TOWARDS QUANTUM SCULPTURE

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ABSTRACT. This paper explores how our notion of matter changes when classical physics is replaced by quantum physics. In connection with that I present some of my sculptures inspired by quantum physical phenomena.

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1. THE CLASSICAL VIEW OF MATTER

We consist of matter and so does everything around us. The history of science reveals that our conception of matter is of fundamental importance to our world view. The modern view of matter emerged during the Renaissance, culminating in Newton's theories of mechanics and gravity. In that framework, each portion of matter is viewed as possessing a well-defined path through space, a *trajectory* consisting of a certain location for every point in time[1]. Many aspects of the physical world could be explained convincingly within the Newtonian framework, such as thermodynamics, acoustics, or celestial mechanics, which led to great confidence in the theory. One strange aspect of the theory was that all trajectories are precisely determined for all times and therefore completely predictable by a given set of initial conditions[2] which seems at odds with our impression of possessing free will.

An unquestioned aspect of matter was its perceived continuity. Matter was never seen to suddenly disappear and reappear. Similarly, matter was viewed as possessing an unequivocal identity: Portions of matter were assumed to either be separate or to be touching each other, but not to be penetrating each other. Matter was generally assumed as being confined by well-defined boundaries.

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[1] The trajectory can be calculated by adding up all the forces acting on the particle, inserting them into Newton's Second Law $\vec{F} = \frac{\mathrm{d}}{\mathrm{d}t}\vec{p}$, and solving the resulting equation.

[2] such as a particle's position in space together with its velocity

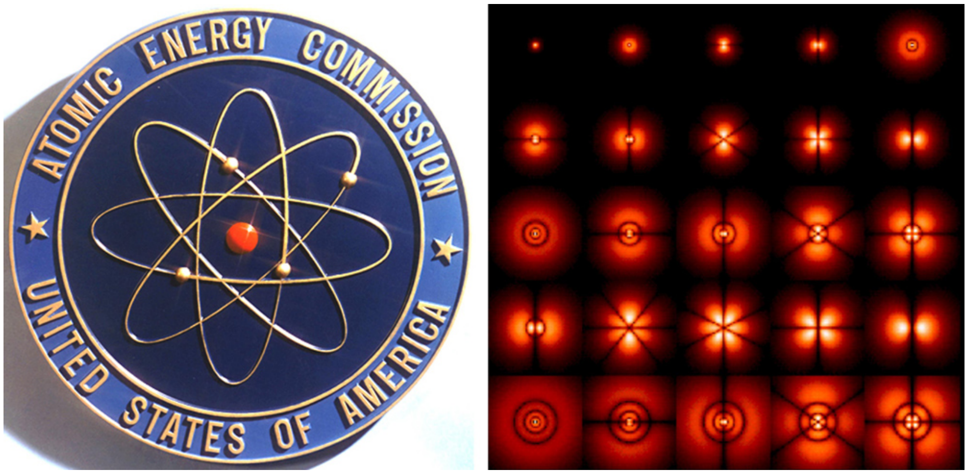

Figure 1. The left panel shows a cartoon image of an atom with the electrons orbiting the nucleus. The right panel shows calculated electron probability densities for an atom in different states of excitation. This particular example is of hydrogen, the smallest atom. Atoms of the other elements look very similar.

2. The quantum view of matter: What does an atom look like?

The building blocks of most matter we encounter are atoms. Single atoms look and feel very different than the bigger portions of matter they make up. First of all, atoms do not 'look like' in the literal sense of the word, because they are much smaller than the size of light waves and therefore invisible[3]. It is instructional to see, how atoms *do not* look like - the left side of Fig. 1 gives a typical example of such a cartoon image of an atom.

