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Science + dance = bodystorming

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In everyday life, gravity and inertial forces often dominate our movements; in the cell, these forces pale in comparison to thermal forces. The violent, collisional world of the cell, where water moves faster than a jet airliner, can be difficult to imagine. To develop our intuitive understanding of cellular and molecular processes, we are exploring the concept of 'bodystorming', where human 'movers' act as molecules that diffuse, undergo reactions, and generate/absorb forces.

Getting started

For the past few years, we have worked together to explore how science can be informed through dance and vice versa. As a starting point, we considered the concept of 'catastrophe', an important feature of microtubule self-assembly [1], where an abrupt, stochastic switch from an assembling state to a disassembling state allows dynamic microtubules rapidly to explore the intracellular environment. Catastrophe is vital for proper formation of the mitotic spindle, and some of the more widely used anticancer drugs (e.g., paclitaxel) specifically target microtubule self-assembly.

We came to focus on catastrophe after a chance meeting sponsored by the Institute for Advanced Study (IAS) at the University of Minnesota, through which we had separately developed collaborative projects under the general theme of 'time'. One project focused on 'Catastrophe', a research collaborative organized by D.O. and his brother Thomas C. Odde (film studies), that explored disruption of time from the multiple perspectives of art-making, biology, and engineering. The other project was entitled 'Wreck', an exploration of the depths of physical and psychological endurance in the face of impending destruction, developed by C.F. as artistic director of the Black Label Movement (BLM) Dance Company. Under the direction of Ann Waltner, IAS required us to meet with other collaborative leaders, which prompted us to propose The Moving Cell Project, where the concept of microtubule catastrophe would be explored through dance (Box 1).

Basic moves

The cytoplasm is a violent place. The root-mean-square speed of a molecule is:

$$v_{\mathrm{rms}} = \sqrt{\frac{3k_B T}{m}} \qquad [1]$$

where k_B is Boltzmann's constant, T is absolute temperature, and m is the mass of the molecule. For water, the most abundant molecule in the cell, the root-mean-square speed exceeds 600 m/s (1400 m.p.h.). As water molecules move at these speeds, they collide with other molecules moving at similar speeds, creating an extreme collisional environment. It is these collisions that give rise to diffusion, the apparently random movements of molecules. For a dance to convey a cellular process, such as microtubule assembly, it is important to first appreciate the thermally driven environment within which this process occurs. Fortunately, BLM embraces physicality and seeks safe ways in which collision and contact can be incorporated into dance. To convey this philosophy, BLM often refers to its dancers as movers (Figure 1).

To simulate diffusion, we started with training exercises where a coin flip determined the left–right and forward–backward movements of the dancers. Although we have not formally checked that the movers are executing truly random walks, one gets the impression that they are (it is a challenge to demonstrate true randomness; we routinely use computers to simulate diffusion even though we know that computers are deterministic machines). Initially, movers were protected by body suits, but we found that these were too cumbersome. Instead, we focused on developing trust within the movers. An overarching principle is that movers should neither seek nor avoid collisions. In fact, we routinely adjust the rate of random stepping to adjust the contact level, equivalent to increasing/decreasing the temperature.

Once we had movers diffusing, we added bond formation. If the movers face each other when bonded, they can form dimers. Because the Debye screening length (the distance over which attractive forces are felt between macromolecules) is typically of the order of 1 nm or less, the bonds do not form until the movers are in direct contact. When the bonding is front to back, self-assembled linear filaments can form. We simulate bond breaking in various ways, typically by throwing balls at the bonded partners. We then enclose all the movers in a circle of movers holding hands to simulate enclosure of the diffusion and reactions within a membrane bilayer. Working with a professional dance company means that the movers have a high degree of physical intelligence and can build trust quickly. This allows us to move rapidly with a robust range of physicality available to express the scientific concepts.

Which model?

Initially, our plan was to convey scientific concepts, such as microtubule catastrophe, to a lay audience through dance.

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Box 1. Useful links

Robert Hammel Vimeo Site
http://vimeo.com/30346802 – video documenting The Moving Cell Project (20 minutes).

