Early motion pictures led to new understanding of the natural world. The late-19th-century research of the photographers and scientists who pioneered the field of chronophotography allowed photographic depictions of motion nearly two decades before the Lumière brothers filmed workers leaving their factory. We begin this paper considering the fundamental nature of how objects and their motion are visible or are made visible, and how that visibility is in turn recorded. This is not only a philosophical puzzle, but a statement of fact: When photographing an image, we have the luxury of light reflecting off the world around us. This basic assumption does not apply when objects and structures are substantially smaller than the wavelengths of visible light. In that case, we use other means of imaging and visualizing, with different rules and response times. Using scanning probe microscopy, scientists can enter a largely unexplored territory of which we do not yet know the basic “look and feel” [1]. In this paper we discuss how some of the rules of representing motion at the macroscale with apparatuses such as cameras might be applied at the nanoscale to give us greater understanding of this nanoworld and to force us to consider the parameters that define it.

The Frames Themselves

In 1878, photographer Eadweard Muybridge designed a system of triggers and shutters on multiple cameras to capture sequential images of a galloping steed and settled a dispute for horse-racing aficionado and California Governor Leland Stanford [2]. Those first shadowy silhouettes frozen on the racetrack did not move but nevertheless captured what before then had only been intuited: that at full gallop a horse indeed flew, lifting all four hooves from the ground [3].

The inception of motion picture photography is thus actually a form of stop-motion animation called pixilation, where images are taken from varying points of view or intervals. Popular examples of pixilation include Nick Park’s Wallace and Gromit animation series (1989–2009), composed from manipulated plasticine, and Norman McLaren’s Neighbors (1952), which animated human actors and their physical surroundings.

A well-established French physiologist, Étienne-Jules Marey, further refined Muybridge’s process into the field of chronophotography. After the publication of Muybridge’s first images, Marey fitted a rifle with a rapid-shooting camera and captured animal locomotion on single frames of film from a fixed point of view.

Here their work diverged. Muybridge continued photographing people of every shape and condition through countless motions to make inroads into an “inexhaustible subject,” cataloguing how we move [4]. Meanwhile, Marey improved his photographic gun in order to capture ever smaller samples of time. These strategies reveal important distinctions in the work of the two pioneers; Marey’s concern was the most perfectly detailed analysis possible. He never intended to “reproduce what the eye could already see” [5].

Marey’s innovations in high-speed photography persist today [6] and have led directly to variable-frame-rate cinematography, which allows for extreme slow motion. Examples crop

Very Small Horses: Visualizing Motion at the Nanoscale

Simon Tarr and Paul S. Weiss

The presentation of realtime data and animations can lead to new understanding and, in some cases, misunderstanding, of the phenomena represented. How can fundamental nanoscale structures, properties and responses be represented in data, motion and other forms? What are the keys to understanding, representing and sensing the nanoscale, and how do these differ from our intuition, which is based on our experience with macroscopic phenomena?

Simon Tarr (artist), Department of Art, University of South Carolina, Columbia, SC 29208, U.S.A. E-mail: <simon@sc.edu>.

Paul S. Weiss (scientist), California NanoSystems Institute, University of California, Los Angeles, Los Angeles, CA 90095, U.S.A. E-mail: <psw@cnsi.ucla.edu>.

The papers in this special section began to take shape during the presentations and workshops at the conference “Images of the Nanoscale: From Creation to Consumption,” held at the University of South Carolina, 25–27 October 2007.

See <www.mitpressjournals.org/toc/leon/45/5> for supplemental files associated with this issue.

© 2012 ISAST


439
The rules that govern these two forms, as well as their phenomenological differences, may give insights into the portrayal of events at the nanoscale.

Animation is the apparent creation of “life” from lifelessness, taking what cannot move or be seen to move and depicting it by direct photography, or by capturing artwork or illustrations of a subject and then presenting the resulting still images sequentially, in adherence to certain principles, in order to create the illusion of motion. First, the still images must be presented at sufficient speed to create such an illusion. For example, in American cinema, 24 images are presented in 1 second; apparent fidelity to living motion increases as the frame rate rises. Second, each frame must be hidden from view before the next can be presented. In a movie theater, this intermittent interruption takes the form of a rotating shutter blocking the projector’s light while each subsequent film frame is readied, plunging the audience into darkness between each frame.