The most misleading aspect about this kind of imagery are the planet-style ellipses that are a standard feature of such images. In truth the electrons are quantum objects. That means as long as they are not detected, they simply do not possess a precise location and therefore the whole concept of a trajectory becomes meaningless. The physicist says, "The electron is not localized". What the electrons possess before detection is merely a likelihood to be found somewhere. An interesting aspect about this *probability density*, as this likelihood is

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[3] Only objects bigger than the wavelength of light - a few hundred nanometers - reflect light back into our eyes or microscopes. The electrons even of a big atom have no significant chance of detection farther than a nanometer away from the nucleus.

called, is that it is typically a smooth function smeared out in space. So even though we cannot use light to create an image of an atom, we are still able to draw a meaningful picture of the ”electron cloud” by visualizing the calculated or measured probability density that tells us the likelihood of finding the atom’s electrons. The right panel of Fig. 1 shows such images. This particular probability density was calculated on the computer but there is no reason to believe that it would look differently if obtained experimentally.

A quick glance at the fuzzy images already illustrates one important aspect that holds true in the whole (quantum) world: Things ultimately do not have a hard edge or some sort of well-defined boundary where one thing ends and another one starts. In reality, assigning objects an individuality based on such a boundary is not more than a convenient approximation. When we measure where exactly the electron is, we will detect it only at one specific spot within the region of significant probability density. If we repeat this same measurement we will probably detect the electron at a different spot, but on average more often in the lighter colored regions and less often in the darker regions. After many repetitions of the experiment the smooth and fuzzy character of the probability density will manifest itself by approaching the theoretical prediction as drawn in the images ever more closely, but the single measurement is never exactly predictable. So what determines exactly where we will detect the electron in a single experiment? The answer was famously shocking to Einstein since it is ”nothing”: The location of the electron is not determined by anything, it is genuinely random. And that lack of knowledge does not reflect, as initially thought, a shortcoming of quantum theory. It is, on the contrary, a crucial aspect of it. It has been demonstrated convincingly that the mere assumption of the existence of ”hidden variables” somehow encoding information about the exact location where the electron will be detected, contradicts the experimental results. This breakdown of strict causality highlights the second important aspect of the quantum world: The world is ultimately non-deterministic, or to put it differently, some things do happen without a cause. One nice implication of this finding is that it gives us new hope regarding our free will.

3. Monument to Chomp

In 2003, while I attended art college after having switched careers from physics to art, I was contemplating how the ideas encountered in quantum physics could be reflected in sculpture. A first connection occurred to me unexpectedly while I built a fence to protect a vegetable

Figure 2. "Monument to Chomp" (2003) by Julian Voss-Andreae. Wood and steel, height 3' (90 cm). The right panel shows a detail.

patch from our highly energetic border collie, Scout. The dog grabbed one of the posts and immediately attacked it with a relentless staccato of vigorous bites. Right before Scout managed to break the stick I took it back quickly. After coating it with lacquer and mounting it to a steel base I displayed it as (my own) art, shown in Fig. 2. The many irregular and un-aimed dog bites have narrowed the stick fairly regularly around the middle and because the dog needed to balance the stick horizontally in his snout, the likelihood of getting hit by his teeth is highest around the middle of the stick. This process reminded me of the build-up of a well-defined and regular electron density distribution out of many single stochastic events, as discussed above.

At the same time the dog made the stick fuzzy by chewing up the surface symbolizing the decay of the precise boundary in quantum physics as mentioned above. Although the "Monument to Chomp" was initiated with humor, it contains several aspects that I find intriguing in the context of quantum sculpture. Another aspect of importance in the history of sculpture and related to quantum theory, is the visual and conceptual tension between the 'constructive' (as in 'geometric' or mathematically simple) shape of the lumber and the 'organic' decay of the simple form [1].

4. Moving quantum objects and the double-slit experiment

So far we have looked only at a stationary system like the electron probability density around an atom's nucleus. Even though the electrons of an atom are in motion in the sense that, upon detection, they are found to possess a certain velocity, their distribution as a whole does not change. Let us now look at moving quantum objects, like a flying atom or cluster of atoms.

The trajectory of its point-like center of gravity is the classical description of a moving object. In quantum physics, the abstraction of the point expands into a fuzzy cloud. Instead of the classical "the object is exactly here" we have to be content with a likelihood to find the object in the vicinity of the classical center of mass. Again all we can know is a statistical law but one that is known to be obeyed very precisely.