Twin Cities Public Television
http://www.mnoriginal.org/episode/hit-the-moving-cell-project/ – interview with D.O. and C.F. and project clips (10 minutes)

http://www.mnoriginal.org/episode/black-label-movement-hit/ – edited extended excerpt of BLM performing 'HIT' (10 minutes)

Institute for Advanced Study
http://ias.umn.edu/2011/09/22/moving-cell-2/ – video podcast of a joint class between BMEN 5351 Cell Engineering (D.O, instructor) and DNCE 3010 Modern Dance Technique (C.F., instructor) held in the Barker Dance Studio at the University of Minnesota (85 minutes)

Chicago Tribune *review of 'HIT'*
http://articles.chicagotribune.com/2011-03-11/features/ct-live-0312-same-planet-dance-review20110311_1_dancer-dance-center-collisions

Twin Cities Star Tribune *review of 'HIT'*
http://www.startribune.com/entertainment/stageandarts/139153774.html?refer=y

BLM website
http://www.blacklabelmovement.com/

David Odde's laboratory
http://oddelab.umn.edu/

Although microtubules are central to eukaryotic life and the target of many cancer treatments, they remain virtually unknown to the general public. Using dance to convey basic ideas is not entirely novel; perhaps the most famous example is a dance performed by Stanford University students in the 1970s entitled 'A Protein Primer' (http://www.youtube.com/watch?v=u9dhO0iCLww). Since the 1970s, advances in computer animation have led to beautifully rendered depictions of cellular processes, such as the 'Inner Life of the Cell' video from XVIVO Scientific Animation and BioVisions Multimedia at Harvard University (http://multimedia.mcb.harvard.edu/anim_innerlife_music.html). Nevertheless, the medium of dance remains a vital means of communicating science, as evidenced by the success of the 'Dance Your Ph.D.' contest, an annual event organized by John Bohannon, a correspondent for *Science*. John has joined our Moving Cell Project and together we have explored the extent to which dance can be used as a communication medium in science, most recently exemplified in a dance performance at the 2011 TedX-Brussels conference (http://www.ted.com/talks/john_bohannon_dance_vs_powerpoint_a_modest_proposal.html).

Figure 1. Black Label Movement 'movers' Eddie Oroyan and Carl Flink collide in a simulation of the thermally driven environment of the cell.

In either dance or computer animation, key decisions must be made about what to include in the performance/animation and what not to include. Naturally, every scientist will have his or her own unique scientific views, just as choreographers will have their own unique perspectives. The question then becomes, which model for a cellular process should be depicted? A model from a major textbook or a recent review article? Or perhaps a new model that a scientist is developing? In choreographing a dance, a scientist is making key decisions about which model to depict. In choosing to depict a cellular process in a way that differs from how another scientist would depict it, we have the beginning of a potentially constructive scientific discussion. It occurred to us that dance could potentially be informative not only to the general public, but also to scientists at the cutting edges of scientific knowledge as they articulate their hypotheses through the dances that they choreograph.

Bodystorming: rapid prototyping of hypotheses

One might wonder whether one can 'prove' anything using dance; why not just use mathematics or computer simulations to make testable predictions from hypotheses? In fact, this is a standard approach in our research and is fast becoming standard in cell biology research generally, as described in this special issue on synthetic biology. Because of the complexity of cellular processes, we generally need to solve equations numerically or perform Monte Carlo simulations, depending on whether the dynamics are fundamentally deterministic or stochastic [2]. In practice, doing theory via computer simulation requires a significant investment in computers and time spent programming and debugging code. It is often weeks or months before useful simulation output is obtained; when the simulations are done, we are left with the task of interpreting the output. Often we need to revise the output statistics from the simulation and try different ways of plotting the results or making animations of the output. Even when the model makes testable predictions that we test experimentally and find to be correct, we often do not intuitively understand why the model behaves in the way that it does. This last phase of modeling, model deconstruction, is now taking us at least as much time as the model construction phase. A modeling project can continue for months before we start to feel confident that the model is physically sound, makes testable predictions that are correct, and is sufficiently deconstructed that we understand it intuitively.

Dance provides us with a useful complement to computer simulation, allowing us to rapidly prototype hypotheses without having to code and debug each one on a computer. Using the basic moves described above, we can rapidly explore the consequences of our hypotheses using movers. Because these dances are most useful at the earlier brainstorming stage, we refer to the process of dancing out our

Figure 2. Scientists and Black Label Movement 'movers' simulate filament self-assembly, an example of bodystorming.

hypotheses as bodystorming (Figure 2). Often we see in the first few moments of a bodystorming dance that the experimentally observed behavior will not emerge under the hypothesized rules. What is especially interesting is when the reasons for the discrepancy are not evident to the scientists as the dance unfolds. At this point, we engage in a dialog with the movers: why is the expected behavior not occurring? Unlike the computer, the movers can engage in discussion with the scientists and with each other. In addition, the scientists themselves can become movers and inhabit the cell that they are imagining, which can be a profound and visceral experience. If there are N people engaged in the dance, there are of the order of N^2 possible discussions that can take place after the dance. By contrast, in the traditional approach, the computer is mute and the task is left to the scientist to interpret the numerical output in tabular, graphical, or animated output form. It is interesting to note that there is a general trend toward agent-based simulations in cell biology [2]. In the case of bodystorming, the agents are human beings who can reflect on their experience in the simulation.

