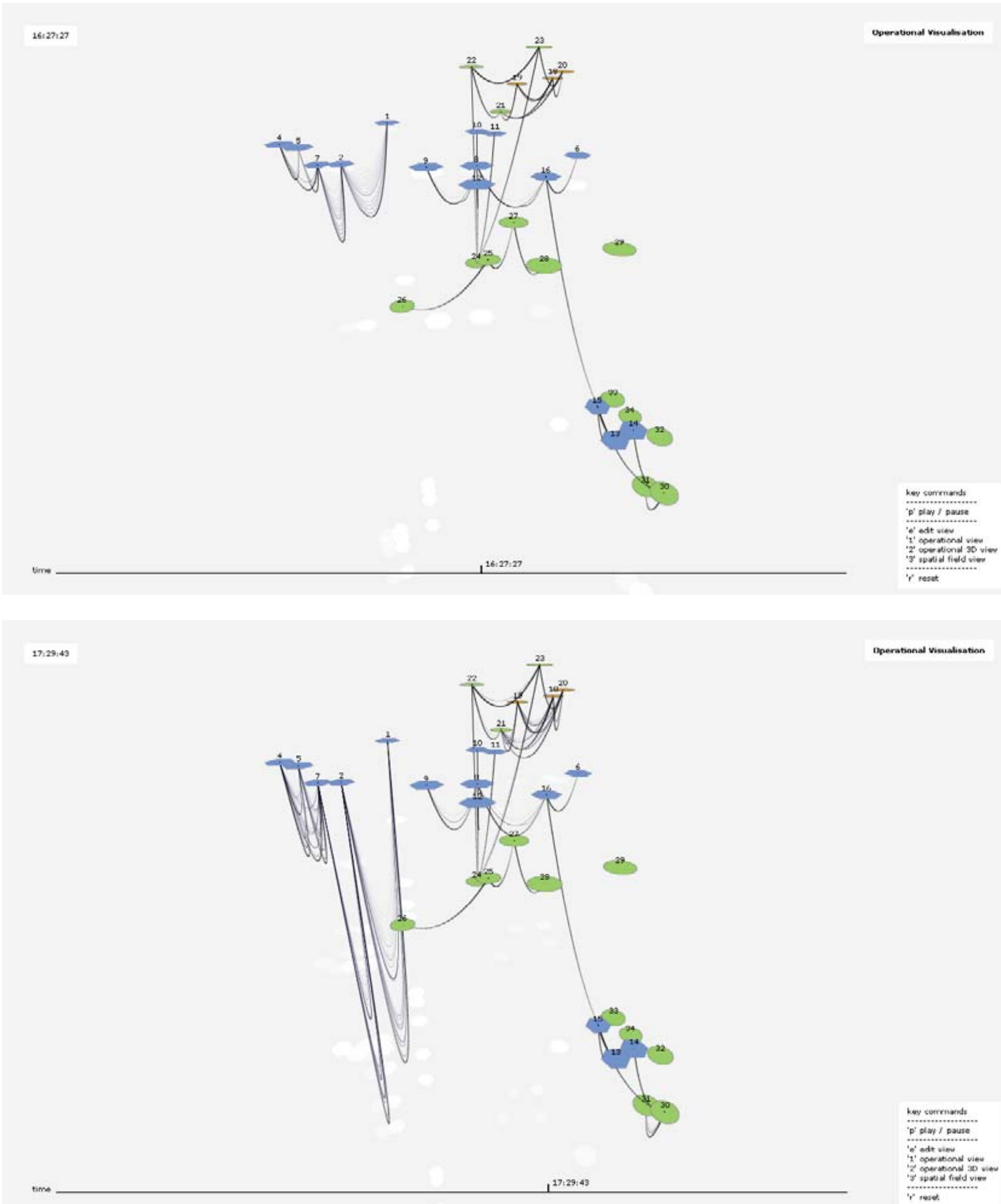
An integrated software application was built that could be used by the design team during planning of a new installation, or for tweaking an existing set-up. It was important to make it sufficiently open to accommodate changes during the design phases. The aim is that both spatial and behavioural design development can be informed by simulating the consequences of different decisions. The application consists of three parts: operational behaviour, spatial field conditions and the operational interface. In the interface, the user can tweak the topology of the neighbourhood maps and other behavioural parameters, with the different aspects synchronised and updated simultaneously. As we explain in the following sections, the operational and spatial behaviour of the system became tangible through dynamic visualisations emphasising different aspects of the system.

The operational visualisation shows how the internal patterns of communication build up differentiated networks over time. The components are first organised according to their topological relationships, so that connected parts are laid out next to each other spatially[7]. A dendrogram representation organises the topologically nearest pairs into trees, showing clusters of communicating nodes. Besides the organisational view, the user can also view the spatial configuration of the nodes as they are mounted in space[8]. In both views, links that are more frequently used increase their physical length to generate a hanging chain model. The resulting expression mirrors certain aspects of the physical structure, in that a catenary geometry is reminiscent of an elevation of a single layer in the Hylozoic installation.

The spatial visualisation treats the environment as a fluctuating field that is reinforced by the Hylozoic actuators[9]. The visualisation is built up as a 3D field that increases in strength for each actuation, but with a slow decay. The spatial intensities are visualised similar to a contour map for terrains; for each threshold value, a semi-transparent contour surface is drawn. This can help the designer plan how to set up neighbourhood maps and delay timings that determine how local sensor activations propagate and generate spatial affordances for the visitors. In visualising activity as a set of spatial intensities, we are trying to reveal the hidden patterns of activation and responses over time.



7 Operational diagram over time. The hanging chains embody the material language of the installation and give an impression of which links are used more often for communication.



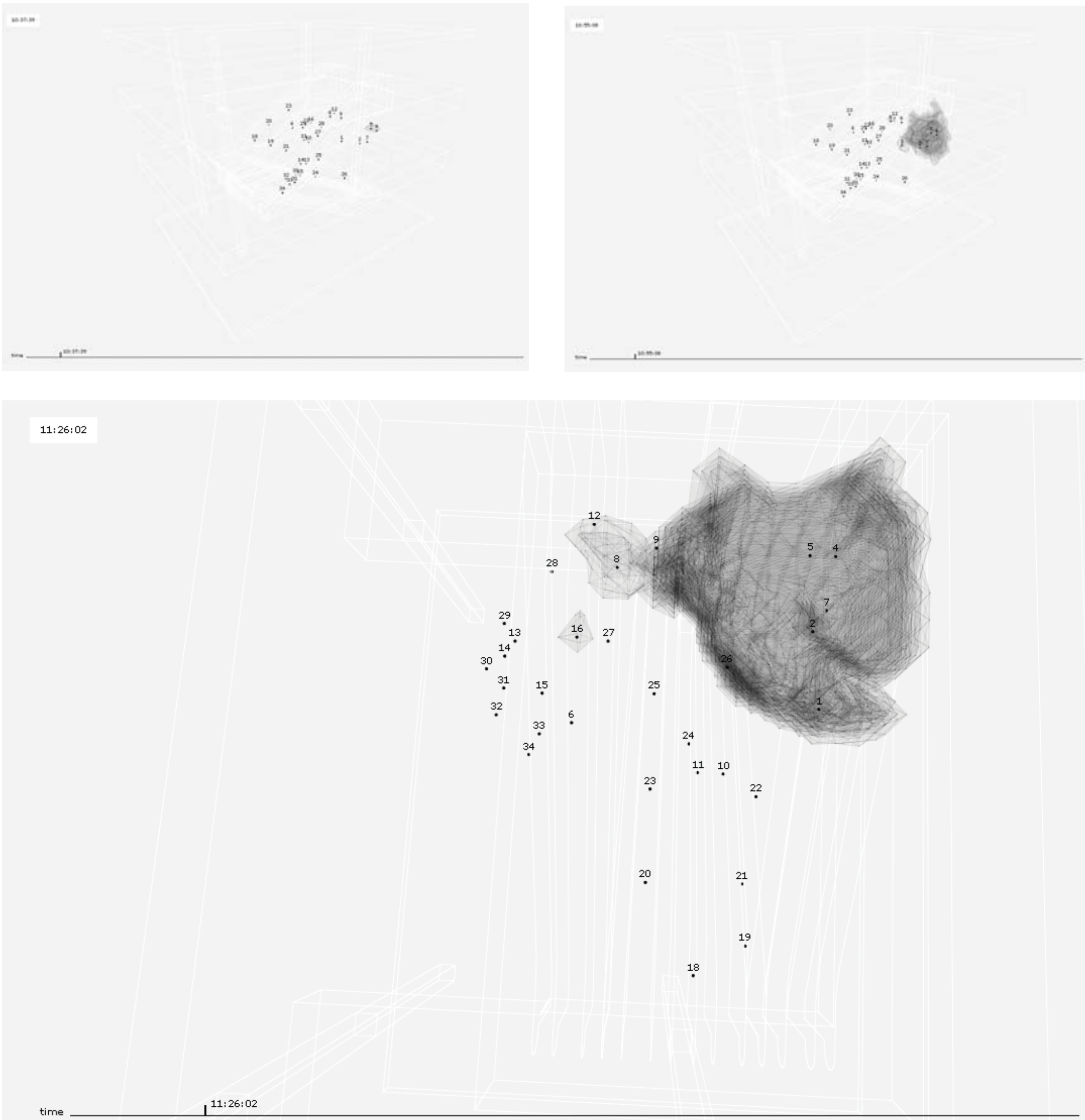
8 Operational diagram as a spatial model. Here the chains follow the spatial structure of the installation, which gives the advantage of being able to overlay the spatial and organisational levels.

The input data, in terms of deciding the scenario or log file that would be used as input, is determined at the time of execution by passing the filename as a parameter. CDR also developed a graphical user interface where some of the input parameters could be dynamically changed immediately during run time. For example, timing delays specify how the input activations trigger responses and communication with neighbour nodes, and can be changed through the manipulation of sliders. The most important interaction element is perhaps the live linking and un-linking of nodes in the neighbourhood maps. What would previously be specified as node IDs in a text file and checked against a diagram of the spatial layout can now be manipulated directly in the 3D configuration. Some data read-outs were also included to suggest quantitative measures of performance.

It is still not fully clear how the research and development described here will feed into the design thinking and development of the *Hylozoic Series*. The set of tools and capabilities offered by the system have still not been fully applied in the design of a particular exhibition, including the workflow for integrating and applying the findings in a systematic way. However we found out early on that in a workshop setting, immediate findings and strategies could be adapted through interactive re-linking, and checking the resulting spatial patterns visually. An important aspect to test, for example, might be how local the responses ought to be, either directing the curiosity of the visitor, or keeping the visitor interested in exploring their immediate neighbourhood.

