SPACE-TIME IMAGERY IN ART AND SCIENCE

Norman Zabusky

"From the invisible atom …everything is movement. … All movement is the product of two factors: time and space." Introduction to *La Methode Graphique dans les Sciences Experimentales*, 1878. Étienne-Jules Marey (1830-1904)

I want to share a journey, a moveable feast from science to art. The scientist knows that reality is embodied in understanding and utilizing theory and experiment. The classic example is Newton's formulation of calculus that led to classical mechanics and an understanding of aspects of planetary motion. Such processes have been refined over the centuries and with the help of computers they provide the backbone for predicting planetary or particle motion. Technological developments are also revolutionizing the approach to data-intensive environments with a technique I have named "visiometrics" and will discuss below in the context of evolving space-time phenomena.

The artist has progressed in different cultures from primitive early beginnings, through innovating new forms and techniques and, finally, taking avant garde steps. Success seems to reside in what the younger generations want and have the power to mediate over time . Not being an art historian, I will consider for the purposes of this paper Etienne-Jules Marey (1830-1904), Eadweard Muybridge (1830-1904), and Marcel Duchamp (1887-1968).

Edweard Muybridge[1,2] was the first to systematically develop equipment and techniques to photograph the movement of quadruped and bipedal gait along with a variety of other movements, motions, and human athletic activities. Muybridge's work has often been discounted as merely "art," but it was an important qualitative look at movement. Modern texts have detailed diagrams of normal and abnormal gait that look like they were sketched from his plates or photographed using methods similar to his. He influenced many artists and inspired Marcel Duchamp to paint "Nude Descending A Staircase."[1] Clearly there is inspiration, emotion, and art in Mubridge's work. By using scientific analysis and invention he was at the forefront of creating techniques that were later used to quantify motion and gait analysis. His work had a great impact on animation and led to the development of film.

Figure 1. Marey's visualization for flow around a sphere.

Étienne-Jules Marey (1830-1904)[3,4,5] "was a physiologist, doctor, biomechanics engineer, and inventor in 1882 of chronophotography, a technique anticipating stroboscopic photography. He was obsessed with motion and its *visualization*. He undertook to make *movement* visible by 'graphical' recording. He studied walking and did research on muscular forces and applied them to physical education…"[4] His research allowed the establishment of techniques that optimized human muscle movement. He also studied the gait of horses and humans, birds and insects achieving flight. At the end of his life, he was engrossed in photographing movements of air, flow around bodies, e.g. the sphere in Fig. 1. He could be considered the "father" of flow visualization. He lacked scientific *sitzfleisch* and so left to others the task of quantifying and analyzing the pictures.

Marcel Duchamp (1887-1968) was a painter, tinkerer, inventor, and chess player.[7] He was a creative spirit who knew instinctively when to "move-on" for his greater good. In his final years, he earned his living selling other artists' works, especially paintings. As Robert Lebel notes, Duchamp, " was more than 70 years old when he emerged in the United States as the secret master whose entirely new attitude toward art and society, far from being negative or nihilistic, had led the way to Pop art, Op art, and many of the other movements embraced by younger artists everywhere. Not only did he change the visual arts but he also changed the mind of the artist."

Duchamp is arguably best known for his "Nude" and his "readymades." In an interview with Katherine Kuh,[7] he remarked "You know at that time, in 1912 … I think the idea of describing the movement of a nude coming downstairs while still retaining static visual means to do this, particularly interested me. The fact that I had seen chrono-photographs of fencers in action and horse galloping (what we today call stroboscopic photography) *gave me the idea for the Nude*. It doesn't mean that I copied these photographs … *The whole idea of movement, of speed, was in the air* [italics mine]." Furthermore, when asked by Kuh, "Why do you think the "Nude Descending a Staircase" caused a greater furor than some of your other works?" Duchamp responded, "Probably because of the shock value due to its title…" So he was also a master of what today in public relations is called "spin."