To see whether BLM movers could facilitate scientific dialog and debate, we invited biochemists Dyche Mullins (University of California San Francisco) and Enrique De La Cruz (Yale University) to join us in a rapid prototyping experiment. Along with John Bohannon, who suggested the term bodystorming during these sessions, we explored a wide range of scientific questions. Perhaps most stimulating was the question of the effect of macromolecular crowding on association rates *in vivo*. Most of our kinetic and thermodynamic measurements have been made *in vitro*, but we do not yet fully understand how the macromolecules of the cytoplasm affect kinetics and thermodynamics [3]. Therefore, understanding crowding is vital to linking our understanding of *in vitro* biochemistry to *in vivo* biochemistry and cell biology. Although we did not settle any issues definitively, we developed a better intuitive understanding of crowding, and the issues that were raised prompted us to go back to the laboratory to set up rigorous computer simulations, work that is ongoing. In this case, bodystorming allowed us to engage in rapid prototyping to identify key issues for further exploration by more traditional approaches.

A new way of teaching?

One exciting aspect of the collaboration is how the BLM movers have responded positively to the science. The BLM company members are highly trained professional dancers with scientific backgrounds of varying extent. We have found that abstract concepts, such as diffusion and self-assembly, are relatively easy for a dancer to understand when put into concrete physical terms. When we teach science, students are normally seated and the teaching is largely verbal and visual (e.g., lecture with whiteboard and/or computer slides). When we teach science to dancers, both teacher and students are on their feet and in motion. This allows the teacher and student to bring physicality into the learning process, which we suspect is especially effective for students whose thinking is intimately linked to physicality (e.g., dancers and athletes). The integration of bodystorming into our educational system seems relatively unexplored. We envision possible collaborations between teachers in physical education, arts, and science, with students encouraged to learn actively through participation in a cellular (or physical–chemical) process. A future science classroom might look more like a dance studio or gymnasium than a room filled with desks aimed at a whiteboard, or teaching can even move out of the classroom and into the outdoors.

Mutations and engineering

One early challenge in the collaboration was that the dancers would sometimes propose to move in ways that were incongruent with our current understanding of the scientific concept we were trying to convey. The motivation for these proposals was often to develop dance movements with aesthetic value. Although it was tempting for the scientist to dismiss these suggestions as scientifically invalid, we found that it was best not to be too strict in the artistic interpretations. First, the BLM movers are artists, and for a two-way collaboration to work effectively there needs to be room for artistic freedom, so that the movers do not simply feel like automatons executing an algorithm. Second, the scientists should keep an open mind. Perhaps the dancers have injected a new idea into the process. These proposals could be regarded as 'mutations' and allow the sort of 'what if?' experimentation that helps us to build our physical intuition and reasoning. Can we successfully predict how this mutated dance will unfold, even though we highly doubt that a cell could ever work that way? The ability to understand how a mutant dance will unfold connects very directly to engineering, where we attempt to steer the system in a direction that has a health or technological benefit. This could help us to address the issue of which molecules to target (e.g., via drugs) to achieve a desired therapeutic outcome. Making up new and bizarre rules should not be discouraged.

Feeding back into dance

Another advantage of collaborating with a professional dance company is that the movements developed through the collaboration may inspire new works of performance art. In our case, the basic moves described above (e.g., diffusion, reaction), led to a broader exploration of the use of impact in creating dance works. In particular, the explo-

Figure 3. Patrick Jeffrey and Eddie Oroyan create a curling microtubule protofilament in the new Black Label Movement dance 'HIT'.

ration of the technique of impact required to manifest the violent interior of the cell suggested to us that there was a choreographic application of this vocabulary useful for examining human relationships. In a quartet entitled 'HIT', Carl removed the prohibition of violent physicality in healthy human relationships to examine a dysfunctional community of people. When microtubules disassemble, their protofilaments curl outward releasing mechanical strain energy, a process that is now integrated into 'HIT' (Figure 3) to capture a moment of violent control between two men. 'HIT' is an example of how this collaboration is leading to serious and recognized art-making (see links to critical reviews of 'HIT' in Box 1).

Future outlook

The Moving Cell Project has led us in many surprising directions. We recently provided advice to the Citizens League of Minnesota, a public policy group that is interested in exploring the application of bodystorming to complex policy issues. In our own work, we are now planning joint group meetings in a dance studio, which will allow even greater integration of science and dance into our work. Last summer we visited the Marine Biological Laboratory (MBL) in Woods Hole, MA and provided a bodystorming capability to the community there through the physiology course. Students and faculty participated in bodystorming and rapidly prototyped hypotheses driving their research projects during the course. In general, the close integration of dance and science offers new opportunities to learn, teach, and drive new discoveries across disciplinary boundaries.

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