

GENEALOGIES OF SPACE

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"The body is then lived in volumes . . . which dilate, contract, change their shape. The body opens up to the world surrounding it by including the voids just as much as the wholes."

-Kitsou Dubois

On a high school biology trip to Wallops Island in 1995, my classmates and I were informed that we should not "worry" if we stumbled upon the headless carcasses of a dolphin and porpoise. Our hosts, somewhat delicately embarrassed, explained that NASA had taken the heads. Sure enough, we soon found the sun-baked remnants. The heads were missing, and it was oddly difficult to tell the porpoise apart from the dolphin.

What on Earth would NASA want with these heads? Our fanciful teenage instincts at the time told us they must be studying telemetry, and wanted to investigate the Dolphin's use of sonar. We thought that was pretty funny and unrealistic, but we clung to it. Nowadays, we have a different theory. As a friend who was with me at the time recently put it, "if they can use those heads to help us breathe on Mars, more power to them."

This paper examines some of the history and implications of cell biology research in the "free-fall" micro-g conditions of outer space orbit. In as much as the micro-g environment affects molecular activities, it is the goal of this text to outline a few foundations for nanotechnologists interested in conducting experiments in space. The final third of this paper explores more abstract, metaphoric and imaginative approaches to the small, the human, and the large.

Enter Nanotechnology

The "father" of nanotechnology, Eric Drexler, is considered by many lab scientists in "the field" of nanotechnology as an unrealistic, misinformed, eccentric dreamer. There is a significant ideological split amongst nanotechnologists (3) who fall on

opposing sides of the fundamental question: Is chemistry mechanizable? This is the vision being "sold" to congress but not necessarily the reality. In a now famous contestation of Drexler's views, Richard Smalley claimed Drexler's insistence on unrealizable nanomachines has "scared our children" and misled funders. At the heart of Smalley's argument is the sense that Drexler simply does not know enough about chemistry and its tricks - the rules of engagement, so to speak. Molecular robots, the Smalley side argues, are just not feasible.

Drexlerians reply that they already exist as RNA, and their future visions are admittedly irresistible. In his now canonical 1986 work, "Engines of Creation", Drexler devotes a full chapter ("The World Beyond Earth") to the role of nanotechnology in space research. Drexler is particularly attracted to the notion of "self-replicators" that can fix damaged parts of a skin tight space suit, and gossamer space craft that can accelerate with enhanced solar sails (which he calls "lightsails"). It is in space that the dreams of nanotechnology could realize their full potential, travelling across the universe, cheaply. In another part of his book, Drexler attacks the notion of aging, boldly claiming that we can solve this problem, or at least drastically reduce it, and wondering which generation will be the first to do so.

Certain implications of the Drexlerian vision of nanotechnology are clear: the human species will evolve into long-living alien forms and spread across the solar system. Regardless of the accuracy of this vision, the fields of nanotechnology, biology, and spaceflight will continue to collide in multiple ways. This paper focuses on the most basic interaction, in which a very large scale setting, the free-fall orbit around the Earth, creates an environment that changes the nano-sized molecular actions of biological tissue.

Micro-g Cell Biology

Since much of the reference literature (as well as NASA itself) uses the term "microgravity" I will do the same here, yet it is important to note that the force of gravity when in orbit around the Earth, is not that different from the force of gravity at the surface of the Earth. "Micro-g" refers to a lack of measurable *acceleration* caused by the gravitational *force*. This distinction will hopefully make the reader's conceptualization of

what is actually *happening* in this "weightless" environment slightly clearer or more profound. The "g" in Zero-g or Micro-g refers to acceleration, not to gravity itself. Astronauts and cosmonauts do not experience acceleration due to gravity, thus creating an effect of weightlessness, but they do experience gravity (gravity is what keeps them in orbit!).

Evolution has not had to adapt to changes in gravitational acceleration, it has remained a constant force. At the 2001 Symposium Celebrating Forty Years of U.S. Human Spaceflight, one of the speakers, Mary Ellen Weber, noted, "The human body has evolved over millions of years under the force of gravity. Every system in your body - how your fingernails grow, how you digest food, how you circulate blood - has evolved to use gravity." (2) Weber goes on to explain, for example, that the biological systems which "read" our water levels are contained in our neck, and in space humans require 30% less water. (Of course we must remember, when scientists and aerospace scholars say, "our bodies are used to gravity" they mean we are used to the acceleration caused by gravitational force.)