When I first saw a picture of the Nude (prior to discovering Muybridge and Marey), I was not shocked by the title, or gratified by the "violent coloring" and "touch of deliberate distortion," as Duchamp remarked about his portrait of Dr. Dumouchel (1910). I was amazed by the fact that a non-scientist attempted to communicate the excitement and challenge of representing complex kinematics (the descending motion of a human) in *space-time*. But now I realize it was a kind of cartoon of the works of Marey.

SPACE-TIME IN STEM (SCIENCE, TECHNOLOGY, ENGINEERING AND MATHEMATICS) STUDIES

For the uninitiated, whenever one mentions "space-time," one usually thinks of Einstein and the curved space of gravitational phenomena. This shows up if one searches for "space-time" in Google images. My meaning is entirely different. It has to do with how to represent complex information from data-intensive "evolutionary" experiments and particularly computer simulations. Let's examine how space-time (ST) imagery helps to unravel the information contained in large-scale computer simulations of nonlinear and complex phenomena.

MY BEGINNING IN PHYSICS

When I began studying nonlinear lattices in the early 1960s, I produced the first ST diagram of the solution of a nonlinear partial differential equation (PDE), the Korteweg-de Vries equation,[8] first derived in 1895 to describe the movement of surface waves on shallow water. This diagram was obtained laboriously by observing computer simulation print-outs made by me and Gary Deem. We plotted by hand the location of maxima of the solution on the spatial (horizontal) coordinate versus time (vertical coordinate). Gary and I also made the first computer-generated 16 mm film of the KdV and nonlinear lattice.

1. COMPUTATIONAL PHYSICS

The computer is used by *STEM* people to make simulations of ideal and practical systems. Through various kinds of visualization and quantification techniques, these people eventually obtain a deeper understanding of the emerging natural or technological phenomena. This computational approach applies to all disciplines and requires mathematical equations to represent the system, whether a space craft going into a moon orbit or the short-term weather prediction of our planet. In the former, a few ordinary differential equations (ODE) suffice, if the planetary motions are prescribed. In the latter, many partial differential equations are required to describe the ocean-atmosphere interaction with solar energy forcing and internal feedbacks, e.g the effect of: a massive volcano, changing area of snow cover in arctic regions, etc.

Easy to use software has been developed and engineering undergraduates are regularly taught how to set up simulations for non-complicated problems in a matter of minutes to hours. For example, the motion of a single "point" mass attached to an ideal *linear* spring can be described by a *linear* ODE and it undergoes a so-called "harmonic oscillation." If many such springs and masses are tied together on a one-dimensional line, the motion of this "lattice" is much more complicated, but it can be analyzed and understood. This situation changes immediately if the springs are made *nonlinear*, for then the motion is "anharmonic" and the principle of *linear* superposition cannot be used, so the motion is best found by means of simulation.[11] Another example of a nonlinear oscillator is a swing undergoing a large-amplitude motion, which can be idealized as a point mass pendulum.

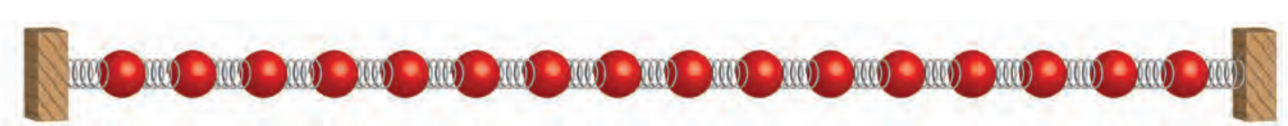
The first computational study of the dynamics of the nonlinear lattice, namely N identical masses coupled by identical *nonlinear springs* arranged on a line (one-dimensional), see Fig. 2, arose in the early 1950s. Physicists Enrico Fermi, John Pasta and mathematician Stanislaw Ulam , (FPU),[9] were overjoyed to obtain sufficient computing time at Los Alamos on the "MANIAC", one of the first digital computers. Such a lattice system supports left and right going "longitudinal" waves (like sound waves in a metal) and for their initial location of the particles the results were unexpected and paradoxical, as described in their 1955 report. A breakthrough in understanding came about ten years later with the discovery of the *soliton* by Kruskal and myself, as described in many books and websites.[10,11] This led to a remarkable mathematical breakthrough by Kruskal and colleagues[15] and many scientists around the world, which I will not discuss here.

