Joseph Paradiso (US)

Speculating across Scale, from Sensory Landscapes to Radical Subatoms

I live for those moments when I'm engaged in a project that I know has the potential to change everything, but I don't yet know exactly what it's "good for." Like the alchemists of old, my research is supported by interest in the "gold" that might be mined from my inquiries, but such practical transmutation isn't what motivates me in the end. The special times are when my team and I have created a technical "elixir" that evokes myriad exciting futures, but it's not clear which vein will reward auric ambition—when we live simultaneously in all possible universes that unfold from our work, but commercial interests haven't yet collapsed its cosmic wave function into markets.

Most of my research over the last decades has centered on sensing as opposed to mechanical actuation. Accordingly, my first forays into "radical atoms" explored smart materials as what I termed *Sensate Media*—essentially dense sensor networks realized on a smart surface. As with most Radical Atomists, my inspiration came in part from the pioneering *Smart Matter* work done at Xerox PARC in the 1980s, but I was interested in building sensate skins instead of doing distributed control, exploring a vision of dense sensor/processor "soup" that realized new kinds of smart material. My team built our first incarnations of this in the early 2000s, such as the *Trible* (a reactive sphere tiled with a sensor network), *Pushpin Computer* (a planar surface upon which hundreds of networked smart sensors can be arrayed like pushpins), and the *Z-Tiles* (sensate networked floor tiles made in collaboration with the University of Limerick in Ireland). We proceeded to smaller scale with the *S.N.A.K.E.* skin (all on flex PCB) and the *ChainMail* (a sheet of small rigid nodes linked by flexible or stretchable interconnects). Our current work in this area is exemplified by *SensorTape*—a vision of a dense linear sensor network embodied as a conventional roll of one-inch-wide adhesive "tape" that can be spooled off, cut, and rejoined as desired, enabling any object or surface to which it is attached to attain a multisensory capability. The underlying technology is rapidly evolving, enabling sensors and electronics to be printed or applied as stickers, the substrate to become stretchable, and certain elements to be self-powered, allowing sensor tape to be applied to material and remotely interrogated for "perpetual" operation. Dr. Katia Vega, a visitor in my research team, is exploring the application of such flexible sensor/actuator arrays as interactive on-skin "smart makeup" in what she terms "Beauty Technology"—an intriguing bridge between wearable and implantable systems.

Looking at coarser scales, the vision of Radical Atoms melds with distributed robotics. Although this is a field with a legacy going back decades, recent developments in materials, miniaturization, communication and fabrication enable distributed mobile actuators to be realized on increasingly smaller scales. As nanotechnology and MEMS are driving the bottom here (often driven by extreme visions of in-vivo healthcare), there's plenty that you can do in the middle, as coin-sized mobile microrobots are now fairly easily made, and open questions abound, ranging from system applications to cooperative control, as witnessed by the worldwide abundance of research conducted with these devices. We've taken a particular slant on this at the Media Lab, colored by our interest in wearable systems. In collaboration with Stanford colleagues, our recent *Rovables* microrobots are biomemetic constructs designed to crawl over clothing to function as dynamic user interfaces as well as performing a variety of collective tasks that span medical and aesthetic purposes.

That said, biology still humbles current microrobot capability. One of the prime deficiencies in technology here is in energy—insects and micro-organisms acquire energy from their surroundings by ingesting food and nutrients, and hence can keep functioning until they die (of course, they can self-reproduce and heal too—extreme challenges for electromechanical constructs). Existing technology for energy harvesting in microrobots is still extremely limited, as the available conversion/storage volume is very small and our electronics aren't yet able to easily tap into common nutrients or exploit digestion. In work launched a decade ago, we have explored a different approach here, adopting another inspiration from nature. It generally takes much more energy to physically move than it does to transmit information. Additionally it seems that nature lacks the vocabulary to evolve an effective radio, which is better manifest in silicon than via biology—this is one place where electronics wins. Hence we've constructed a set of devices that offload energy-consuming mobility to other agents in the environment. Termed *Parasitic Mobility*, our nodes demonstrate the idea of hitching "rides" on passing vehicles, people, etc., attaching and detaching at their convenience. This is modeled after the common natural process of "phoresis"—e.g., insects and micro-organisms using larger animals for transportation. Devices can also transport themselves symbiotically by being attractive to people to carry and afterwards discard when they are no longer useful, ready to be picked up by somebody else. Pens and pencils have long held this niche (bringing along parasitic advertising), and we start to see mobile electronics follow this pattern as well—again hinting at a fascinating near-future where our physical electronics use us to stochastically move them where they desire.