In an entry in the Wiley-Verlag Encyclopedia of Molecular Cell Biology and Molecular Medicine entitled "Cell Growth in Microgravity" (8), the authors Sundaresan, Risin, and Pellis explain that in addition to bone and muscle loss, 'cephalad fluid shifting', and 'neurovestibular disturbances', astronauts and cosmonauts experience "space sickness", an overall reduction in the capacities of the human immune system. As has been observed, the immune system is also affected by *stress* and *radiation*, so it remains unclear to what extent microgravity itself is responsible. Still, microgravity and suspension experiments with mammalian tissue both in space and on the ground seem to show that shifts in the immune system do occur in response to changes in gravitational forces. As the authors note, "More than 120 experiments have been performed in space during the past 15 years that demonstrate that microgravity induces changes in single cells."

The ESA's description of its Biorack facility, designed for use on board the Columbus shuttle and lost with its destruction in 2003, notes "space flight is known to affect the human immune system's response, which may increase astronauts' vulnerability to infectious disease. Bacterial biofilm growth has also been found to be faster in space than on Earth; antibiotics may also be less effective in microgravity."(5)

In particular, mammalian cells are affected (certainly *in vitro* and possibly *in vivo*).

Amongst mammalian tissue, different cell types are affected differently: some, like bone and muscle cells, experience reduced functionality, and others, like liver cells and cartilage, experience increased 3-dimensional aggregation and secretion. Specifically, both the "mechanotransduction" (the translation of physical forces into chemical processes) and "transmembrane signaling" (communication between cells) are affected by microgravity. As a result, proteomics (protein structure) and genomics (gene expression) are both affected. All this because of the near *absence* of acceleration in the environment.

At the core of this ongoing research is a question: how *aware* are cells of the g-force conditions of their environment? At what level of interaction does the resulting *biological event* take place? Is the event an additive effect of various small changes on the *organelles* (elements of the cell, mitochondria, the nucleus, etc)? Is it caused by pressure on the *cytoskeleton* (the internal filament-like structure that supports the cell's form) induced by varying densities of organelles and the surrounding *cytoplasm* (the cell's liquid which contains both cytoskeleton and organelles)? Is the cell indirectly responding to an environmental change in the liquid outside of it, or does the cell have a direct "gravity sensor" (or rather a "g-force sensor")? The root cells of plants are known to possess such a 'sensor', which lets the cells know which way the ground is. "Gravitropism" describes the gravitationally-directed growth of plants, and its discovery dates back to Darwin.

Sundaresan, Risin, and Pellis note that fluids in microgravity have "no density-driven phase separation, no particle sedimentation, and no gravity-driven convection" and so the cell might be responding to the "hostile" environment caused by these absences. Current studies focus on cell movement, signal transduction, and fluid dynamics.

These studies not only have direct impact on the understanding of *negative* Human biological responses to spaceflight, but also have the potential to promote *positive* aspects of microgravitational organogenesis. Organogenesis is the process by which the three germ layers of an embryo develop into organs. The simple question here is, what *can* we grow in outer space that we *cannot* grow on Earth? Turning back to Drexler and his nano-fascination, we see an immediate implication for those nanotechnologists who want to control molecular assemblers. Microgravity allows, in Mary Ellen Weber's words, "a very quiescent environment" for examining things like

protein structure, for instance.

Biological Experiments in Space

Following plant-growing experiments on the Salyut-6 and Salyut-7 space stations, MIR was rife with biological experiments (9). In 1990 the Kristall Module was added to the MIR space station, in which crystallographic, geophysical, and biotechnological experiments took place. One of the early experiments, Svet, was also the most successful, allowing 680 days of experiments. Svet, meaning 'light', was a space greenhouse contributed from Bulgaria and Czechoslovakia, and successfully grew lettuce, peas, and radishes. Adding to Svet, Svetoblok-M and Svetoblock-S were used to grow wheat and potato tubers from a culture and Svetoblock-G to study seeds. An earlier greenhouse, Fiton (1987), grew onions and radishes and cedar seedlings. Another greenhouse, the Magnetogravistat, grew wheat, flax, arabidopsis and ginseng in magnetic fields aboard the Salyut and MIR stations. Lithuania's BKM unit studied anti-mutation in plants. Czechoslovakia's Chlorella-A grew algae.

Station guests were not limited to plant specimens. Georgia's IFS-2 studied amphibians. Other guests to MIR included six Japanese tree frogs, fish, crustaceans, and mollusks. And in 1990 the Soviet/Czech Inkubator-2 studied the embryology of Japanese quail: the chicks hatched, but did not fare so well (though supposedly later experiments were more fruitful).

Amongst the Soviet biotechnological experiments on MIR's Kristall Module, Svetlana and Ruchei were used for electrophoresis (a purification process) of anti-viral samples, Rokomb for cell hybridization (where two different kinds of cells fuse to form a third *synkaron* cell), and the *bioreactor* Vita for microgravitational cell cultivation (see also Maksat and Biokrist experiments).