FUTURE RESEARCH

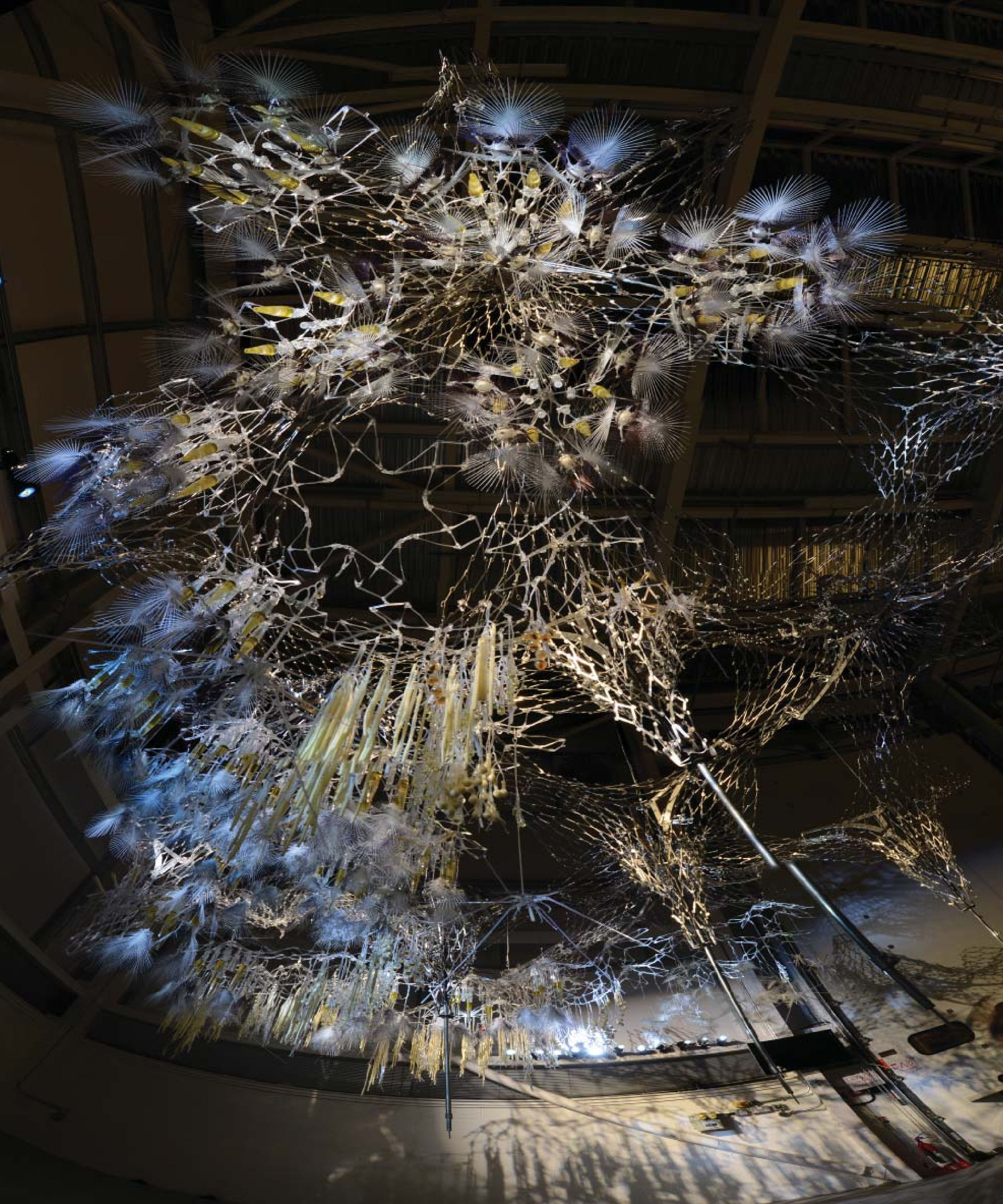
We have shown here how we use the principle of anticipating behaviours of both visitors and the adaptive environment as a design material itself, and how the process of working with emergent systems can be combined with more traditional design practices, which demand a certain sense of control or predictability. Our aim is to create models where emergence and predictability are symbiotic. In other words, where a bottom-up and top-down model inform each other in real-time. It is important not to design a completely predictable, over-determined solution – what might be classified as overfitting in machine learning - nor a completely erratic system that is incapable of having design intention.



9 Spatial field diagram. The densities of the spatial field build up over time and show how the systems actuations are distributed in the exhibition space.

In further collaborative efforts there is an exciting prospect of embedding learning behaviours in the system itself. How can the *Hylozoic Series* learn from correlations that occurred, between visitors and its own spatial patterns, in order to engage in truly adaptive interchanges as in Gordon Pask's conversation theory?[10] By modifying one's behaviour a dialogue can take place that incorporates information learnt from the other cognitive system. Only then can one create systems that are truly open for deeper communication with humans.

10 Pask, Gordon. *Conversation theory*. New York: Elsevier, 1976.



Prototyping Protocell Mesh

Michael Stacey & Chantelle Niblock

> "The slightly drifting, labyrinthine spaces that these meshwork and filter systems make might seem far from proudly framed public chambers, but they do offer tangible gathering spaces amidst their multiple hollows and creases."
> Philip Beesley[1]

This book chapter is primarily written by the architecture students of The University of Nottingham Department of Architecture and Built Environment describing their experience of prototyping and installing *Protocell Mesh* over a two year period at the three venues of Prototyping Architecture Exhibition in Nottingham and London in the United Kingdom, and Cambridge, Ontario in Canada. The three essays incorporated into this chapter provide distinct perspectives on working with Philip Beesley.

Prototyping Architecture Exhibition, curated by Michael Stacey, explores the importance of prototypes in the delivery of high quality contemporary architecture - performative architecture that is inventive, purposeful and beautiful. Focusing on construction that is informed by aspiration, knowledge and material culture, *Prototyping Architecture* places a particular emphasis on research and experimentation showing how trial assemblies can inform architecture. In post-digital design practice the prototype remains a vital means of design development, setting out impending systems and material futures with the potential for technology transfer from other industries. It highlights the role of low carbon architecture and offsite manufacturing in maximising the effective use of materials and resources, whilst delivering environments that facilitate human well-being.[2]

Omar Kahn, one of the co-chairs of ACADIA 2013, observed, "This exhibition is a retort to sceptics who claim computational technologies

1 Chantelle Niblock, Building with Beesley, in *Prototyping Architecture: the conference papers* edited by Michael Stacey Riverside Architectural Press 2013, p.296

2 Michael Stacey, *Prototyping Architecture*, Riverside Architectural Press. Canada, 2013, P3.

facing page

3 Protocell Mesh, Nottingham, 2012

are reducing architects' engagement with materials and making. To the contrary, it celebrates the incredible creative production that results from experimenting with new technologies and techniques to push the boundaries of architectural design"[4].

4 Omar Kahn by *email to the authors* August 2013.

The students' engagement with *Protocell Mesh* was facilitated by their studio tutors Dr. Chantelle Niblock, who runs the Digital Architecture and Fabrication Studio [DAFS] at Fifth Year MAch/Diploma, and Professor Michael Stacey, who convenes Making Architecture Research Studio [MARS] at Sixth Year MAch/Diploma. Both these studios are based on design research and are directly linked to our research group at Nottingham, Architecture and Technology Research Group (ATRG). The primary mode of design research in MARS is making[5], and considering how the decisions related to architecture develop as physical realisations. Sverre Fehn eloquently states, "all architecture is dependent on construction. Construction seeks the earth; it falls upon it. The eye, light, and thought, that which spatially disturbs these words, [is] construction"[6].

5 Michael Stacey, Frances Stacey and Laura Gaskell, *Studio MARS Brief 2013-14*, University of Nottingham, 2013

6 Quoted by Per Plaf Fjeld, *The Pattern of Thoughts*, 2009, Monacelli Press, p182

MAKING WITH PHILIP BEESLEY

Emma Eady, Vikash Patel and Dominic Ward[7]

7 Emma Eady, Dominic Ward and Vikash Patel, *Studio MARS Making and Field Research Report*, University of Nottingham, 2014, pp. 41-69.

Prototyping Architecture Exhibition

During our 5th year at the University of Nottingham, we were involved in the construction of the *Protocell Mesh* installation for the Nottingham and London venues of the Prototyping Architecture Exhibition. The MARS field trip to Canada included assembling the Mesh for the final stage of this exhibition in Cambridge Galleries. As part of this field trip we were invited to visit Philip Beesley's architectural practice in Toronto as he encourages students to participate in the construction of his projects. The development of team building and understanding of the manufacturing process through making becomes as much a part of the end result as the three-dimensional space.

Protocell Mesh

Protocell Mesh is constructed from a series of chevron shaped components that are arranged to form a suspended meshwork canopy[8]. The meshwork is primarily composed of aluminum and acrylic scaffolding that, held under tension, creates a flexible, hyperbolic grid shell[9]. This structure then supports suspended filters containing a protocell carbon capture chemistry. The

facing page top

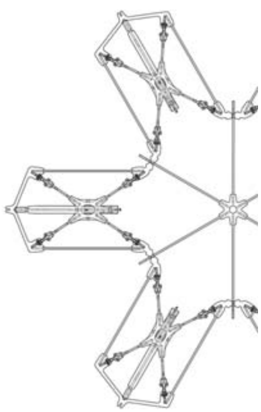
8 Suspended chevron mesh canopy

9 Ohrstedt P., and Isaacs H., eds., 2010. *Hylozoic Ground: Liminal Responsive Architecture*, Philip Beesley. Cambridge: Riverside Architectural Press.

structure consists of three layers; the acrylic/aluminium lily structure, the ghost layer and the protocell chemistry. Philip Beesley describes his designs as an engineered landscape; "an artificial layer that extends and supports a living system"[10]. The mesh becomes a new artificial scaffold to support the near-living chemistry. These ideas experiment with the possibilities for a future façade that is adaptive to its surroundings.

10 Ohrstedt P., and Isaacs H., eds., 2010. *Hylozoic Ground: Liminal Responsive Architecture*, Philip Beesley. Cambridge: Riverside Architectural Press.

Our initial encounter with *Protocell Mesh* had been at the end of September 2012. A set of diagrammatic plans were given to demonstrate how our project had been explored two-dimensionally[11]. These were to be the instructions to produce the complex three-dimensional space. Students felt there was an amazing contrast between the simple instructive diagrams and the final intricate mesh. The diagrams were flat and informative allowing us to engage with the construction process simply, creating a dialect between architect, constructor and user. The simplicity exaggerates how the materiality and configuration of the project is key to its visual impact.