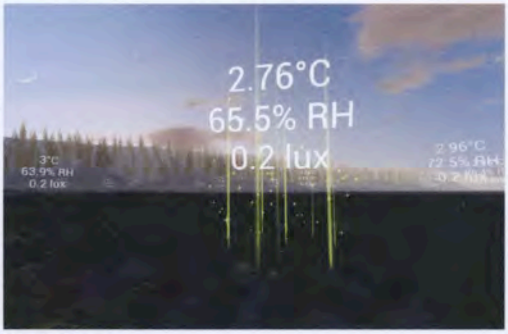
The basic constituents of matter don't stop at atoms. For over a century we've known about electrons and the atomic nucleus, which consists of protons and neutrons. And since the 1960s, we've known that these nucleons are each built from three quarks in a "sea" of field-carrying gluons. Hence, although the energy scales involved here are far beyond that of material science and chemistry, it's fun to consider thinking past Radical "Atoms" into Radical "Subatoms." The Chinese science fiction author Cixin Liu engaged in wonderful speculation here in his award-winning 2006 novel *The Three-Body Problem*, where he envisioned a proton existing in nine dimensions being unfolded into in 3D (where it occupied a planetary scale) by malevolent alien scientists, who then lithographed a planetary-scale supercomputer onto it, folded it back into compact 9D space, then sent it to Earth to unleash considerable mayhem (it was capable of actuation by "borrowing" energy to be paid back towards the end of the universe). Although theories of grand unification tend to require fundamental particles (which the proton is not, as it is made of quarks) to extend into compacted extra dimensions, Liu is taking massive artistic license with the science of his so-called *Sophons* here at several levels—but nonetheless, the vision he articulates entertainingly pushes the fanciful limits of what one could consider Radical Subatoms.

The subatomic realm has held a huge resonance for me, as I've spent many years working as a high-energy physicist, and have recently launched a collaboration with the ATLAS (one of the two main detectors at the Large Hadron Collider) to bridge experimental subatomic physics and music. Termed *Quantizer*, my student Juliana Cherston and our CERN collaborators have built a framework for composers to author generative music atop real-time ATLAS detector data. At the project website, you can "tune in" to ATLAS data as it arrives, interpreted by several different composers who have built mappings via our framework, with more to come.

More generally, I've been fascinated with the use of large data sources (e.g., as above with the LHC detectors) as artistic canvases. Although this has been explored somewhat via prior sound art and visualization, the quantity and richness of data sources available today are exploding as the Internet of Things unfolds and tools to extract structure from it are increasingly developed. For the last decade, my research team has been engaged in a

Artem Dementyev

Rovables



Donald Derek Haddad, Gershon Dublon

DoppleMarsh

Joseph Paradiso

ReflectingCubeChaos

series of projects aimed at mapping human perception onto rich sensor network data under what we call *Cross Reality*—where ubiquitous sensor/actuator networks are "wormholes" tunneling real-world information to and from virtual environments that enable users to experience a "resynthesized" reality incarnated via a game-engine browser—an environment where the sense of presence is extended via manifestations from densely-deployed sensors. Freed from physical constraint, you can see and hear information streaming at scale from the physical world as interpreted into your own sensorium by artists and composers. One of our earlier installations, *DoppelLab*, was shown at Ars Electronica in 2011. *DoppelLab* enabled virtual visitors to experience spatialized sensor information and hear obfuscated audio from distributed microphones as they drifted through a virtual 3D model of our Media Lab building across both space and time.

Our recent work has focused on a retired cranberry bog in southern Massachusetts called *Tidmarsh* that's being restored to a natural wetland. We've deployed hundreds of low-power sensors across this beautiful natural landscape to capture the environment's response to this restoration. In addition to storing this multimodal data for ecological analysis, we are manifesting it (including spatialized sound from over 30 distributed microphones and hydrophones) in a virtual world as a networked sensory landscape, so online visitors can experience this space in both an informative and aesthetic way. The distributed sensors and microphones in our *Tidmarsh* environment drive a music engine that produces a spatial sound stream that reflects real-time conditions and events in the marsh as interpreted via four different composers, who have employed our generic musical mapping framework. Conditions at *Tidmarsh* "play" musical pieces that are always unfolding and evolving and reflect the present physical character of the actual place.

Through such networked sensory landscapes, we have re-synthesized the world of real atoms into a virtual experience interpreted via aesthetic mappings. Returning to our free-wheeling exploration of Radical Subatoms and associated particles, Ed Fredkin and Tom Toffoli showed that simple classical contact interaction (ignoring scattering dynamics) between elastically colliding particles are capable of universal computation in their *Billiard Ball Computer* model devised at MIT in 1982. In the mid-80s, I became fascinated by the kinematics of such particle trajectories in a perfectly reflecting cube, where a single particle, launched from the center of one face of the cube, classically and losslessly reflects off of each face, essentially iterating a recursive map at each reflection.

Due to strong nonlinearities near the edges of the cube, when the particle trajectory approaches the sides of a face, it becomes very sensitive to small changes in state, evoking chaotic behavior and fractal characteristics. If one plots the distance traveled by the particle before it comes within a finite radius of where it started (or the number of bounces it encountered before returning, etc.) as a function of the angles at which the initial particle was launched, fascinating graphics can be generated that exhibit the symmetry of the cube along with very complex fractal-like regions—indeed, playing with this system occupied much of my spare time during the heyday of Mandelbrot Set graphics.

As we've traversed immense scale, from networked sensory landscapes to Radical Subatoms and particle scattering, I'll close this essay with the key phrase remembered from Richard Feynman's classic 1959 talk that launched nanotechnology—"There's Plenty of Room at the Bottom"—and abundant creative inspiration all the way down!

http://resenv.media.mit.edu