Lets examine what FPU found, and in particular, how *visualizations and quantifications* of the nonlinear lattice simulations evolved over the years. An obvious way to represent the motion of N masses is to plot the curves (functions) of the displacement of each mass on the line at discrete (or sampled) times. These graphs weren't very revealing. Another way, very commonly used by *STEM* workers, is to plot curves of the *energy* of the harmonics versus time, as shown in Fig. 3.

That is, a completely equivalent way to represent the particle displacement and velocity is by a sum harmonic amplitudes of the sine-plus-cosine functions of the space variable *x*. Here they were quick to observe that the initial generation of higher energy harmonics reversed itself much later in time and the system returned almost to its initial condition, in their case a single sine wave. This *near-recurrence* was counterintuitive, for the commonly held belief was that the system would evolve to a state of *equilibrated energy.* That is, the average energy in each mode is the same.

Kruskal and I decided to view this discrete system as a *dispersive-and-nonlinear continuum* (or "string"). Kruskal derived what was felt to be a model equation to give the observed phenomenon, namely the Korteweg-deVries (KdV) partial differential equation. We changed the parameters somewhat, but the results in terms of energy sharing and near-recurrence were the same and we produced the first ST diagram in our 1965 publication, as mentioned above. Fig 4, shows a version, produced by a student on a desktop computer circa 1995.

Figure 2. Lattice of masses coupled by nonlinear springs. The masses can move only in one dimension and the two ends of the chain were assumed to be fixed, i.e. $u_0=u_N=0$



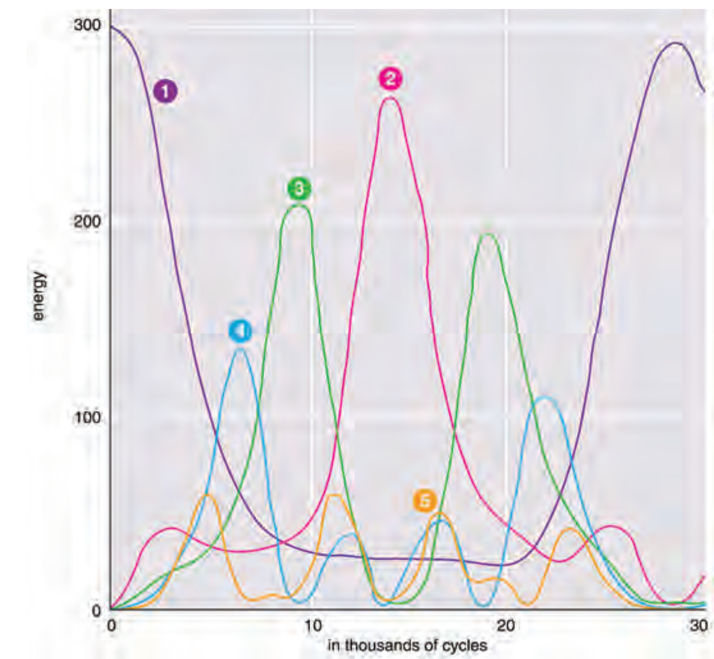


Figure 3. FPU near-recurrence of the energy in the low modes for a nonlinear lattice with N=32 and fixed ends.This is a colorized representation of the original hand-drawn figure, where modes are: 1 (magenta); 2 (red); 3 (green); 4 (blue); 5 (yellow).