11 Two dimensional drawing of an assembled "ghost" element

Fabrication began at the University of Nottingham, with acrylic components being laser cut in the Built Environment's Centre for 3D Design with aluminium components cut in Derbyshire by FC Laser. True file to factory production, which bypassed the Atlantic Ocean, the unit group of 15 students, was split into groups of 3 and 4 to begin assembly of the acrylic lilies. After a series of successful generations, a system of standardised sets of parts had been developed with a tested laser-cut snap-fit joint. Whilst on the site visit to Beesley's practice in Toronto, he explains, 'Methodology in the initial production focuses on the component itself, clarifying and refining the composition[12]. This proved to be fundamental to the mesh's successful construction, given the construction team's unfamiliarity with the initial design.

12 Ohrstedt P., and Isaacs H., eds., 2010. *Hylozoic Ground: Liminal Responsive Architecture*, Philip Beesley. Cambridge: Riverside Architectural Press.

The modular structure consists of slightly varying acrylic 'bones' that are used multiple times in varying positions to create the structural mesh layer. This methodology has regularly occurred within the sculptural pieces. The chevron link acts as the core piece in the structural mesh; once clicked into place, the single component can create a carpet structure that resembles a woven textile. The use of tessellated geometry of hexagonal and rhombic arrays creates a symmetry and regular tiling system. By progressively connecting the pieces, complex lily forms are created that, once fixed together, form the scaffolding for the chemistry systems that hovers below.

Thousands of components were delivered, with parts systematically organized for the launch of the construction. As in a typical manufacturing line, sub-assemblies were formed by groups constructing the different fragments of the structure. This allowed us to break down the instructions and focus on perfecting a methodology for each individual aspect of the construction, accelerating the process. A classroom in the gallery was transformed into a working assembly line. The system allowed the group of students to assign roles and manage themselves; we became a small working community, commonly working with the same end goal.

The acrylic components snapped together with a system that did not require any fasteners; the aluminium components utilized a slot fit joint relying on tension to keep the form. Cable ties were often needed to hold the aluminium chevrons in place until the umbrella tension rods could support the lily scaffold.

By working closely with both materials it was clear how they had foregone a thorough exploration of the material qualities, manipulating the acrylic and metal to allow for bending and compression under tension.

After the intense two-day lily assembly workshop, we began hanging the structures from the roof of the Woolfson exhibition hall. The process required us to work as teams to adjust the heights of the lilies and, once elevated, fix them together. Specialised acrylic joints were attached to allow the acrylic 'ghost layer' to clip onto the mesh and hang the protocell systems. After six days, the team had finished construction of *Protocell Mesh.*

their ability to design a set of components to produce an amazing mesh system that is both visually attractive but structurally smart demonstrates that through rigorous prototyping and analysis an architecturally coherent finalised product can be produced. The meshwork design allows for ease of transportation and installation both nationally and internationally, demonstrating a flexible system that proves adaptive to change and reconfiguration. This allows for further expansion and development where new prototypes can be easily accepted. The process allowed a group of students to become a successfully functioning construction community. Much like many complex buildings, as a large three-dimensional structure, is it hard to comprehend how it is made. Through a method of interaction with singular components, a body of knowledge began to develop through an understanding of material limitations, layering compositions and making.

PROTOCELL MESH AT PROTOTYPING ARCHITECTURE EXHIBITION: THE CAMBRIDGE EXPERIENCE

Peter Blundy, Samuel Critchlow and Michael Ramwell [13]

First assembled in Nottingham, 2012, the installation made its way to Cambridge Ontario (via London) for its final display at the University of Waterloo Architecture, Cambridge, Ontario.

Protocell Mesh integrates first-generation prototypes that include aluminium meshwork canopy scaffolding and a suspended protocell carbon-capture filter array. The scaffold that supports the installation is a resilient, self-bracing meshwork waffle composed of flexible, lightweight chevron-shaped linking components. Curving and expanding, the mesh creates a flexible hyperbolic grid-shell[14]. The installation very subtly moves or expands in response to human occupancy through a chemical process of capturing the carbon dioxide exhaled and converting it into calcium carbonate.

This is a fascinating idea, however in practice the mesh's flexibility is limited and instead can be appreciated aesthetically and intellectually as a beautifully evocative conceptual piece. These works may be in their early stages, however it is an interesting venture relevant to our current times of technological innovation. Concepts fundamental to the installation involve scale and component production. Currently, the application of the research

13 Peter Blundy, Samuel Critchlow and Michael Ramwell, *Material and Culture*, University of Nottingham, 2014, pp.247-264.

14 Michael Stacey, *Prototyping Architecture*, Riverside Architectural Press. Canada. 2013, p.59

remains at the scale of a non-structural installation within an existing building. However, the component work does show theoretical promise for applications within architecture.

The Problems of Components

Breaking a constructed element down into a series of standardised components has many advantages[15]. One advantage is that, often, the way that the components are designed to fit together means that they may also be easily disassembled and reassembled (this is of particular benefit to temporary structures and installations). However, one of the counter-problems to this advantage is that, under the strain of such a tectonic act as construction, there may be permanent distortion applied to the component itself, making it difficult or impossible to disassemble and reuse. This was evidenced during our assembly of *Protocell Mesh* as the installation had been constructed previously, on two separate occasions.

15 Assembled array of Philip Beesley's acrylic chevrons

Structural Innovations

Innovations to the *Protocell Mesh's* structure are currently in development at Philip Beesley Architect Inc. New scaffold structures have been developed from lasercut acrylic, with radial slot-like perforations, which is heated and subsequently expanded using a manual rig. Following the introduction of aluminium with Nottingham's 2012 collaboration, the studio has also experimented with similar aluminium structural components.

Where Michael Stacey observed of the studio's work in 2007: 'They taken one process, laser cutting, and two materials, acrylic and mylar, to produce an inventive and immersive three-dimensional installation cut from flat stock sheets and using minimum material with the minimum of waste[16]. This is now being extended by project-based research and development, replacing hundreds of hand assembled components making a rigid structural mesh with single expanded components. These new forms still originate from sheet material but are fully formed into three dimensional components of future meshworks.

16 Michael Stacey, From Flat Stock to Three-Dimensional Immersion, in: Philip Beesley, ed. *Kinetic Architectures and Geotextile Installations*, Riverside Press, p.62, 2007. Second Edition 2010.

CRAFTING: FROM THE PRIMITIVE TO THE DIGITAL: REFLECTING ON THE BODY OF WORK OF PHILIP BEESLEY

Dominic Ward [17]

With the beginning of the Industrial era, the context in which crafting existed changed forever. The crafters of trade; stone masons, carpenters and many more, had previously crafted products of necessity. With increasing competition from industrial machines, the crafters struggled to provide services and craft products as efficiently and as cheaply as their contemporary counterparts. As Adamson argues, "Artisans were drummed out of work by machines, with tragic consequences both for the experience of the makers themselves and the quality of the things they produced"[18]. This was combined with a fear that crafting would be lost forever and in response the Arts and Crafts movement was formed. Influential individuals, such as William Morris, championed a revival of crafts and challenged a total reliance on the industrial system.

The Arts and Crafts movement was born out of a growing concern about Britain's rapid industrialisation. The leading art and social critic, John Ruskin believed that increasing industrial manufacture was having a profound effect on the creative arts and British society on a whole. Ruskin theorised that "without dignified, creative human occupation people became disconnected from life"[19]. He wanted British workers to have pride in the work they produced and promoted the revival of traditional crafting, encouraging a return to a "simpler way of life"[20]. This simplification corresponded almost harmoniously with Augustus Welby Norhmore Pugin's two great rules for design[21], outlined in the first chapter of his written lectures, *The True Principles of Pointed or Christian Architecture*:

> First, that there should be no features about a building which are not necessary for convenience, construction, or propriety; second, that all ornament should consist of enrichment of the essential construction of the building.[22]

Now with the birth of the digital age, comes an even higher level of competition. Today, the innovation of technology means industry can create the most intricate of products. Traditional crafting of the past is yet again being challenged by these new technologies. The aim of this discussion is to consider the role of corporeal "hands-on" crafting and ascertain whether there is still a place for this in a time when digital processes continue to be an established tool in both the design and making of architecture.

17 Dominic Ward Craft in *Contemporary Architecture*, University of Nottingham, 2014

18 Glenn Adamson, *The Invention of Craft*. London: Bloomsbury Publishing Plc, 2013, p. XV.

19 Fiona MacCarthy, Morris, William (1834–1896), designer, author, and visionary socialist. In: *Oxford Dictionary of National Biography* (online ed.). Oxford University Press, 2009.

20 Ibid.

21 Augustus Welby Northmore Pugin, *The True Principles of Pointed Or Christian Architecture*: Set Forth in Two Lectures Delivered at St. Marie's, Oscott. [e-book] London: W. Hughes. Available at: Google Books <https://play, google.com/store/books/details/Augustus_Welby_Northmore_Pugin_The_True_Principles?id=SKhLAAAAMAAJ> [Accessed 1 January 2014], 1861, p. B.

22 Ibid.

Defining Crafting

The reference to skill and the hand has become synonymous with the today's idea of crafting. Towards the end of his introduction to *The Invention of Craft*, Glenn Adamson profoundly states that to him, "craft has always meant something like making something well through hand skill," no more and no less[23]. Such a broad definition covers a vast array of skilled activities, from a local village baker to the master stonemasons of ancient Rome.

In *The Craftsman*, Richard Sennett eloquently introduces crafting by describing a carpenter's workshop[24]. Although he later goes onto discuss the topic in all its various forms, the carpenter, a well-known artisan, serves as a tangible analogy for crafting. It is the notion of the well-practised hand of the carpenter and the knowledge learnt through years of experience.

While it is clear that skilled manual work, developed through years of tactile experience, can be defined as crafting, the notion of crafting today encompasses a much wider collection of activities. In *Re:Crafted*, Marc Kristal explores the unconventional notions of craft and defines it on a much broader sense, "a method of making that combines a vast store of skill-based knowledge"[25]. This simple definition of the term does not confine crafting to the physical, nor does it reference the context of making. Despite the author's attempt, Kristal goes onto explain that even this broad description isn't enough to define the modern perception of crafting.

Amidst the new digital era with automated methods of production the modern definition of crafting has become almost infinite. The simple reference to hand and skill does little to contain our perceptions. A well trained digital designer surely possesses skill and the products of their work have been produced by hand, even if this may be through the interaction with a computer. It could be argued that the simple reference to skill and hand is a passive attempt to define something, which constitutes far more in the contemporary world we live in.