Bioreactors are devices that grow biological tissue. In 1973 Skylab hosted the first bioreactor in space, the *Woodlawn Wanderer 9*. The Group of Space Biology's Dynamic Cell Culture System (DCCS) for the continuous (self-feeding) cultivation of mammalian and plant cells, first flew in 1989 aboard the Soviet Biokosmos 9 satellite. The Vita (or MKM-1) was flown in 1990 aboard the Kristall module. Large bioreactor

Space Tissue Loss (STL) systems flew on U.S. shuttles between 1992 and 2003. Fully automated, the STL systems could handle embryos as well as cells cultures.

After NASA began using the MIR space station in 1995, experiments with their "Rotating Wall Vessel" bioreactors began. The Rotating Wall Vessel bioreactors (RWVs) provide low shear-force environments, which enables the delicate self-association of cells. These experiments showed that alternative structures could form in microgravitational environments. Low shear force RWV environments can also simulate microgravity on Earth, allowing for simultaneous control experiments to be conducted on the ground.

Another low shear force environment, the Swiss space "Sophisticated BioReactor" (SBR-I), originally designed for the cultivation of yeast cells, enables continuous cultivation. Weighing just 610 grams, it flew in 1994 and 1996 on STS-65 and STS-76. It is a "miniature" bioreactor jointly developed by Mecanex S.A. and the Institute of Microtechnology of the University of Neuchâtel.

The second version (SBR-II) flew as part of the Biopack in the ill-fated STS-107. Before it was lost in the Columbia tragedy, the Biopack was "a reusable multi-user facility developed by the European Space Agency (ESA) that enables biological experimentation under varying gravity conditions." (6) Subjected to a range of gravity levels, from microgravity ("zero-gravity") up to 2g, the samples are to serve as a basis for understanding microbiological processes in space.

The uses of the SBR-II included in the Biopack included "*in vitro* organogenesis of pancreatic islets, thyroid tissue, liver, vessels and especially cartilage, the study of the mechanism of organogenesis in low-g and the set-up of procedures for the production of implants for medical applications."(4)

This last point, the "set-up for the production of implants" is interesting. Working in microgravity allows for 3-dimensional cell and tissue growth, a process known as "self-association". And while the RWV bioreactors on Earth can simulate the microgravitational environment, there is a limit to the size of the tissue that can grow. In orbit, in space, tissues can grow much larger. Also, there is almost no gravitationally induced *convection* in microgravity, and so unstirred cultures can form gradients, or patterns. New structures can come to being that are not possible on Earth.

It is reasonable to assume, then, that the first human liver or heart to be grown

and successfully transplanted will come to existence thanks to research conducted while in orbit around the Earth -- our very human biological system can be studied there, and large tissue structures grown in "weightlessness".

Mammalian cells and tissue, bacteria, fish, plants, insects will continue to be guests of the International Space Station's Biolab facility, in the ESA's Columbus module, launched in February of 2008. The Columbus module also hosts a Microgravity Glove Box, in which additional biotechnological experiments can take place.

Scale

By way of transition to the more imaginary part of this paper, it is useful to consider the notion of scale, in terms of our psychological understanding, or conceptualization of physical space. The *order of magnitude* in which the typical human body is measured is 0 (10 raised to the 0 power) or 1 meter. An order of magnitude of 9 (one billion meters) gives us the Earth and the Moon in orbit around it. In counterbalance, an order of magnitude of -9 (a billionth of a meter) is a nanometer and is the unit with which we measure cellular components like DNA. It becomes obvious that the human scale lays in the balance between the inconceivably small and the inconceivably large. Go down an order of magnitude from DNA (to -10) and we have the electron cloud around a carbon atom. Go up an order of magnitude from the Earth and Moon (to 10) and we have part of the solar system. To put it another way, our bodies are as "removed" spatially from the order of magnitude of a cluster of our own cells as we are from a cluster of our own cities (five orders of magnitude offset in either direction).

A Human Experience

Let's temporarily switch our focus away from objective science at the sub-cellular level, and towards subjective human experience - specifically, the human experience of micro-g environments. In doing so we may illuminate an argument for a Drexlerian "bottom-up" approach to cellular study by way of intuition.

In an article "Body, Movement, Dance and Weightlessness" (11) the dancer Kitsou Dubois describes the psychophysical effects of "zero-gravity" performance. The "Magic" and "Sacred" movements she experiences in zero-gravity seem to erase the distinction between the cognitive and psychoanalytical - creating, in Dubois's words, "a sensation of eternity."