The third requirement only reveals itself when differentiating live-action film from animation: The positions of the moving subject must overlap from one frame to the next in order to obtain the appearance of movement; otherwise the subject seems to disappear from one frame and appear in the next, disconnected from the previous image. Animators call this phenomenon “strobe.” We will explore it further, as it relates to problems of the depiction of motion at the nanoscale.

Filming motion in real time differs from the animation process, due to the most obvious distinction between them—in live action the recording device captures what unfolds, while in animation the camera is dormant until invoked to shoot a single frame. Running at 24 fps, a motion picture camera will expose each image in a sequence for 1/48 sec before blocking light from hitting the frame for another 1/48 sec while preparing the next frame to be exposed. At the macroscale, there is only so far that a subject could possibly move between frames, so there will always be overlap from one frame to another. If a subject moves so fast as to displace itself completely from one frame to the next, the length of the exposure of each frame will render the subject as a blur in both frames, which satisfies the requirement of overlap between frames. Figure 1 illustrates the blur in between frames filmed at a standard frame rate, using a child running through the image field. The child is moving fast enough that few details are visible, and the edges of his body are not completely resolved. The blur increases the area the subject takes up in each frame and creates overlap from frame to frame; it appears to the viewer to be a natural depiction of motion.

Figure 2 shows similar motion, adjusted so that the moving subject does not blur. Each individual image is exposed for only 1/1600 sec, the same relative exposure as if the motion were filmed at 800 fps. If viewed in motion as video, these movements are jerky, exemplifying the strobe effect.

These figures illustrate problems of depicting movement that become more complicated with animation. Space and time between frames become critical factors for one reason that fundamentally differentiates animation from other types of filmmaking; an animator may pause for an unspecified amount of time between each frame’s inscription. The subject before the camera may move and change as much or as little as desired. The camera may move or change point of view. Any condition may change any number of times. Therefore, there is no functional difference between two sequential frames of an animated film and two unrelated photographs. There is only the a posteriori determination of whether the subject seems to move convincingly. The illusion of motion, then, comes entirely from the content of the frame when combined with the techniques applied by the animator when situating the material.
The Space within the Frame

In their 1981 memoir, *The Illusion of Life*, Disney Studios animators Frank Thomas and Ollie Johnston presented “The Principles of Animation,” a list of internally developed studio rules of thumb that describe how to exaggerate expressions, compose a staged action and communicate emotion [7]. Most important on their list is “squash and stretch,” animators’ strategy of deforming a subject to give a better sense of character and material. In their simplest example, a simple circle is represented as a bouncing ball by deforming it to depict velocity and impact (Fig. 3). While critical to the animator’s ability to convey the essence of a moving subject, squash and stretch gives an additional benefit that Thomas and Johnston did not mention: Stretching a subject further as it moves faster is one way to solve the problem of strobe.

Marey’s advances in chronophotography and Disney’s pursuit of character appeal through expressive distortion together indicate the two ways to depict motion: Alter the frame of reference for time or distort the visual characteristics. These two basic approaches have analogues necessary for meaningful depiction of individual images at the nanoscale; the complications are multiplied when faced with motion.

What We “See” at the Nanoscale

Measurements at the nanoscale are limited by the tools that have been developed for it. The scanning tunneling microscope (STM) and the atomic force microscope (AFM) do not give direct views of the nanoscale world—that is, there is no eyepiece as one would find in a simple optical microscope. Instead, images or series of images are constructed by scanning with a sharp probe tip to measure the spatial contours of electrons around a molecule on a surface, the hardness of a nanoscale structure or other properties. Importantly, multiple properties can be measured simultaneously in these mechanical scans to get more comprehensive views of samples [8]. With both the STM and the AFM, images are acquired and constructed slowly because of the requisite time spent scanning the surface—typically seconds to minutes. Thus, recording motion with these instruments is challenging [9,10].

Objects at the nanoscale are often displayed with distorted proportions compared to their measured dimensions (e.g. Figs 4 and 5). Part of the reason that this convention has been accepted is that the objects we measure typically do not match the physical dimensions expected for them. For example, consider the STM image of a single Xe atom on a nickel crystal surface shown in Fig. 4 [11]. The imaged region shows a 40 Å × 40 Å area of the surface on which a single Xe atom is adsorbed. Measurements of crystals of solid Xe and gas-phase Xe₂ molecules lead us to believe that Xe atoms are ca. 4.4 Å (0.44 nm, where 1 nm is one billionth of a meter) across. Instead, the Xe atom in the STM image has an apparent height of 1.5 Å and a breadth of 6–8 Å, full width half maximum (i.e. the width at the waist of the peak at half its height); the nickel substrate at-
objects are barely visible as the modulated background around the Xe atom. These features are consequences of the image _not_ being a photograph but rather an image generated by an STM, in which the electrons around the atom-surface system are mapped. The second reason that such images are shown in this manner is to fill space. Without exaggerating the apparent height, most of these images would appear rather flat and nearly featureless. Images at the nanoscale are more precisely defined as surface maps or simply spatial data.