Digital Era

Comparable to the questions provoked by the Industrial Revolution, the new digital era has brought to question the position of crafting and its role in design. The relationship between the designer, the maker and the product has become even more blurred. Years ago, architects would laboriously sketch

23 Glenn Adamson, *The Invention of Craft*. London: Bloomsbury Publishing Plc., 2013, pXXIV.

24 Richard Sennett, *The Craftsman*. London: Penguin Books, 2008, p9.

25 Marc Kristal, *Re:crafted: Interpretation of Craft in Contemporary Architecture and Interiors*. New York: The Monacelli Press, 2010, p6.

multiple drawings and make beautifully crafted physical models, realized in final representations and taken to site. The architect's physical interaction with each process kept them engaged with each project and encouraged a sense of pride in a final product. The architectural design process can now almost all be performed by "the lowing of keys and clicking of mice"[26]. Even the final construction stage can be performed by the machine, through the advancement of manufacturing technologies; Professor Behrokh Khoshnevis, from the University of Southern California, believes he has created a large concrete printer capable of printing a house in under a day [27].

26 Michael Stacey. Digital Craft in the Making of Architecture. In: Bob Sheil, ed. 2012. *Manufacturing the Bespoke*. West Sussex: John Wiley & Sons Ltd. pp58-76.

27 Business Standard. New 3D Printer Can Build a House in 24 Hours. [online] Available at: <*http://www.businessstandard.com/article/pti-stories/new-3d-printer-can-build-a-house-in-24-hours-114011200280_1.html*> [Accessed 12 January 2014]

As the capabilities of the computer have increased, they are increasingly relied upon in architectural design. There are arguably many merits in using digital technologies in the process of design. For one, the chance of human error can be radically reduced. A more obvious benefit is the speed and efficiency in which visions can be explored and represented. There have been huge developments over the last few decades, from the two-dimensional computer-aided design (CAD) to three-dimensional programs such as Rhino. These programs have a vast array of uses in architectural design, from the initial proposal stage to the point of construction. Hand-models can now seemingly be replaced by their digital equivalents or even printed by additive manufacturing; a process in which layers of material are printed to produce a physical three-dimensional model. With these advancements, there is an increasing fear that an over reliance on CAD may lead to designers not participating in learning and developing the intuition gained from physical craft [28].

28 Richard Sennett, 2008. *The Craftsman*. London: Penguin Books. pp19-52.

It is important to remember that the design of architecture demands an understanding that is both tactile and tangible. It is because of this that architectural design of the present era has shifted its focus onto the practice of making. This new era has been defined by the ever developing characteristics of digital design. The work produced using CAD has led to the architect assuming the role of both designer and maker [29].

29 Bob Sheil. 2005. Design Through Making: An Introduction. *Design Through Making*, 75 (4). p7.

Michael Stacey, a professor of architecture and the University of Nottingham, focuses on the digital craft of architecture. He poses the question, "Can the digital design of architecture be considered a craft...?"[30] This questions stems from many of the traditional understandings of craft, which focus on the production of a physical and tangible product. It could be argued that the mouse and keyboard serve as the maker's tools. In the same way a carpenter carves a piece of wood, the architect carves the ones and zeroes of digital

30 Michael Stacey. Digital Craft in the Making of Architecture. In: Bob Sheil, ed. 2012. *Manufacturing the Bespoke*. West Sussex: John Wiley & Sons Ltd. pp58-76.

space. The final product, although not always existing in the physical, has still been devised through the process of thought and hand. From this, it appears that the problem does not lie with the tool of the architect, but lies within the removal of a direct haptic relationship between the maker and the made leading the criticism of digital craft. This also adds to the complexity of how one can define crafting in its truest sense. To address his question, Stacey refers to Sennett's proposition of Linux software as a type of craft. Devoid from any physical output, Sennett suggests the software programmers become engaged with their work, gaining a sense of pride through the development of their skill [31]. Although it is easy to agree with Stacey's suggestion that "a totally cerebral digital crafting of architecture is possible"[32], is this the best practice for the training architect, or does there need to be a more physical interaction with the materials they work with?

31 Richard Sennett, 2008. *The Craftsman.* London: Penguin Books. pp24-28.

32 Michael Stacey. Digital Craft in the Making of Architecture. In: Bob Sheil, ed. 2012. *Manufacturing the Bespoke.* West Sussex: John Wiley & Sons Ltd. pp58-76.

Further Thoughts

In response to Chantelle Niblock asking Philip Beesley his view of the success of the prototype protocell system within Prototyping Architecture, he responded:

> "We developed *Protocell Mesh* with our collaborators, working up to the last moments before opening the exhibition, refining details and adjusting jointing systems, and setting up a new filter system that we hadn't seen working at this scale before. The prototype aluminium meshwork system that we developed together with the school showed tremendous promise for its sheer strength and its tolerance for wide distortions. The glasswork 'reticulum' of lightweight valves and filters showed strong calcium-carbonate precipitate formations, directly demonstrating carbon capture operating. In those ways, I'd say the work was a resounding success. On the other hand, the jointing systems took quite a bit of wrestling and even a bit of blood in the laborious hand-work of their assembly. Next generations for this system will be much more refined, concentrating on making things 'finger-friendly' and faster to assemble. [33]"

33 Chantelle Niblock, Building with Beesley, in *Prototyping Architecture: the conference papers* edited by Michael Stacey Riverside Architectural Press 2013, p.291

Installations are one of the very few experimental frontiers of contemporary architecture; by prototyping *Protocell Mesh* we were taking risks in time and resources, small sums stretched to achieve the maximum, and small groups of students learning by doing journeying beyond the normal confines of studio in terms of time and space. Ultimately, *Protocell Mesh* pushes the boundaries of current architectural expression, exploring possible future architectural spaces based on diffusive interaction.

facing page

34 Aerial view of the completed Protocell Mesh, Nottingham (2012).

It Lives! Promoting Creative and Innovation Thinking in Education

Lucinda Presley, Becky Carroll & Rob Gorbet

A growing number of researchers, experts, and governmental agencies emphasize that a nation's success in today's global economy will be affected by its ability to innovate[1, 2, 3, 4, 5]. Economics authors Thomas Friedman and Michael Mandelbaum point out that, with information as close as our smart-phones, the most important skill is now the ability to process information[6]. Sir Ken Robinson, internationally-recognized author and advisor to Fortune 500 companies, governments, and education, adds that the nations that most effectively train their students to process information innovatively will be the global leaders[8]. These statements are supported by a 2011 General Electric survey of 1,000 business executives in 12 countries which found that 92% of the executives believed that innovation is the main driver of a competitive national economy[9]. In response to this need, *It Lives!* developed and piloted models for promoting these important innovative thinking skills in students.

In the midst of global competitiveness to innovate, there is also a call for international cooperation, which requires these creative and innovative thinking skills. International collaborations that use these creative thinking skills can develop valuable and innovative products and solutions. Additionally, Friedman points out that the advantage will go to the nations and groups that collaborate internationally. He also calls for today's students to be trained in global thinking and collaboration skills[10]. *It Lives!* addresses this need by developing a preliminary model for international conversations between students around science and inventing. For example, *It Lives!* connected middle school students in Texas, USA, and Ontario, Canada via Skype to share their experiences at the intersections of science, innovative thinking and their inventions.

As this global need for innovation in many fields increases, so does the importance of creative and innovative thinking. Noted creativity expert R. Keith

1 Friedman, T. and M. Mandelbaum. (2011). That used to be us: *How America fell behind in the world it invented and how we can come back*. NY, NY: Farrar, Straus and Giroux.

2 Robinson, K. (2009). *The element*. NY, NY: Viking Penguin Group.

3 Florida, Richard. (2003). *The rise of the creative class: …and how it's transforming work, leisure, community, & everyday life.* NY, NY: Basic Books.

4 The President's Council of Advisors on Science and Technology. (2010). Prepare and inspire: K-12 science, technology, engineering, and math (STEM) education for America's future. Washington, DC.

5 National Academies of Science, National Academy Of Engineering, Institute Of Medicine. (2010). *Rising above the gathering storm, revisited: Rapidly approaching category 5*. Members of the 2005 rising above the gathering storm committee. Washington, DC: National Academies Press.

6 Friedman, T. and M. Mandelbaum. (2011). That used to be us: *How America fell behind in the world it invented and how we can come back*. NY, NY: Farrar, Straus and Giroux.

facing page

7 Vibrating whisker from a breathing pore, Sibyl, Venice, 2012

Sawyer points out that, in response to the need for innovative thinking, countries such as the U.S., China, and the European Union are transforming their economies from industrial economies to "creative knowledge economies" where a focus is on producing ideas[11].

What are creative and innovative thinking? Sawyer says that we must move beyond associating creativity only with the fine arts, for creativity is important in a wide variety of applications, including mathematical theory, experimental laboratory science, and computer software[12]. Since, as Sawyer points out, these thinking skills are increasingly used and studied in a variety of applications, there are a resulting variety of definitions and approaches to these skills. Since our work with students and teachers involves both individual and group processing, we have focused on Sawyer's sociocultural approach to creativity. In this approach, creativity is seen in a group context, where it leads to a useful new product or innovation. *It Lives!*, promotes content-specific creative and innovative thinking individually and as a group to create an innovative solution that reflects the creative thinking. It also models for teachers ways in which to integrate these thinking strategies into classroom application.

Furthermore, Sawyer points out that the emerging field of cognitive neuroscience has developed a greater understanding of these important thinking skills[13]. Experts in this field, Sandra Chapman, Ph.D., Director of the University of Texas at Dallas Center for Brain Health, and Jacquelyn Gamino, Ph.D., Director of the Center's Adolescent Reasoning initiative, have successfully studied important aspects of innovative thinking. Through rigorous studies, they have discovered strategies for promoting these thinking skills in students, especially adolescents. They recommend that students blend these interactive strategies: selecting the most important information, synthesizing this information to form abstracted meanings, and applying this synthesis to a creative and novel application[14].

While experts are calling for integrating innovative and global thinking into education systems and strategies exist to foster these skills, we found that there are advancements needed in both countries. In the USA, Po Bronson and Ashley Merryman, in their famous *Newsweek* article, "The Creativity Crisis", point out that children's high scores on the Torrance Test of Creativity were three times more likely to predict that child's future lifetime creative accomplishment than IQ scores. In other words, these creative thinking skills help drive innovation. However, these scores in the USA have been on the decline

8 Robinson, K. (2009). *The element.* NY, NY: Viking Penguin Group.

9 General Electric. (2012). *GE global innovation barometer: Global research report*. Retrieved from http://files.gecompany.com/gecom/innovationbarometer/GE_Global_Innovation_Barometer_Report_January_2012.pdf

10 Friedman, T. (2007). *The world is flat: A brief history of the 21st century.* NY, NY: Picador/Farrar, Straus and Giroux.