But the movement adds another quality, a third important aspect of the quantum world mentioned here: The description of the particle has the features of a moving wave with wave fronts running perpendicular to the direction of its motion.

A very nice way of visualizing the dynamics of those complex wave functions was introduced by Austrian physicist Bernd Thaller in his book "Visual Quantum Mechanics" [2]. His website has some examples of moving quantum objects, for example a simulation of the famous "double-slit experiment" (See [3] and Fig. 3). This experiment is so well-known because, despite its conceptual simplicity, it already highlights all the problems we encounter in interpreting quantum theory. A quantum object (be it a particle of light or of matter) is sent flying towards a screen with two openings, and, after passing through these slits, it is detected at a distance behind the screen. Of experimental interest is the distribution of particles hitting the detector because it is quite different from what is expected if the objects behaved classically (such as balls or bullets would). Instead of detecting what is classically expected, namely two light bands stemming from the two slits, the particles actually display a pattern with not just two but several light and dark bands. The reason lies in the wave nature of quantum objects. The initial wave gets split up into two wave trains. Right after the

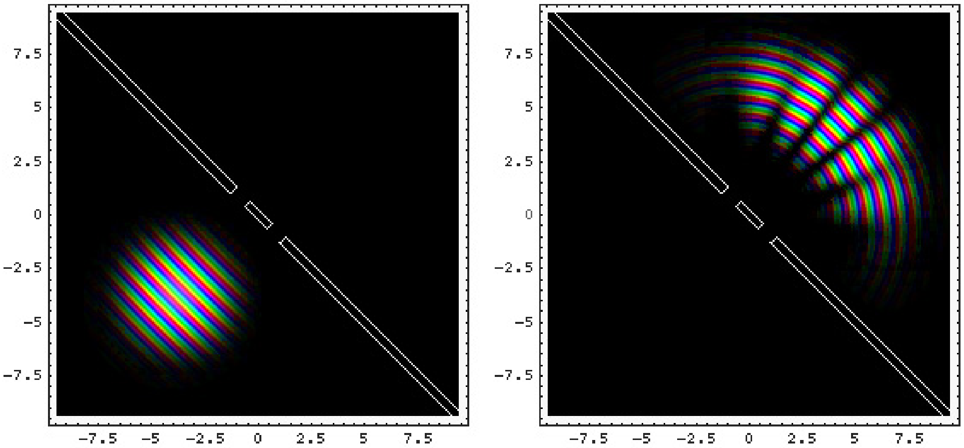

Figure 3. Computer simulation of the double-slit experiment from "Visual Quantum Mechanics" [3]. The quantum object approaches the two openings from the lower left corner (left panel) and splits up into several distinct regions of a significant likelihood to be detected. The detector (not shown) would be located in the upper right corner (right panel). The lighter the image the higher the likelihood to find the particle. The stripes are the wavefronts.

screen they are still separate, but farther back they start overlapping and show, just like water waves, areas where the two waves cancel each other out (dark) and others where they add up (light), depending if they are out of phase or in phase in that direction. This light-dark pattern, known as an *interference pattern*, is the tell-tale signature of a wave. Furthermore, it also shows that this wave went through both openings simultaneously, since both wave trains are needed for interference. Were we to block one of the slits, this interference pattern would disappear.

The problem becomes clear when we now equate a portion of matter, say a single atom, with such a wave, as quantum mechanics demands. If we perform the experiment only once we are not able to tell if the position of the detected atom makes up an interference pattern. Therefore we repeat the experiment many times over, sending one atom after the other through the setup. It turns out that each atom contributes individually to the successive build-up of the same interference pattern. The more atoms we detect, the clearer the pattern becomes, again approaching the quantum mechanically predicted interference pattern ever more closely. So we have the extraordinary situation that something we usually experience as a single, indivisible particle went through two openings at the same time! This is the kind of problem we encounter when trying to make one coherent mental image of quantum phenomena and it is just as puzzling today as it was in the early twentieth century when quantum physics was discovered.