These microscopies provide more than just information about apparent size [12]. For example, the same three nickel atoms imaged on a MoS$_2$ surface at different probing energies (top to bottom in Fig. 5) appear (top), appear at different probing energies (top to bottom), do not appear but have an effect on their surroundings (middle), or appear as depressions because they drive away substrate electrons (bottom). Thus we see that, unlike photographic images, nanoscale images and animations must address important issues of data representation.

**RATES AND SCALES**

When we consider motion at the nanoscale, we must consider translation, reorientation, vibration and rotation. Quantum mechanical molecular vibrations occur faster than trillionths of seconds; these are not typically imaged. Instead, one observes a blurred average of positions of parts of a molecule. Molecules rotate more than a billion times per second; thus, when imaging molecules on surfaces, sometimes the most one can determine is whether they _are_ rotating, in which case features are blurred and thus averaged, or _not_ rotating, in which case individual features are observable [13]. To observe translation or reorientation at the nanoscale, one can adjust the temperature to match the energy barriers to motion such that individual motions are observed in sequences of images [14]. As a touchstone, the average speed of a nitrogen molecule in air at room temperature is ca. 500 m/sec, which would be far too fast to observe with an STM or an AFM. Thus, lower temperatures and/or “stickier” surfaces that impede the motion of adsorbed atoms and molecules enable the observation of motion.

Despite these procedures, the “action” often takes place faster than is measured, and adsorbed atoms or molecules move in and out of position while an image is being recorded. Such an example is shown in Fig. 6, showing benzene molecules condensed laterally in rows along a 1-atom-high step on a copper surface [15]. The molecules in rows 3 and 4 appear “noisy” or broken up in the STM image because they were moving in and out of position while the image was being recorded. The mean residence time of a molecule in one of these positions was a few milliseconds, but the entire image took on the order of a minute to record. Each pixel was recorded individually as the probe tip was held in place, also for one to a few milliseconds. Away from the Cu step, molecules moving rapidly (in a two-dimensional gas) on the atomically flat terraces were not imaged directly, as their motion blurs them.

The motions of single or few molecules can be tracked if moves from one site to another are unlikely on the time scale of imaging (because the energy available due to the temperature is comparable to the energetic barriers to motion) [16]. In this case, sequential images show few changes, which can be identified as in the macroscopic animation and strobe examples above.

Color Plate C No. 2 shows two consecutive frames from a 2-day sequence of images, in which correlated motions of molecules were observed. Sophisticated automated data analysis schemes were used to track over 70,000 molecular motions in this series to elucidate the barriers to motion and the interactions between molecules, between molecules and the surface, and between molecules and the probe used to measure them [17].

**FORCES AND INTERACTIONS**

As noted above, one approach to observing the movements of molecules more precisely is to use surfaces that hold atoms or molecules in place more strongly, as the copper step holds molecules in rows 1 and 2 in Fig. 6. Another approach is to stop recording images and instead to record the motion of molecules moving into and out of position at the probe [18]; this enables the measurement of motion down to the millisecond or even microsecond scale. A novel consideration at the nanoscale is that the probe may be perturbing the object being imaged. One way that such
an effect can be determined is to use a technique from chronophotography—the delay between frames is varied to determine if the measured rates of motion are affected. In the limiting examples the rates are either (1) independent of the frequency of (nonperturbing) measurements, or (2) only dependent on the frequency of (strongly perturbing) measurements.

The perturbation due to measurement can also be used to determine where molecules are moving away from the step that were moving too fast to image. There were also molecules away from the step that were moving too fast to image. (© American Association for the Advancement of Science. Adapted from S.J. Stranick, M.M. Kamna, and P.S. Weiss, "Atomic-Scale Dynamics of a Two-Dimensional Gas-Solid Interface," Science Vol. 266, No. 5182, 99–102 [1994]; <www.sciencemag.org/content/266/5182/99.long>. Reprinted with permission from AAAS.)