11 Sawyer, R. K. (2012). *Explaining creativity: The science of human innovation.* NY, NY: Oxford University Press.

12 Ibid.

13 Ibid.

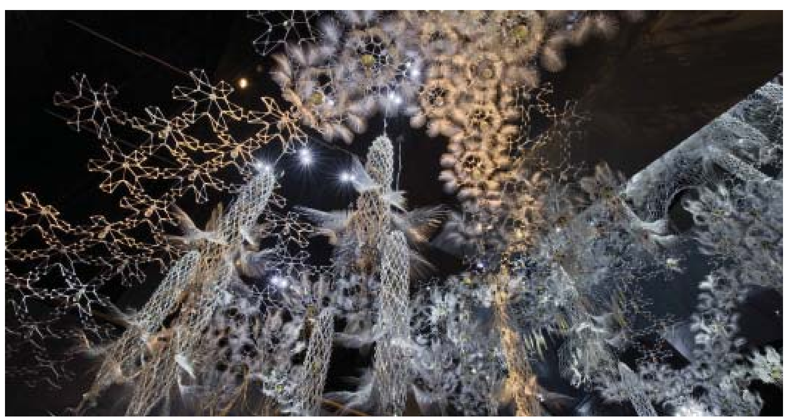
14 Chapman, S., J. Gamino, and R. Anand. *Higher order strategic gist reasoning in adolescence. In The adolescent brain: Learning, reasoning, and decision making.* Washington, DC: American Psychological Association, 2012.

since the 1990s, they point out, especially in kindergarten through sixth grade[15]. These concerns are borne out by US teachers we work with. They report that students often are afraid to take risks for fear of failure or because the challenge seems too great. They also point out that students have trouble synthesizing information to solve problems innovatively. This is due, they add, to standardized tests' emphasis on fact recall.

In Canada, 2012 science scores on the international PISA exam[16] that tests the application as opposed to memorization of science facts, the Canadian students ranked very highly in comparison with other countries[17]. However, it is reported that these scores are declining, that Canada lags in its innovation, and that it must continue to improve students' learning and the outcomes capacity[18].

IT LIVES!: A PROJECT TO ADDRESS CREATIVE AND INNOVATION THINKING IN EDUCATION

Taking into account the need for creative and innovation thinking, the strategies that promote these skills, and the realities of the education systems in Canada and the US, *It Lives!* investigated the integration of these skills with specific science content learning in two schools in the US and one school in Canada. It collaborated with the education department at The Leonardo and local school districts and educators. It also hired a professional evaluator to assess students' attitudes, their growth in content knowledge, and the effect of their innovation/inventing experiences on content learning.



19 The Hylozoic Veil installation established the conceptual framework for the *It Lives!* project, Salt Lake City, 2011.

15 Bronson, P. and A. Merryman. (2010, July 10). The creativity crisis. *Newsweek*. Retrieved from www.thedailybeast.com/newsweek/2010/07/10/the-creativity-crisis.html

16 PISA is the Program for International Student Assessment, first launched in 2000 by the OECD in response to member countries' demands for regular and reliable data on the knowledge and skills of their students and the performance of their education systems. PISA surveys take place every three years.

17 Literacy Newfoundland and Labrador (2013). *Measuring up … and down: PISA 2012 reports on math, science, and reading scores for Canadian students*. Retrieved from http://www.literacynl.com/content/measuring-and-down-pisa-2012-reports-math-science-and-reading-scores-canadian-students

18 MaRS Market Insights (2011). *K-12 education: Opportunities and strategies for Ontario entrepreneurs*. Retrieved from http://www.marsdd.com/wp-content/uploads/2011/11/MaRSReport_Education.pdf

It Lives! – Exploration

Our Investigation

Station #1:
1) What we noticed happening:

2) What were the most important science concepts used? (list the numbers from your Science Concepts sheet)

3) Which other stations use similar ideas and concepts?

Station #2:
1) What we noticed happening:

2) What were the most important science concepts used? (list the numbers from your Science Concepts sheet)

3) Which other stations use similar ideas and concepts?

Station #3:
1) What we noticed happening:

2) What were the most important science concepts used? (list the numbers from your Science Concepts sheet)

3) Which other stations use similar ideas and concepts?

25 Student worksheet with questions for each station

26 Students interacting with components

It Lives! found the use of brain-based strategies formulated by the Center for Brain Health very important in helping students create their inventions and in explaining the growth that we observed. These valuable brain-based strategies derive from recent discoveries in cognitive neuroscience. *It Lives!* discovered the importance of integrating these skills with classroom learning. *It Lives!* also used research-based education strategies. These education strategies included: hands-on inquiry, knowledge transfer, arts/design thinking, visual thinking, problem-finding/problem-solving based on real-world problems, collaboration, communication, persistence, flexible thinking, inventing, science literacy, and emotional engagement[20, 21, 22, 23, 24].

The *It Lives!* project process began during the commissioning of *Hylozoic Veil* in 2011 for The Leonardo art+science museum in Salt Lake City. The *It Lives!* project team identified an opportunity to bring the multidisciplinary nature and ideas of the sculpture into classrooms, helping to connect students' core art and science curricula and providing a context in which to explore creative and innovative thinking and invention.

They designed the *It Lives!* workshop as a way to immerse students in the intersection of hands-on science, engineering, design, and art thinking to help them solve a real-world problem innovatively as a team. The student teams

20 Costa, A.L. and B. Kallick. (2008). *Learning and leading with habits of mind: 16 essential characteristics for success.* Alexandria, VA: Association for Supervision and Curriculum Development.

21 Cropley. A.J.. (2003). *Creativity in education and learning: A guide for teachers and educators*. NY, NY: Routledge Farmer.

22 Gardner, H. (2008). *5 minds for the future.* Boston, MA: Harvard University Press.

23 Starko, A. (2004). *Creativity in the classroom: Schools of curious delight*. Mahwah, NY: Erlbaum.

24 Wiggins, G. and J. McTighe. (2006). *Understanding by design*. 2nd ed. Upper Saddle River, NJ: Pearson.

used exhibit-inspired shape memory alloy (SMA), found objects, and craft supplies to create a kinetic device that can demonstrate the interrelationship between synthesized science concepts, design, and art.

The workshop is comprised of four sequential sessions: an introduction to the sculpture and its components that makes explicit connections between aspects of the sculpture and the core curriculum; a hands-on exploration of science concepts that relate to the sculpture; a creative problem-solving session in which students connect science concepts and use design principles to invent a solution to a real-world problem; and a 'making' session in which students fabricate their inventions using shape memory alloy and then present and promote their inventions to the class.

At each site, the classroom material was tailored to the grade- and board-specific core curriculum. The project team worked closely with teachers to identify core concepts from science and art that they wanted to emphasize for their students. This list of core concepts formed an implicit and explicit basis for the entire workshop. These concepts implicitly informed the questions that the project team poses to the students and the hands-on activities that it designed. Students have to explicitly choose among these concepts in the creativity session and explain how they see the concepts connecting to create their invention. Throughout the sessions, in presentation and facilitation, the project team also uses *Hylozoic Veil's* artistic aspects to further reinforce the connections between art and science.

In Session #1, Exploration, students are briefly introduced to the *Hylozoic Veil* exhibit in a seminar format by Rob Gorbet, one of the creators of the exhibit. Gorbet uses anecdotal narrative and rich images and video to engage the students at a level appropriate to their grade. Following this short introduction, students rotate in small groups between exploration stations where they interact with and observe components of the sculpture[25]. At each station, students are prompted by worksheets to apply the methods of scientific inquiry and their grade-specific science concepts to their exploration of the sculpture's pieces (e.g., What am I seeing? Why is it happening? What science concepts are involved?)[26].

In Session #2, *Hands-On*, students connect their experience from Session #1 to their mandated grade-specific core science and art curriculum. Activities are carefully developed with the teachers to ensure relevance to

27 Grade 5 students use their curriculum on electricity to understand the scuplture

28 A student with plants and drawings of cells

the specific students in the workshop, guided by the core concepts list. For example, students in Grade 5 studying electricity might work in a small group to explore what happens when closing a switch connecting a battery to an active exhibit component[27]. They can then rewire the circuit using alligator clips, and choose from various conductors and insulators to compare the conductivity and resulting functioning of the circuit. Students in Grade 7 studying plant cells might be asked to draw parallels between the elements in the exhibit components in front of them to plant life, or to the functioning of a cell, supported by visuals depicting cellular structure[28]. Students are explicitly asked to consider the cross-over of terms such as balance, form, shape and line from science (e.g., in structures) and art, to emphasize the similarity in design thinking and the creative process.

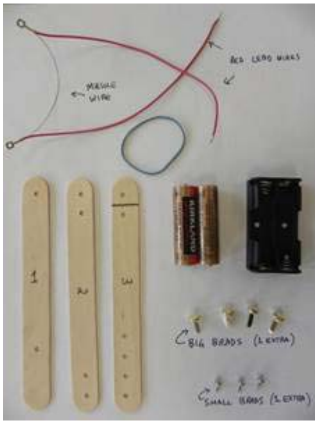
In Session #3, Creative Problem Solving, students are assigned to three-person design teams and are given a challenge framed as "you have been hired by the Discovery Channel to use a novel kinetic device to demonstrate the intersection of three science concepts." A demonstration lever device is assembled at the front of the classroom from a kit we've designed, using the same Flexinol® shape memory alloy wire[29] that is used to generate motion in the *Hylozoic Veil* exhibit components. Students follow along in teams to assemble identical lever devices from their own kits. In 5th grade, they also draw and label their understanding of how muscle wire uses electricity to make a physical change in their device, using required science concepts. They then discuss and reflect on the motions generated and how those motions remind them of concepts from their science curriculum

29 Manufactured by Dynalloy Inc., www.dynalloy.com

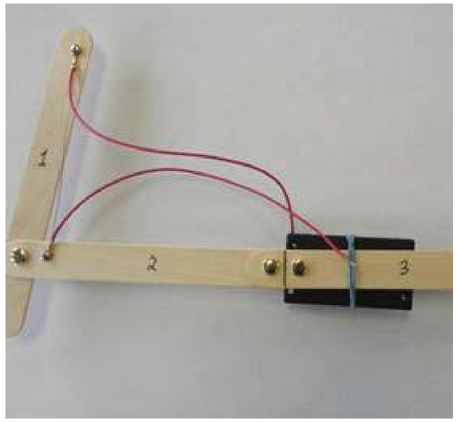
30 Labelled diagram of a student's kinetic device

(e.g., does it remind you of a flagellum, a lever, a volcano erupting, tectonic plate movement, etc.). Students then select the key concepts from their science core concept list that they feel could best be illustrated using their kinetic device. In teams, they draw and label their device, integrating their chosen science and art concepts in their work[30]. This phase of the project uses the brain-based strategies developed by the UT Dallas researchers. Students select from the variety of science information that they had learned in Sessions #1 and #2. They also choose from a list of selected Earth, life, and physical science concepts. They synthesize at least four of these selected concepts to come up with a "big idea", and then apply that synthesis to solve a problem.