Such quantification approaches can be generalized to two, three, and higher dimensions. Diverse applications are now being made: aircraft wake control,[12] weather prediction, etc . Note, the observed robustness of solitons during interaction allowed us to ask mathematical questions that had not been raised previously and insightful transformations were found that allowed an exact mathematical solution to the KdV problem, which verified the numerical solution. So to paraphrase Louis Pasteur, who said of his experiments: "In the field of observation, chance favors only the prepared minds." I say of computer simulations, "In *STEM* research, discovery favors optimal visualizations and quantifications for they prepare the mind."

This appreciation led me to emphasize Ulam's idea of the synergetic assistance that meaningful computer simulations can give to understanding and finally to introduce this mode of working with the term, "visiometrics," namely the visualization and quantification of evolving amorphous objects. Much work has also been done by the computer graphics group at TU in Delft.[13,14]

Here the amplitude of the dependent variable of the KdV is represented in rainbow-color: red,-orange for positive to dark-and-light blue for negative plotted versus space (horizontal) with time downward. The wobbly "streaks" moving to left and right are the unexpected translating and interacting solitons or coherent wave packets. The solitons interact and undergo a "phase" (spatial) shift but otherwise remain unchanged in shape and amplitude. For our chosen initial condition the streaks focus at regular time intervals at different points along the horizontal. This is another manifestation of near-recurrence.

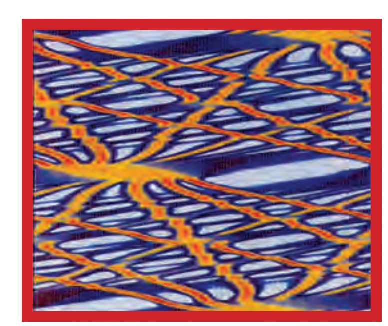


Figure 4. Space-time diagram for Korteweg-de Vries Equation. Time is upward and two near-recurrence periods are shown.

Fig. 5, shows a ST diagram for the nonlinear "cubic" *lattice* obtained recently for N= 256. Here, for the first time, we have transformed (converted) the displacement and velocity of each particle into a discretized version of the continuum, so-called Riemann invariant, that exposes wave-like behavior. We found similar patterns in the simulations of the KdV model of the nonlinear cubic lattice.

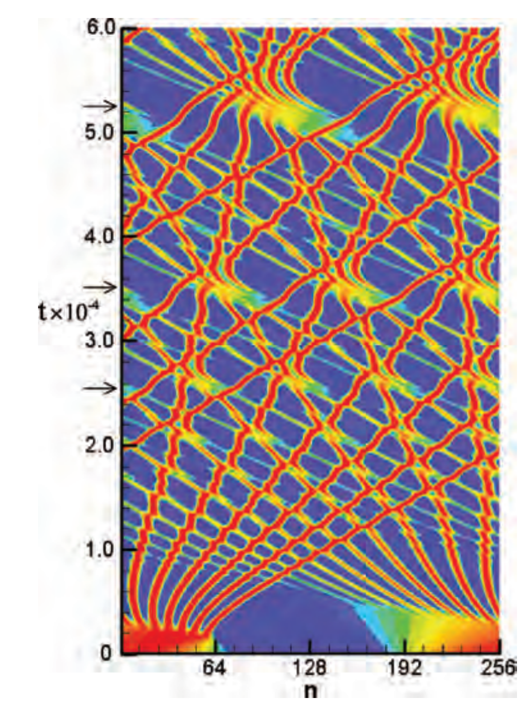


Figure 5. Space-time diagram of the discretized Riemann invariant for the FPU cubic lattice in a right moving frame of reference. Time is upward and one -half of a recurrence period is shown. The arrows indicate increasing times where the soliton streaks focus on the horizontal (spatial) axis at 4,3 and 2 places, respectively.