Motion: A Problem of Scales in Both Time and Space

Consider the child in Figs 1 and 2. In describing the character of the subject’s motion, we have made some assumptions. Based on having seen other children run, we might infer from a single frame that this child is running, but we have decided that we want to observe and to depict the act of running itself. We might want to know specific information about this child’s gait. Do his feet leave the ground? Does his head bob up and down? Does he lead with his chest or hips? These may lead to other indirect questions unavailable to us without that initial direct information. Does gravity act on him as we would expect? Do his shoes fit properly? Did he eat breakfast that morning? We would presume that this camera is an appropriate device for imaging a moving subject. However, having watched a lifetime of movies, we probably would not ask if something important and unforeseen happened in between the second and third frames.

Now imagine that this child, unknownst to us, had gotten into a stash of caffeinated soda just before the filming of these sequences and is now moving with such speed and behavior that we cannot get a decent shot of him running in one single attempt. In that case, individual
frames from separate shots could be used to build an animation based on our understanding of how the subject behaves. The hypothetical result might be Fig. 7, composed from frames of many separate runs past the camera to a best approximation of a single moving subject.

Figure 7 shares similarities with Fig. 1. The camera settings and environmental conditions are identical. Yet the simplest way to know that the motion is not "right" is through intuition and experience from having seen other people run, other children run and this particular child run. By observation and experience, we can determine that the subject is not moving convincingly; something is wrong with the image.

Going back to the initial assumptions of creating motion pictures—that the motion and the character of the motion are both significant and that the device we are employing is able to capture the required data—Fig. 7 poses problems. If the motion and character of motion are unimportant, then this image may suffice, but it precludes asking unanticipated questions with regard to how the subject moves.

Such assumptions are not always apparent when recording images of moving subjects at the nanoscale or when creating animations of nanoscale events. For example, the fact that the molecules away from the copper atomic step edge in Fig. 6 move in and out of position is important and a clue to the nanoscale interactions at work. The “problem” that these molecules appear broken up is a clue to additional motion at or faster than the timescale of recording of the individual molecules. This observation raises the question for the audience of such research—without a foundation for intuiting the motion, what surprises lie in between the frames recorded? It also reinforces the importance of extending the dynamic ranges of nanoscale imaging tools [22].

**IMPROVING REPRESENTATION AND DEPICTION**

Single images of nanoscale objects are problematic and require explanation to contextualize. The complications of depicting motion at the nanoscale are not simply multiplied by the number of still images presented. These moving depictions are more complex in multiple dimensions, not only due to the forces and interactions at play, which affect atoms differently than we would intuit at the macroscale, but also because the instruments used to collect data about these phenomena do not isolate the particular character traits of the motions but record convolutions of many effects simultaneously (notably including perturbations due to the imaging probe itself). Animated visualizations of nanoscale objects and events now capture the public imagination in powerful new ways; these films are made using the same software used to create effects-driven summer blockbuster movies [23]. It is relatively simple to apply data gathered from an STM or AFM into 3D software such as Autodesk’s Maya and then to animate it as one would any object.

Are motion picture depictions of nanoscale events useful? Based on current instrumentation and our current understanding of objects and events at the nanoscale, any motion pictures thereof can only be pieced together and constructed from disparate temporal events—in a word, animated. We must either specify the assumptions and distortions of time, scale and energy, as well as the different forces at play, necessary to make the depictions cinematically palatable, or we will need to elucidate the character of the motions in question so that future animations are not overly conjectural.

Could we devise a guide to orient viewers? What information would such an instrument need to contain? An entire viewing of the Eameses’ _Powers of Ten_ (1968) [24] or its equivalent preceding each nanoscale video would be unwieldy. Perhaps motion pictures will be insufficient to depict complex interactions, just as a single still image is not enough to describe how a person runs.

Our motion-intuition needs to be cultivated. Muybridge and Marey invented new instruments to resolve questions of motion that were at first un-seeable and therefore un-intuitive. These instruments were the forerunners to the art and industry of cinema, itself not an in-tuitable conclusion to be drawn from its technological forebears. Now, watching motion pictures is an indelible part of our cultural lexicon; cinematic grammar is common to us. As we look _beyond_ the visible to examine and portray nanoscale motion, we will not be able to rely solely on conventional cinematic assumptions; we cannot present a depiction in the same way that a series of photographs of horses was captured to give definitive visible evidence that all four hooves leave the ground. We need to take cues from animation, which is predicated on the acceptance of the idea that what is shown is constructed. We are, after all, presenting images akin not to very small horses but instead to very small animations.