In Session #4, *Making*, students use found objects and craft supplies to bring their 2D solutions demonstrating their science concepts, into 3D, built around their SMA devices. The resulting solution has to be visually understandable and represent the integration of at least three science concepts across science disciplines. When complete, each group presents to the class how their invention illustrates their key concepts and why they made the design choices they did. In this session, students solidify and demonstrate their science knowledge. Taking their 2D images into 3D design often involves adjustment in design and materials. They also write an explanation of their inventions, using the science concepts to demonstrate how their invention solved their problem.



31 Components for a student's kinetic device



32 Assembled kinetic device

IT LIVES! RESULTS

To study the impact of the *It Lives!* workshop on students' interests and attitudes toward science and engineering, their content knowledge of key concepts, and their assessment of how visual thinking, strategizing and experience affect their learning, we conducted a pilot study in three schools: two classes of 7th grade students at Palestine Junior High, Palestine, Texas; four classes of fifth grade students at Woodrow Wilson Elementary School in Salt Lake City, Utah; and one class of 7th grade students and one class of 8th grade students at MacGregor Public School in Waterloo, Ontario, Canada, totaling 213 students. In all three locations, students were given two pre- and two post-assessments – one focusing on attitudes/interests and another on content. In addition, teachers were also given a post-assessment to collect data about their perceptions of the program, and the degree to which it promoted science learning, youth engagement in science process skills, and problem-based learning. In addition, we conducted in-person observations of the *It Lives!* program in Palestine and interviewed students about their experiences in the program.

Preliminary data collected from the pilot observations of the program by evaluators, teachers and program implementers, pre-post attitude and content assessments, and from teacher post-assessments, indicate that *It Lives!* provided engaging experiences for youth that combined art and rigorous and appropriate science content, and opportunities for students to develop critical thinking, innovation and problem solving skills.

top

33 Students working on their kinetic device

below

34 Students planning how to design their kinetic device

First and foremost, the *It Lives!* workshop activities were engaging to students. All of the teachers reported that their students were active participants, and highly engaged throughout the course of the project[33, 34]. As Salt Lake City teachers reported in post self-assessments:

> "All students were on task all of the time. Our discussion when we returned to the classroom had a lot of energy and was most positive!"
>
> "They were all on task and enthralled with the project!"
>
> "Students were engaged, learning and excited. I didn't see one student that was not engaged."

The *It Lives!* workshop helped students understand important core science concepts and to make connections between science concepts. As Salt Lake City teachers reported in post assessments:

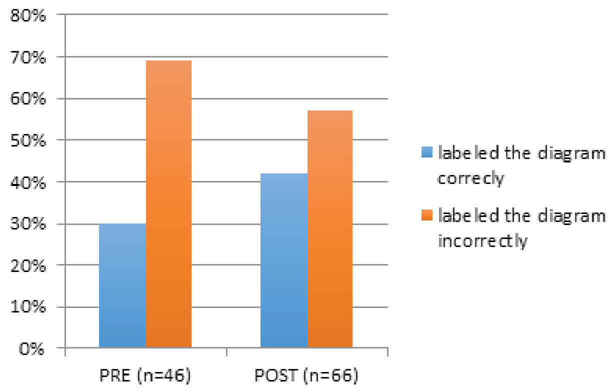
> "It really helped my students understand that a physical change occurred; there was no new substance formed with the muscle wire contracted."
>
> "The chart reading was great, and I loved how it connected electricity with animal adaptations. So creative!"

For example, two 8th grade students we interviewed in Texas were able to articulate the connections between science concepts they were making through the building activity with the muscle wire:

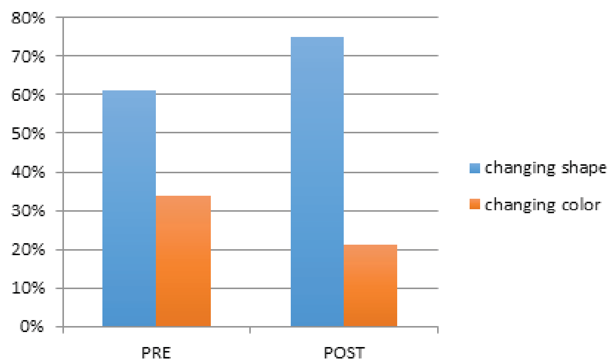
> "We are making an arm out of popsicle sticks. We wanted to do something with the muscular system and structure. It seemed like force and motion and muscles made sense to combine."

Data from pre-post content assessments in Salt Lake City indicated that students had made progress in understanding how circuits work, a notoriously difficult concept for students to grasp[35]. One question on the pre-post assessment asked students to label the power source, switch, conducting wires, and muscle wire in a diagram of a circuit. On the pre-assessment of the Woodrow Wilson 5th grade students, of the 46 students who labeled the diagram, 30% labeled the diagram correctly, while 69% labeled it incorrectly. On the post assessment, of the 66 students who labeled the diagram, 42% labeled it correctly, while 57% labeled it incorrectly. Thus, as the graph on the following page highlights, not only did the number of students who actually labeled the diagram increase by 20 students, the gap pre-post narrowed from +39% incorrect, to +15% incorrect[36].

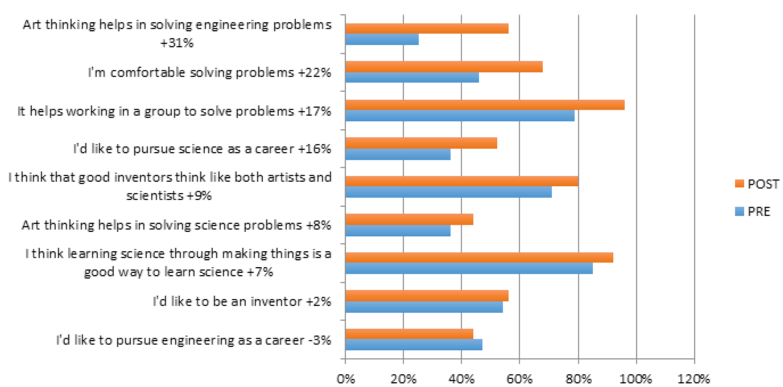
35 Englehardt and Beichner, (2004). *Students' Understanding of Direct Current Resistive Electrical Circuits.* American Journal of Physics, 72, 98-115.



36 Number of students who labelled circuit diagram correctly before and after the excercises



37 Number of students who demonstrated an understanding of the physical change in the shape memory alloy. N=97



38 Pre and post student attitude assessment from a 5th grade class. N=25; percentage of students choosing 4 or 5 on a rating scale, where 5 = strongly agree and 1 = disagree

Another example of the 5th grade pre-post content assessment data highlighting content knowledge gains is shown in the graph below, where students demonstrate their understanding of the physical change in the shape memory alloy (muscle wire)[37].

Students also articulated their appreciation for the inquiry-based methods of exploration the project provided, and how that helped further developed their understanding of key concepts. Students were encouraged to embark on their own inquiries, pursue their own questions, and were supported in working through a design challenge. As two teachers noted:

> Students were given the opportunity to explore their own questions.
>
> It's the way learning should look.

Students appreciated the ways in which the *It Lives!* Making activity allowed them to better understand the science concepts they had been working with in their classroom throughout the year. As one student we interviewed noted:

> We've been studying muscles in science class. For most people, if you work hands-on, you can understand it better. If you build it, and you see an arm moving up and down, it makes more sense.

The careful design and implementation of activities helped students to engage in productive problem-solving, and to develop critical and innovative thinking skills. Students explored components of the exhibit, chose concepts they had been studying in school to combine that connected to the explorations they had done in the first session, assembled a kinetic design from a kit to better understand how the shape memory alloy wire works, then were asked to respond to a design challenge to create something that would demonstrate their concepts to younger students. At every step along the way, students had to conceptualize the design challenge and explain their means for addressing that design challenge. As teachers noted in post assessments:

> I loved how the students were given the responsibility to create their own circuit.
>
> It was clear that the presentation was designed in such a way that it encouraged investigation and problem solving, culminating in an activity that required invention and creativity.

The graph below highlights pre-post attitude assessment data from one 5th grade class of students. The results are ordered from highest percentage of increase to lowest. The graph shows the increases in students' attitudes toward the importance of art thinking in solving problems, their own comfort level in solving problems, their attitudes toward working in groups, and their interest in pursuing science. All but one increased as a result of their participation in the program[38].

Teachers and students alike found value in the *It Lives!* workshop in developing student conceptual understanding, and in enhancing students' creativity, innovation skills, critical thinking and problem solving.

IT LIVES: SUMMARY AND FURTHER PLANS

Our experience with the pilot *It Lives!* sessions is incredibly encouraging and we look forward to being able to enlarge the reach of the program by seeking additional funding. In the next stage of the project we will be further refining the project to further integrate brain-based strategies and more fully address the engineering component. We also will be scaling the delivery to other grade levels and developing a train-the-trainer teacher professional development program. These strategies will help us improve the project, multiply the number of students exposed to the workshop, and enable broader delivery. We expect that this effort will be supported through partnerships with school boards in Canada and school districts in the US in which we've had successful pilots. In addition, we will be working with PBAI, creators of *Hylozoic Veil* and pioneers in near-living architecture, to develop a series of classroom kits that teachers may use for the hands-on portions of the workshop.

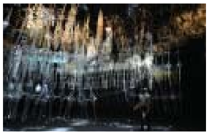
Another avenue we will be exploring, which was tested in the Canadian pilot, will be connecting students internationally through videoconferencing. In the pilot, grade 8 students from MacGregor Public School in Waterloo, Ontario had a 15-minute video conference with grade 7 students from Palestine Junior High in Palestine, Texas. A team of Palestine students presented the design they had completed earlier in the second iteration of the *It Lives!* workshop at that school, and both groups exchanged questions about the design problems they faced as well as about their cultures and environments. We would like to take this international collaboration further, possibly even introducing to the students the idea of remote design teams. These skills will be vital in these students' futures as the world continues, as Friedman says, to "flatten"[39], and global collaboration becomes even more prevalent. Combining these global collaborative skills with creative and innovative thinking and discipline-based knowledge will provide these students a firm foundation for their futures.

39 Friedman, T. (2007). *The world is flat: A brief history of the 21st century.* NY, NY: Picador/Farrar, Straus and Giroux

facing page

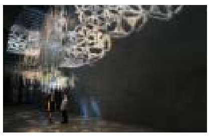
40 Workshops staged at The Leonardo, Salt Lake City in 2013 extended the It Lives curriculum. Children and adults studied the geodesic structures and resilient mechanisms of the Hylozoic Veil sculpture system, and then worked with simple bamboo and flexible silicone tubing joints to make their own triangulated space frame structures.