Offering a lesson from choreography, Dubois keenly notes that "All the bodily messages need to be organized in a different way," and asks, "Can one still be considered the resident of this body that is known but not entirely recognized, or is it really, in this case, a foreign body that will need to be reinhabited and reappropriated?" Speaking of "momentary disincarnation" where we are completely disoriented, Dubois' need to reclaim her body mirrors the cell's need to reclaim its processes, and ultimately our immune system's need to to reclaim its control. One might say that this complete rethinking of the self, a constant tingling or elevated state, is simply an absence of acceleration understood at the cellular level. I doubt it is that simple, but it is certainly metaphorically parallel.

Most importantly, Dubois posits the role of the choreographer as ideal creator of "the whole sign system to be invented in a universe that will soon be part of our cultural consciousness." Simply put, Dubois is clearly aware that movements have meanings, and that these meanings change in a weightless environment. Moreover, there is a deterministic *threat* that the basic power structures inherent in any culture will control our future movements (through design of the spaces we inhabit, for instance). It is critical to preemptively deconstruct such cultural control of our bodies *in the first instance*. Any good artist is an expert at identifying embedded power relationships, and so it is the artist who should invent the language. I recommend also, that they invent the language from the ground-up – in other words, by beginning with the language of the cell.

Indeed, can we not extend this metaphor as an olive branch to the Drexlerian nanotechnologists, and offer them the opportunity to build the a "sign system" of proteins from scratch, by choreographing the motion of proteins in micro-g? Eventually they hope to be designing *new* cells, going beyond techniques of cell hybridization and mutation.

Dubois hints at what a system of signs could be (for instance, "The weightless person has to act with great subtlety, which is rather joyous.") What she refers to as "recreating tensions" that are lost in weightlessness:

"It is no longer an issue of right/left coordination, but of reorganization of the volumes of the body around a subjective axis."

Here Dubois begins to speak of the "spiral" as a way of defining the body's center. While certainly fanciful, it does not hurt to imagine what might happen if a choreographer and a nanotechnologist could collaborate on a project in micro-g spiral-like protein manufacturing, focusing on building tensions where they have been eliminated by the lack of acceleration. It is the choreographer who understands both what is lost and what is to be gained by weightlessness. It is the choreographer who should help the cell biologist.

Dubois continues to evolve her thought, and postulates that the *spiral* movement (or really, torque) of the body enables a new centering. It makes me think: perhaps there is some specific pharmaceutical we will invent to convert the weakness of the cell system into a strength. To evolve ourselves from the inside, and become alien.

"The interior of the body is no longer a fear-inspiring chasm, but rather an infinity of spaces of extreme mobility."

A Quantum Communications Addendum

I might end the paper here, but there is yet another approach to understanding the "small" in the context of the "largeness" of planetary orbits is to consider explorations in quantum mechanics. Space-QUEST ("Quantum Entanglement for Space Experiments") is a proposal to install a Quantum transceiver outside the Columbus module on the ISS for launch by the end of 2014. The idea is to conduct space-to-ground communications tests - "The unique features of space offer extremely long propagation paths to explore the limits of the validity of quantum physics's principles."⁽⁷⁾ Quantum Key Distribution allows for "unconditional security" - meaning that all eavesdroppers are detected. It may be interesting to follow the political struggles over control of QKD experiments on the ISS.

Consider also that the Interplanetary Internet is to be tested on board the International Space Station later this year. The protocol, designed in collaboration with

Vint Cerf (who also wrote the protocols for our Earth-bound internet) hopes to develop "a set of communication standards and technical specifications to support rich networking in space environments." The development of a disruption-tolerant networking system (DTN) will inevitably push forward our own terrestrial network. Today's satellites primarily use the Deep Space Network developed back in 1964.

Quantum communications experiments and a new space networking platform are some of the bits and pieces of a new road map for aerospace. Modest estimates predict a quantum computer being built in about 50 years. As pointed out, such a computer will operate at the logical level of the universe, and could possibly be the brain of a nanomachine. Assuming nanotechnology infiltrates all aspects of our lives as it is predicted to by some, we can notice immediately a few major implications for aerospace.

LEMMA I. Certain computational operations will only be possible in zero-g.

LEMMA II. The Best Artificial Intelligence or Machine Learning Instruments can only "exist" in outer space.

Along with an alien growth, an alien form of thought will literally descend upon us. The vacuous orbital shells about this planet will host the most advanced logic and the most versatile cellular organisms, informing us not only of their visual discoveries, but also of their conclusions.

It is easy to imagine a quantum-computing and encrypted Interplanetary Internet satellite system growing biological tissue. The truth is, information abounds - from the real to the surreal to the impossible to the obsessive. As science increasingly masters the invisible, it is going to require more and more talent to parse reality. What is "necessarily-so" from what is merely "possibly acceptable". In other words, welcome to the 21st century, things are going to get pretty strange! Remember, to *conspire* is to *breathe together*.

LEMMA III: Civilizations on Mars will be separatist and conspiratorial.

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