SPACE-TIME IN ART

What kind of art are these space-time images? For me the aesthetic experience is the element of revelation and surprise through optimal choice of variables, enhanced by choice of color and juxtaposition of data sets. The KdV and nonlinear lattice ST images preserve for me the eureka excitement I felt that evening that the soliton idea emerged to Kruskal and me as the possible answer to the near-recurrence paradox. In some sense the ST diagram, although abstract when dealing with 2D and 3D data sets, is a "low-complexity" form and according to Jurgen Schmidhuber's beauty postulate, they are beautiful. Perhaps we can call this new form *"Visio-art."*

Finally, all this led me to explore my interpretation of the meaning of science and art. In 2000, I gave the keynote talk at a Science and Art symposium, ScArt3,[15] and also showed a computer animation, "Cosmic Vortex Projectiles", made by Pittsburgh artist , Hilary Shames with verbal input from me. (I benefited much from my association with Hilary during 2000-2005). I organized the follow-up conference , ScArt4.[16] In 2003, I was interviewed for a Research Channel show on art and modern science[17] and in 2005 gave an invited American Physical Society lecture on visiometrics.[18] (The URLs at[15,16,17,18] are worth a visit).

NOTES:

1 Rebecca Solnit, *River of Shadows: Eadweard Muybridge and the Technological Wild West* (New York: Penguin, 2003).

2 Pribut, August 3, 2010, "Muybridge: Art, Motion and Biomechanics," 98.6: *Pribut's Blog*, http://www.drpribut.com/blog/index.php/2010/08/muybridge-art-motion-and-biomechanics

3 Marta Braun, *Picturing Time: The Work of Etienne Jules Marey* (Univ. of Chicago Press, 1992).

4 Marey and Muybridge are discussed in, http://www.univie.ac.at/cga/history/enlightenment.html

5 Mouvements de l'air, Etienne-Jules Marey, photographe des fluides, joint edition Gallimard / Réunion des musées nationaux, Collection "Art et artistes", 2004.

6 Figure from E. J. Marey: le mouvement en lunière, an exhibition in January, 2000 at the Fondation Electricite de France, Espace Electra was devoted to his works.

7 Marcel Duchamp, interview broadcast, *Monitor*, BBC, March 29, 1961. Also published in The Artist's Voice (italic), ed. Katherine Kuh, 1983.

8 "Soliton," Norman J. Zabusky and Mason A. Porter, *Scholarpedia*, http://www.scholarpedia.org/article/Soliton (2010).

9 Norman J. Zabutsky, "Fermi-Pasta-Ulam, Solitons and the Fabric of Nonlinear and Computational Science: History, Synergetics, and Visiometrics," *Chaos* 15 (2005), doi:10.1063/1.1861554.

10 Norman J. Zabusky and M.D. Kruskal, "Interaction of 'Solitons' in a Collisionless Plasma and the Recurrence of Initial States," *Physical Review Letters* 15 (1965): 240-243, doi:10.1103/phys.rev.lett.15.240

11 Norman J. Zabutsky, "Computational Synergetics and Mathematical Innovation," *Computational Physics* 43 (1981): 195-249.

12 "Secret Life of Vortices," CSElab, http://www.cse-lab.ethz.ch/

13 F.H. Post, B. Vrolijk, H. Hauser, R.S. Laramee, H. Doleisch, Feature Extraction and Visualization of Flow Fields, in: D. Fellner, R. Scopigno (eds.) Eurographics 2002: State-of-the-Art Reports, pp. 69-100. See http://visualization.tudelft.nl.

14 D. Silver, F. Post, and A. Sadarjoe, "Flow Visualization," (1999), http://graphics.tudelft.nl/publications/silver1999.pdf

15 Norman J. Zabutsky, "Scientific Computing Visualization - a New Venue in the Arts," Science and Art Symposium (2000): 1-11.

16 ScArt4: 4th Science and Art Conference, Supported Rutgers University, New Brunswick, N.J., 2005. Conference website: http://mechanical.rutgers.edu/scart4/.

17 "From Art to Modern Science: Understanding Waves and Turbulence, an interview with Norman J. Zabusky," by Paul Leath, *By The Book*, Research Channel, July 24, 2003.

18 http://www.mechanical.rutgers.edu/scart4/LaPorte.APS,DFD.Soli,VPasSHOWN112303.pdf