5. A buckyball is a particle is a wave

My graduate work in physics was concerned with a modern extension of the double-slit experiment. The double-slit experiment was devised and first conducted in 1802 with light, establishing the wave-like aspects of its nature. In 1927 and the ensuing few years, similar experiments with ever larger portions of matter (electrons, atoms and even a small molecule, H_2) were performed for the first time[4]. Extending such experiments to particles of larger mass is of deep interest since it allows shedding light on one of the most important problems in physics, namely how and why the transition from quantum physics to classical physics occurs. Since for fundamental physical reasons heavier particles require a smaller distance between the two slits in order for their interference pattern to be seen, larger masses could not be probed for a long time. It took almost 70 years until, thanks to microchip technology, sufficiently small devices could be manufactured to extend the old double-slit experiment to much larger particles.

I joined Anton Zeilinger's research group[5] in Vienna in 1999 to participate in an experiment probing the then by far heaviest particles ever in a double-slit type of experiment. The particle we used was a beautiful molecule with the odd name *buckminsterfullerene*, consisting of sixty carbon atoms arranged in the shape of a soccer ball. The buckyballs (as they are often called affectionately) were shot through 10' (3 m) of vacuum with a microfabricated grating in the middle serving as the double-slit. The openings where about 50 nanometer wide and twice that much apart from each other. Scaling up the proportions of the experiment into our size regime (with the 1-nanometer-diameter buckyball assumed as having the size of a soccer ball), the slits would have the width of ordinary soccer goals but the kicker standing on earth would have to shoot the ball to the moon. In summer 1999 we saw the first interference pattern, confirming that even such comparatively large particles indeed display quantum behavior [4].

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[4] see references in [5]

[5] http://www.quantum.at/zeilinger

FIGURE 4. "Quantum Buckyball" (2004) by Julian Voss-Andreae. Fabricated bronze, diameter 2' (60 cm).

6. BUCKYBALL SCULPTURES

Inspired by Leonardo's 1509 drawing of a truncated icosahedron[6] (as the buckyball is known to mathematicians) for a renaissance mathematics textbook, I welded my first buckyball from sheet bronze in 2004 (Fig. 4). I noticed that the windows in each facet provide the material for another, smaller buckyball. I reiterated this procedure, thereby creating a succession of four buckyballs. I placed the buckyballs inside each other, attaching them in place by running thin rods radially through the sixty vertices. It is appealing to me in that context that the nested structure echoes the repetitive structure of a spherical wave, emanating from a central source. In addition to that it seems the open, air-filled structure of the piece is especially suited to convey the ephemeral nature of a quantum object.

This aspect of creating a sculptural object consisting of comparatively little material while occupying a considerable volume of space interested me because it is a natural way to create a metaphor for the quantum nature of matter. I started making larger buckyballs from steel consisting only of the edges, culminating in a piece fabricated from 2" (5 cm) round tubing with a diameter of 30' (9 m) that I first

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[6] See for example image 2.2 on p. 6 of [5]

FIGURE 5. "Quantum Reality (Large Buckyball Around Trees)" (2006, reinstalled 2007) by Julian Voss-Andreae. Trees and steel. Size of the structure 30' x 30' x 30' (9 m x 9 m x 9 m). The sculpture floats in the air supported by and intersecting with three large firs.

installed in 2006. Now permanently installed in a park-like setting in Portland (Ore.), the buckyball is suspended in the air above arm's reach over a sloped terrain with a small creek running under it (Fig. 5). Three very large and straight Douglas firs arranged in a fairly regular triangle are growing through the structure echoing the symmetry of the buckyball. The orientation of the buckyball is chosen such that two opposite hexagons, one at the bottom and one on the top, are lying between the trees on horizontal planes.

The main reason that such a basic shape succeeds as a piece of art is its placement within nature. Despite the considerable size of it, the buckyball's visual impact is quite subtle due to the relative thinness of the tubing and the natural color of the corroding steel. The trees intersecting the buckyball dissolve the mathematical shape, symbolizing quantum physics' revelation that matter has no clear-cut boundary. On a more general level, the installation is concerned with the dichotomy between nature, symbolized by the trees, and culture, represented by the mathematical shape. Reading the sculpture and its surroundings this way, culture hovers between the poles of embracing nature and caging her.