Hylozoic series projects 2011-2013



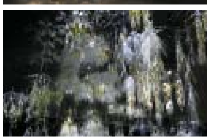
EPIPHYTE CHAMBER, 2013

Aleph Project, National Museum of Modern and Contemporary Art, Seoul, Korea



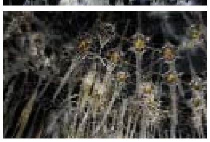
EPIPHYTE SPRING, 2013

Triennial of Fiber Art, Hangzhou



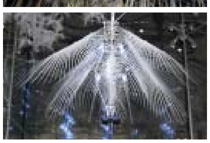
RADIANT SOIL, 2013

Espace Fondation EDF, Paris



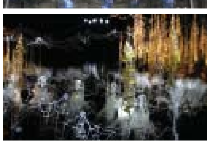
EPIPHYTE VEIL, 2013

EXIT Festival, Maubeuge, Creteil, Lille



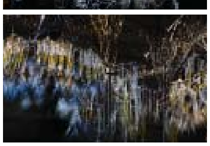
AURORA, 2013-

Simons, West Edmonton Mall, Edmonton



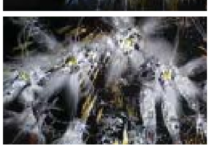
PROTOCELL CLOUD, 2013

Digital Art Festival, Taipei



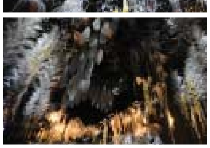
PROTOCELL MESH, 2012-13

Prototyping Architecture, Wolfson Hall, Nottingham University 2012/London Building Centre, London UK 2013/Design, Riverside Gallery, Cambridge ON



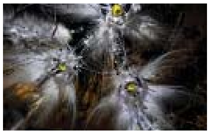
HYLOZOIC SERIES: EPIPHYTE GROVE, 2012

Meta.Morf Festival, Trondheim, Norway



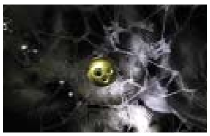
HYLOZOIC SERIES: SIBYL, 2012

Biennale of Sydney, Cockatoo Island, Sydney



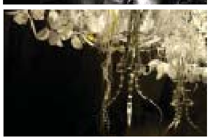
HYLOZOIC SERIES: VESICA, 2012

City Gallery, Wellington, New Zealand



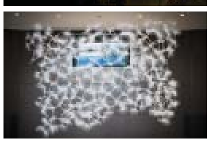
PROTOCELL FIELD, 2012

DEAF Festival, Rotterdam



HYLOZOIC SOIL: ESPACIO, 2012

Fundacion Telefonica, Madrid

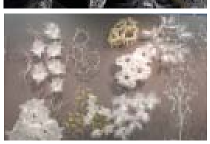


CLOUD BROCADE, 2011-12

Stitches: Suzhou Fast Forward, WORKshop, Toronto 2011; Festival Bains Numeriques, Paris, France

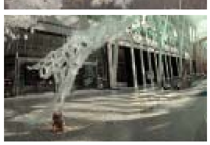
HYLOZOIC VEIL, 2011-

The Leonardo, Salt Lake City



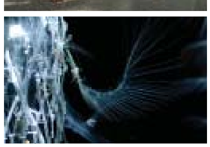
HYLOZOIC GROUND COLLABORATION, 2011

Cambridge Galleries Design at Riverside, Cambridge, Ontario



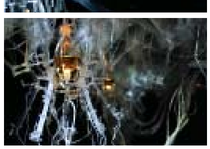
SARGASSO, 2011

Brookfield Place Galleria, Luminato Festival, Toronto



HYLOZOIC SERIES: STOA, 2011

Lexus Hybrid Art Show, Moscow



HYLOZOIC SERIES: SAINT-EXUPERY FIELD, 2011

Festival Chemins Numeriques, Reims

About The Hylozoic Ground Collaboration

The Hylozoic Ground Collaboration is a research group associated with the School of Architecture, University of Waterloo. Their research is based on interdisciplinary design methods that integrate industrial design, digital prototyping, chemistry, mechatronics engineering, advanced digital visualization and education. The Collaboration's sculptural work forms part of The Hylozoic Series. These experimental projects focus on immersive, digitally fabricated, lightweight textile structures and interactive kinetic systems that use dense arrays of microprocessors, sensors and actuator systems. These environments combine synthetic and near-living systems in pursuit of a distributed emotional consciousness.

The Hylozoic Ground Collaboration is led by Waterloo professor and experimental sculptor/architect Philip Beesley. Current lead collaborators include Rachel Armstrong, Becky Carroll, Christian Derix, Rob Gorbet, Lucy Helme, Asmund Izaki, Dana Kulic, Chantelle Niblock, Lucinda Presley, and Michael Stacey. 15 artists, designers, architects, and engineers currently work in association with the collective.

Author Biographies

RACHEL ARMSTRONG is a Co-Director of AVATAR (Advanced Virtual and Technological Architectural Research) specializing in Architecture & Synthetic Biology at The School of Architecture & Construction, University of Greenwich, London. She is also a 2010 Senior TED Fellow, and Visiting Research Assistant at the Center for Fundamental Living Technology, Department of Physics and Chemistry, University of Southern Denmark. Armstrong is a sustainability innovator who investigates a new approach to building materials called 'living architecture,' which suggests it is possible for our buildings to share some of the properties of living systems. She collaboratively works across disciplines to build and develop prototypes that embody her approach.

PHILIP BEESLEY is a professor in the School of Architecture at the University of Waterloo. A practitioner of architecture and digital media art, he was educated in visual art at Queen's University, in technology at Humber College, and in architecture at the University of Toronto. At Waterloo he serves as Director for the Integrated Group for Visualization, Design and Manufacturing, and as Director for Riverside Architectural Press. Dedicated to expanding the role for the arts integrated within architecture, Beesley has worked in sculpture, next-generation digital media and cross-disciplinary experimental visual art for the past three decades. He has focused on public buildings accompanied by field-oriented sculpture and landscape installations, exhibition and stage design. His experimental projects in the past several years have increasingly worked with immersive digitally fabricated lightweight 'textile' structures, while the most recent generations of his work feature interactive kinetic systems that use dense arrays of microprocessors, sensors and actuator systems. Beesley's work was selected to represent Canada at the 2010 Venice Biennale for Architecture, and he has been recognized by the Prix de Rome in Architecture, VIDA 11.0, FEIDAD, two Governor General's Awards, and as a Katerva finalist.

BECKY CARROLL has worked for Inverness Research since 1990. Her work has involved studies of K-12 mathematics and science education, as well as studies of exhibition and program development in the informal science field. In the informal field, her areas of interest include studies of collaboratives and networks, programs for youth, exhibition development projects, and professional development for museum professionals. In the formal field, she has participated in studies of mathematics and science program improvements and teacher professional development. Past and current projects in the informal domain include studies of the TEAMS collaborative; YouthALIVE!; Community Science Workshops; and the Precollege Science Collaborative and ITEST grant programs at the American Museum of Natural History; exhibit development projects at the North Carolina Museum of Life and Science and the Exploratorium; as well as the TexNET and Playful Invention and Exploration networks. On the formal side, projects include the Rapid City Math Science Partnership, the Appalachian Math Science Partnership, the Wyoming Middle School Mathematics Initiative, the Gilbert Systemic Science Plan (LSC), and the Appalachian Rural Systemic Initiative.

CHRISTIAN DERIX directed the Computational Design Research group [CDR] of Aedas architects in London UK, since its foundation in 2004 to 2014. Now independent, CDR develops computational simulations for generative and analytical design processes with an emphasis on spatial configurations and human occupation. Derix studied architecture and computation in Italy and the UK and has taught the subject at various European universities since 2001, including University of East London, University College London, Milan Polytechnic, Technical University Vienna and as visiting professor at Technical University Munich. Currently he is associate professor at IE University Madrid and visiting professor at the University of Sheffield. In 2002, he set up the Centre for Evolutionary Computing in Architecture (CECA) with Paul Coates at the University of East London, which they co-directed until 2010. The work of CDR has recently won award commendations for their Spatial Simulation framework at awards such as the 2010 Presidents Medal for Research in Practice of the Royal Institute of British Architects (RIBA), the 2011 Italian Compasso d'Oro for user-participatory algorithmic design of the VITA Shelving System for MDF Italia or the Centre for Tall Buildings and Urban Habitat's (CTBUH) 2012 Innovation award for the computer-activated responsive façade of the Al Bahar towers.

ROB GORBET received his PhD in Electrical Engineering from the University of Waterloo in 1997. He is currently an Associate Professor at the Centre for Knowledge Integration at the University of Waterloo, cross-appointed to the Department of Electrical and Computer Engineering. He is also a key member of Gorbet Design, a Toronto-based design firm, Philip Beesley Architect Inc. (PBAI) specializing in public interactive artwork and experiences. Since 2008 Rob has been a key collaborator with the Hylozoic Ground Collaboration, providing technical expertise and conceptual input to the Hylozoic Series of near-living architectural environments. He also is the Collaboration's lead on the educational outreach aspects of the work. He is an interdisciplinarian, a mechatronics specialist, a practicing technology artist and an award-winning teacher. His favourite course has him teaching with Fine Arts faculty to teams of upper-year engineering and fine arts students who collaborate to create kinetic sculptures. He is interested in the design of interactive artworks and the process of learning across disciplines. In addition, Gorbet's collaborative interactive artworks with other artists and designers have been exhibited at ISEA2006 in San Jose and at many galleries and shows in the Toronto area.

LUCY HELME is a Senior Designer within the Aedas|R&D Computational Design Research group, having joined the practice in 2009. Since then she has been developing and applying computational techniques on a wide range of architectural projects, from masterplanning to data visualization. She also regularly communicates the work of the group through lectures and university teaching. Prior to joining Aedas, Helme completed a MA in Industrial Design Engineering at the Royal College of Art, graduating in 2008. During her final year project she developed a system for the design and manufacture of customizable small buildings for the domestic garden using generative design and computer aided manufacturing techniques. Helme also has a strong background in science, completing a PhD in materials physics in 2006 and publishing in leading journals in the field.

ÅSMUND IZAKI worked as a senior designer and researcher at Aedas R&D Computational Design Research since 2007. During his time with Aedas he has developed computational models for urban planning, architecture, and furniture through code. This takes the form of interactive tools and methods that have been applied in projects both internally, and as an external service or in collaboration with industry or academic partners. Examples of projects he has worked on during this time range from the interactive interface for the VITA shelving system, visibility analysis for the 9/11 Memorial Museum in New York to research about modelling perceptual and experiential aspects of architecture. Izaki holds an MArch from NTNU, Norway, where he specialised in architecture and adaptive systems. After finishing his studies he worked with the architecture group servo and the interaction design office Kram/Weisshaar on projects that have been exhibited and published widely internationally. He has lead courses on topics related to design and technology at Konstfack University College of Arts, Crafts and Design and at The Royal Institute of Technology in Stockholm.