**Acknowledgments**

This collaboration began at a 2007 workshop, “Images at the Nanoscale: From Creation to Consumption,” a gathering of a diverse group of scientists,
artists, historians and philosophers, supported by the National Science Foundation. We thank Davis Baird for organizing this meeting and for including us. We also thank Peter Atkins, Mark Cohen, Heidi Rae Cooley, Mark Garrett Cooper, Felice Frankel, Roald Hoffmann and Akihiro Kusumi for helpful discussions, and Caspar Tarr for sprinting past the camera for the figures. Paul Weiss thanks the Department of Energy (#DE-FG02-07ER15877), the NSF and the Kavli Foundation for support.

References and Notes

Unedited references as provided by the authors.

14. Moore and Weiss [8].
17. Moore and Weiss [8]; Han et al. [16]; Sykes et al. [16].
21. Weiss [1].

Manuscript received 19 September 2011.

Simon Tarr is a filmmaker and artist who teaches animation and digital art at the University of South Carolina, where he is Coordinator of the Media Arts program. His films are available at <www.quarknova.com>.

Paul Weiss is a scientist and educator who serves as Director of the California NanoSystems Institute. He is also the Fred Kavli Chair in NanoSystems Sciences and a Distinguished Professor of Chemistry & Biochemistry and of Materials Science & Engineering at the University of California, Los Angeles.
Human exploration of the moon has become the subject of renewed interest, with upcoming space missions from all the space-faring nations, as well as private companies. In late 2008 the Indian Space Agency, ISRO, launched the Chandrayaan 1 mission to the moon.

The moon has profoundly influenced the human imagination over the centuries, in the domains of myths, religion, art and science. A variety of cultures have generated rich narratives about the moon. The moon is more than a mere object—it is also an image, an illusion, a picture. It inspires stories about lunacy as well as love. It has regulated our lives in a fundamental way by catalyzing calendars based on its movement. Stories of navigation are incomplete without the shadow presence of the moon.

The engagement of poetry, art and literature with the moon has had a profound influence on these activities. The moon also has a political significance—new space projects related to the moon by countries such as Japan, China and India are fundamentally tied to the new articulations of what these countries are and want to be.

The Leonardo Special Section “Re-Imagining the Moon” will remind us of this historical, cultural and scientific trajectory in which the moon plays an important part even as it suggests new, contemporary reflections on the moon. The section aims to publish articles from a variety of disciplines and hopes to receive articles that explore various social and cultural aspects related to the moon as well as those that engage with the relation between the moon and the artistic and scientific imaginations. Reflecting the universality of this influence, we seek articles from countries and cultures throughout the world.

We are also particularly interested in documenting artists’ projects connected to current space exploration missions to the moon and collaborations between artists, scientists and engineers on moon projects.

Submissions: Send manuscript proposals to Leonardo, 211 Sutter St., Suite 501, San Francisco, CA 94108, U. S. A. E-mail: <leonardomanuscripts@gmail.com>.

Authors are encouraged to submit a manuscript proposal before sending a full manuscript.

Author Instructions: <www.leonardo.info/isast/journal/editorial/edguides.html>.

The project is part of the activities of the Leonardo Space Arts Working Group: <www.leonardo.info/spaceart/spaceartproject.html>. The project follows on the Bangalore Space and Culture Symposium held in 2007, a collaboration of the National Institute for Advanced Studies, The Arts Catalyst, Leonardo/OLATS and the Srishti School for Art, Design and Technology: <http://cema.srishti.ac.in/space/?cat=5>.

Sundar Sarukkai, trained in physics and philosophy, has a Ph.D. from Purdue University. His research interests are in the areas of philosophy of science, philosophy of mathematics, postmodernism, phenomenology and philosophy of art, drawing upon both Western and Indian traditions. His books include Translating the World: Science and Language (University Press of America, 2002), Philosophy of Symmetry (IIAS, 2004) and Indian Philosophy and Philosophy of Science (CSC, 2005). Currently he is professor and dean of the School of Humanities and head of the Centre for Philosophy at the National Institute of Advanced Studies, Bangalore, India.