7. Quantum Man

My former boss Anton Zeilinger once remarked jokingly that the fact that the wavelength of a walking human happens to be approximately the Planck length[7] cannot possibly be a coincidence. This comment made me think of how such a wave function would look and a few years later I created a sculpture inspired by this idea. Using pieces of steel sheet arranged parallel and constantly spaced to represent the wave fronts, I modeled the shape of a stylized human walker (See Fig. 6). I welded short pieces of steel rod irregularly positioned to connect the slabs. The combination of the regularly spaced slices with the irregularly positioned connecting rods evokes associations with stochastic events and, more concretely, with the formulation of quantum mechanics in terms of Feynman's path integrals[8]. After finishing I noticed the most striking aspect of the piece: When approached from the front or back, the sculpture seems to consist of solid steel, but when seen from the side it dissolves into almost nothing. The sculpture's appearance changes drastically with a small shift of the viewer's perspective. This effect provides a striking metaphor of the dual nature of matter with the appearance of classical reality on the surface and cloudy quantum behavior underneath [6].

8. Conclusion

I believe that the advent of quantum physics in the sciences and the rise of modernism in the arts represent two facets of the same profound shift in the evolution of humankind. The uneasiness we tend to experience when dealing with either illustrates how little we have grappled yet with the consequences of this paradigm shift, comparable in depth to the renaissance. The works presented in this paper try to help explore the character of this shift and make it part of our collective consciousness by taking it out of the isolation of the intellectual realm into the sphere of sensual experience.

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[7] 1.6×10^{-35} m, a (very small) distance of presumably fundamental meaning in physics. The Planck length and similar units derive very simply from the three major constants c, $\hbar$, and G.

[8] The path integral formalism is a tool for calculating quantum mechanical probabilities by adding up all possible paths ("sum over histories"). This is done by slicing up time to parameterize arbitrary paths.

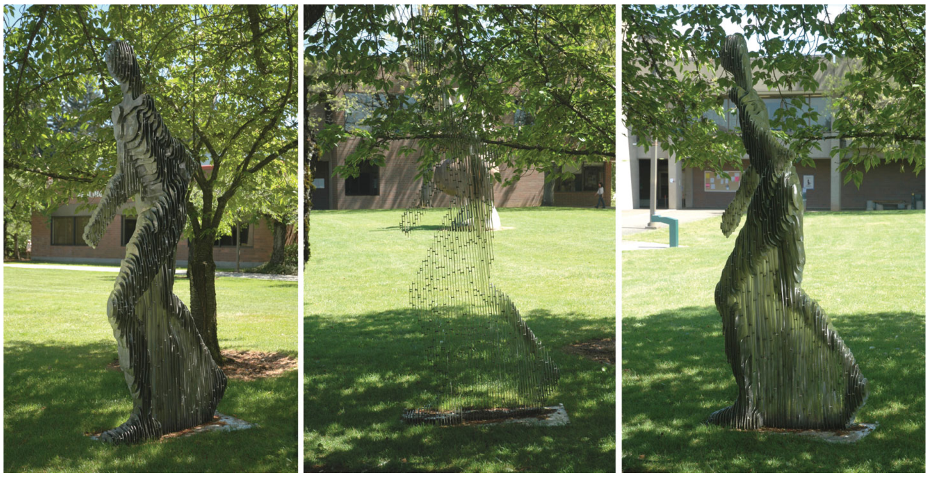

FIGURE 6. "Quantum Man 2" (2007) by Julian Voss-Andreae. Stainless steel, height 98" (2.50 m). The image shows the same sculpture in three different views. When viewed right from the side (middle panel), only the edges of the vertical slabs show, making the sculpture seem to disappear.

This essay is based on a talk given at Wonderfest 2006 at UC Berkeley and Stanford University.

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