DANA KULIĆ received the combined B.A.Sc. and M.Eng. degree in electro-mechanical engineering, and the Ph.D. degree in mechanical engineering from the University of British Columbia in 1998 and 2005, respectively. From 2002 to 2006, she was a post-doctoral researcher at the CARIS Lab at the University of British Columbia, developing human–robot interaction strategies to quantify and maximize safety during interaction. From 2006 to 2009, she was a JSPS Post-doctoral Fellow and a Project Assistant Professor at the Nakamura Laboratory at the University of Tokyo, working on algorithms for incremental learning of human motion patterns for humanoid robots. She is currently an Assistant Professor with the Electrical and Computer Engineering Department at the University of Waterloo, Waterloo, ON, Canada. Her research interests include human motion analysis, robot learning, humanoid robots and human–machine interaction.

CHANTELLE NIBLOCK, MArch, PhD, is Course Director of MArch Technology and Lecturer in Architecture at The University of Nottingham since 2010. She is co-convenor of a Diploma Studio [RIBA Part 2] in Digital Architecture and Fabrication, which focuses on developing design methodologies and innovative facade design. She is a member of the Architecture & Tectonics Research Group at The University of Nottingham. Her research and teaching interests include: architectural design thinking (pedagogy and practice), digital fabrication, prototyping in architecture, and collaborative design across disciplines. Her current research includes the Hylozoic Ground Collaboration research programme with the University of Waterloo, School of Architecture and University Southern Denmark, Center for Fundamental Living Technology, this research is funded by Social Sciences and Humanities Research Council, Canada. Her PhD, sponsored by AHRC, investigated the influence of free-form modelling on the process of designing, using a comparative protocol study between expert and novice architects. During her Masters of Architecture course she specialised in CAAD and explored a pre-digital design by Frederick Kiesler.

LUCINDA PRESLEY integrates the fine arts and creative thinking with science, technology, engineering and math (STEM to STEAM) in school and museum settings. She is Executive Director of the Institute where Creativity Empowers Education Success (ICEE), which uses the arts and creative thinking skills to promote STEM engagement, learning, and 21st century problem-solving skills. Presley works nationally and internationally, developing school and museum programming, writing curriculum, and training teachers. She works extensively with: The Exploratorium in San Francisco; The Exploratorium's Playful and Inventive Exploration (PIE) project; NASA's Jet Propulsion Lab, Arizona State University's Mars Education Program, Britain's art/science/creativity initiative, Ignite, the Hylozoic Ground Collaboration, The Leonardo art/science/technology museum in Salt Lake City, the National Museum of Women in the Arts in Washington, DC, and The University of Texas at Austin's Texas Regional Collaboratives for Excellence in Science and Math Teaching.

ALI-AKBAR SAMADANI received his B.A.Sc. and M.A.Sc. degrees in Electrical and Computer Engineering from the University of Kuwait (in 2006) and the University of Manitoba (in 2009), respectively. Currently, he is pursuing a Ph.D. degree at the University of Waterloo, Canada, where he works on developing computational models for affective movement recognition and generation. His research interests are machine learning, affective computing, time-series analysis, human motion analysis and human-machine interaction.

MICHAEL STACEY is Chair in Architecture and Director of Architecture at the University of Nottingham, where he leads the Zero Carbon Architecture Research Studio [ZCARS]; which focuses on the design of zero carbon homes in Nottingham, which this year includes an entry to Madrid: Solar Decathlon 2010. He is also Research Professor at University of Waterloo, Ontario. His research is centred on extending the boundaries of the possible, whilst combining quality and affordability and thus informing the built environment. Themes within his research include: digital fabrication, form finding in components and architecture, offsite manufacture, façade design and procurement, emergent materials and sustainability. Current research programmes include is the study of zero carbon architecture, the development of technology for the built environment over the past 100 years, digital fabrication and architecture, a green guide for aluminium and a studio design guide for the use of concrete.

HYLOZOIC VEIL
The Leonardo, Salt Lake City, 2011

Collaborators
- Rachel Armstrong
- Philip Beesley
- Rob Gorbet

Project Lead
- Hayley Isaacs

Phase 2
- Becky Carroll
- Christian Derix
- Lucy Helme
- Asmund Izaki
- Dana Kulic
- Lucinda Presley

PBAI Core Team
- Eric Bury
- Martin Correa
- Brandon DeHart
- Carlos Carrillo Duran
- Zachary Fluker
- Liav Koren
- Andrea Ling
- Elisabeth van Overbeeke
- Anne Paxton
- Kristie Taylor
- Jonathan Tyrrell
- Erica Yudelman

HYLOZOIC SERIES: SIBYL
18th Biennale of Sydney, Cockatoo Island, 2012

Collaborators
Rachel Armstrong
Alain Baril
Philip Beesley
Philippe Baylaucq
Rob Gorbet
Mark-David Hosale

Project Lead
Martin Correa
Jonathan Tyrrell

PBAI Core Team
Sue Balint
Eric Bury
Brandon DeHart
Susanne Eeg
Pedro Garcia
Andrea Ling
Elena Moliotsias
Leonor Munoz
Anne Paxton
Adam Schwartzentruber
Mingyi Zhou

Production (Toronto)
Fysal Amirzada
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Miho Inaba
Anjali Jaywar
Andrea Lau
Ian Lie
Tosin Sanni
Taiana Selbach
Tomasz Smereka
Patrick Svilans
Siubhan Taylor
Chris Tron

Production (Australia)
Callum Andrews
Nicola Balch
Alain Baril
Philippe Baylaucq
Tom Bingham
Annabel Blackman
Marston Bowen
Anthony Burke
Dean Calabrese
Lorraine Chan
Kathryn Chang
Natali Dundovic
Jay Griffin
James Guerrisi
Joshua Harrex
Sophie Harris
Adam Hoh
Patrick Issa
Holly Julian
Megan Julian
Jo Kinniburgh
Francesca McInnes
Eleanor Peres
Wajdy Qattan
Frances Robinson
Lena Thomassen
Dean Wall
Chen Zhuang

PROTOCELL MESH
Nottingham & London, England; Cambridge, Canada, 2012-13

Collaborators
- Rachel Armstrong
- Philip Beesley
- Rob Gorbet
- Martin Hancycz
- Jackson Hunt
- Chantelle Niblock
- Andrew Schoones
- Michael Stacey

Project Lead
- Jonathan Tyrrell

PBAI Core Team
- Martin Correa
- Sue Balint
- Eric Bury
- Brandon DeHart
- Pedro Garcia
- Andrea Ling
- Anne Paxton
- Adam Schwartzentruber
- Mingyi Zhou

Fabricators/Manufacturers
- FC Laser Nottingham
- Romco Toronto
- KJ Laser Toronto

University of Nottingham
- Samantha Bracey
- Kaplan Pirgon
- Madeleine Ike
- Zainab Oyekan
- Yue Dai
- Jinfan Xie
- Michael Shupac
- Thomas Corbett
- Alisdair Gray
- Nimesh Mistry
- John Comer
- Luis Mejias
- Philip Gilder
- Natalie Panayidou
- Emma Eady
- Vikash Patel
- Dominic Ward
- Vasileios Sougkakis
- Kostas Fetsis
- Nicole Ong
- Benjamin Fisher
- Katherine Tokarski
- Matt Fielding
- Joel Day
- Anthony Kong
- Jonathan Davidson
- Minesh Patel
- Peter Blundy
- Samuel Critchlow
- Michael Ramwell
- Jenny Grewcock
- Amarveer Bains
- William Hathaway
- Jonathan Hallett
- Mush Rad
- Laura Gaskell

AURORA
Simons, West Edmonton Mall, Edmonton, 2013

Artist

Philip Beesley

Project Lead

Eric Bury
Andrea Ling

PBAI Core Team

SSue Balint
Martin Correa
Brandon DeHart
Susanne Eeg
Pedro Garcia
Jonathan Gotfryd
Elena Moliotsias
Anne Paxton
Adam Schwartzentruber
Tomasz Smereka
Patrick Svilans
Jonathan Tyrrell
Mingyi Zhou

Production (Edmonton)

Tony Abitegeka
Franchesca Agoncillo
Natasa Baic
Chris Brodt
Russell Davidson
Emily Devereux
Daniel Eshpeter
Rosalyn Estoque
Brook Hendry
Nicole Howard
James Kokotilo
Shaunna Kossatz
Mark Lafond
Bertha Ng
Evelyn Pankiv
Stephanie Palosky
Marah Pantzer
Vallen Rezazadeh
Julie Sikora
Mikenna Tansley
Carson Tarnasky
Ashley Truong
Anastasiya Valetka
Jack Wear
Laurie Wear
Katrina Whiteman
Amy Wowk

EPIPHYTE CHAMBER
MMCA, Seoul, Korea, 2013

Collaborators
Rachel Armstrong
Brandon DeHart
Rob Gorbet
Dana Kulic

Project Leads
Martin Correa
Jonathan Gotfryd
Andrea Ling

PBAI Core Team
Sue Balint
Matthew Chan
Vikrant Dasoar
Faisal Kubba
Salvador Miranda
Connor O'Grady
Anne Paxton
Eva Pianezzola
Sheida Shahi
May Wu
Mingyi Zhou

Production (Toronto)
Parantap Bhatt
Jessica Carroll
Gelene Celis
Rayana Hossain
Nada Kawar
Yonghan Kim
Pedro Lima
Parham Rahimi
Kearon Roy Taylor

Production (Seoul)
Cheon Hari
Hanjun Jo
Boram Kim
Yonghan Kim
Taehyung (Richard) Kim
Hyeon Min Lee
Gyoung Hun Park
Sudam Park
Nuri Shin

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DIFFUSIVE PROTOTYPING

Philip Beesley

USING AFFECT TO INCREASE EMPATHY IN NEAR-LIVING ARCHITECTURE

Ali-Akbar Samadani, Dana Kulic & Rob Gorbet

3. PBAI

7, 9, 12, 17. Dana Kulic and Rob Gorbet

ANTICIPATING BEHAVIOURS

Asmund Izaki, Christian Derix & Lucy Helme

2. PBAI

7-9. Aedas Computational Design & Research

EMPOWERED MATTER: THE DYNAMIC CHEMISTRIES OF HYLOZOIC GROUND

Rachel Armstrong

2. PBAI

33. Simone Ferracina

IT LIVES! PROMOTING CREATIVE AND INNOVATION THINKING IN EDUCATION

Lucinda Presley, Becky Carroll & Rob Gorbet

7 & 19. PBAI

25-34, 36-38. It Lives!

PROTOTYPING PROTOCELL MESH

Michael Stacey & Chantelle Niblock

3, 11, 34. PBAI

8, 15. University of Nottingham