Humanistic Mathematics Network Journal

Issue 15 Article 13

7-1-1997

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Recommended Citation
Levine, Howard (1997) "See-Duction: How Scientists and Artists Are Creating a Third Way of Knowing," *Humanistic Mathematics Network Journal*: Iss. 15, Article 13.
Available at: http://scholarship.claremont.edu/hmnj/vol1/iss15/13

SEE-DUCTION
How Scientists & Artists Are Creating A Third Way Of Knowing

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> ***"If we trace out what we behold and what we experience through the language of logic we are doing science; if we show it in terms whose interrelationships are not accessible to our conscious thought but are intuitively recognized as meaningful, we are doing art."***
>
> **Albert Einstein**

In his 1959 Rede Lectures, C. P. Snow coined a now famous phrase—The Two Cultures—that has acted as a cautionary note for much of our modern life: "I believe the intellectual life of the whole of western society is increasingly being split into two polar groups. Intellectuals at one pole—at the other scientists. Between the two a gulf of mutual incomprehension—sometimes hostility and dislike, but most of all lack of understanding. They have a curious distorted image of each other. Their attitudes are so different that, even on the level of emotion, they can't find much common ground." Maybe so, but Lord Snow never met Brent Collins[1] or John Conway:

> As a boy John Conway was fascinated by knots. So much so that he spent weeks whittling complex knots out of solid blocks of wood so that he could study their form and shape from every conceivable angle. Today, Conway is still interested in visualizing knots which he often does by inviting friends to "dance" while holding different colored ropes. Brent Collins is also interested in visual representation, but for Collins the objects have esoteric names such as 'one-sided surface with opposed chiralities' and 'Haken surfaces of figure eight knots.' Even his explanation of his work is arcane, "The linear patterns are never arbitrary but issue as abstractions of the logical motifs constellated in a particular composition."

Who's the artist and who's the scientist? Does it really matter what we choose to call them if they are both engaged in the same fundamental activity? Not according to Collins: "Scientists' forms are elaborated through first a collection of data looking for underlying relationships, quantifying them, and then seeing how they may be visually represented. I go direct to the visual representation. But clearly the whole modeling process is internalized in the human brain." (In case you haven't guessed, Conway is a world renowned Princeton mathematician; Collins is a sculptor whose works have been exhibited at Fermi Labs, the National Center for Supercomputing Applications, and AAAS.)

What Collins and Conway understand, and what Snow overlooked, is that not only are scientists and artists engaged in the same basic task—interpreting the fundamental nature of both the universe and our place within it—but they do so by employing the same essential artistic and scientific skill: seeing and interpreting. Furthermore, and Snow could not have foreseen this 35 years ago, both of these disciplines are using computers to discover and experiment with new observational opportunities, to give form and shape to dry mathematical equations, and to search for meaning among seemingly random, chaotic data. In using the computer as a tool to help us see and make sense of what we see, artists and scientists are creating a new and important third way of knowing: *see-duction*—the visualization, simulation, and modeling of real world phenomena using computers. In so doing, *see-duction* is helping to break down the artificial barriers between the two cultures.

FROM SCIENCE TO ART

What is the greatest scientific discovery of all time? Twentieth century denizens might choose the Theory of Special Relativity which unifies matter and energy or the discovery of DNA, the information code for all life forms. Those with a longer view might select the Theory of Natural Selection or the Laws of Motion. Still others might argue that since all science is based on mathematics, the greatest scientific discoveries have been mathematical: the invention of zero or the insight that all geometrical shapes can be numerically represented. But each of these great intellectual achievements pales in significance to the correct answer, the discovery that allows all other scientific achievement to occur—the invention of the scientific method.

Twenty-five hundred years ago the ancient Greeks invented *deduction*—a logical system of reasoning that started with indubitable axioms and employed precise rules to generate theorems (new knowledge); this was the birth of mathematics, the first great scientific way of knowing. Five hundred years ago the early Renaissance thinkers invented *induction*—a formal system of rules governing observation and experimentation designed to give us knowledge of the natural world; this was the birth of science, the second great way of knowing. Today, an interdisciplinary group of revolutionary scientists and mathematicians are inventing the third great way of knowing, *see-duction*:

Bill Thurston is one of the world's best mathematicians. A Fields Medal (the Nobel Prize for mathematics) winner and Director of Berkeley's Mathematical Sciences Research Institute, he is best known for his work establishing a deep connection between topology and geometry. As one might expect, his papers (i.e. "Three-dimensional manifolds," "Kleinian groups," and "Hyperbolic geometry") are not easy bedtime reading. The pleasant surprise is that one need not read the paper in order to understand the concepts. The Geometry Center at the University of Minnesota (Thurston is also a director there) has produced an award winning video, Not Knot[2]*, that uses animation to show and explain the concepts and reasoning behind Thurston's ideas. In fact, since he has not yet provided a complete paper-and-pencil proof of his theorem, the video stands as the proof. Although it is certainly not a technique without controversy, computer-aided visualization is allowing mathematicians to embrace a long cherished dictum of empirical science: Seeing is believing (and understanding).*

Although it is certainly not a technique without controversy, computer-aided visualization is allowing mathematicians to embrace a long cherished dictum of empirical science: Seeing is believing (and understanding).

In 1963 Edward Lorenz sowed the seeds for a scientific revolution when he published a dull-sounding paper ("Deterministic Nonperiodic Flow") in a somewhat obscure journal (Journal of Atmospheric Sciences)*. Today, we recognize Lorenz's work as the foundation for chaos theory—the study of systems governed by nonlinear rules and equations which can be so sensitive to minor fluctuations that their behavior seems chaotic. The classic statement of such a system is Lorenz's, "The flapping of a butterfly's wings in China today may lead to a tornado in the Midwest next month." Thirty years later, a new generation of climate modelers is still struggling with chaos, but now they are aided by a staggering and ever-growing amount of computational power. The best current model is the National Center for Atmospheric Research's (NCAR) Community Climate Model, but competitors with names such as MOM (Modular Ocean Model) and POP (Parallel Ocean Program) are also seeking to develop a coupled atmospheric-ocean climate model. If the possibility of accurate, long term weather forecasts is still in question, the utility of visualizing the output from reams of arcane equations is not. As scientists continue to simulate increasingly complex phenomena (i.e. ozone depletion, economics), the knowledge gained from seeing these simulations on a computer screen will be the truest test of their worth and validity.*

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There is one image that we never tire of seeing—the image of the human body. Whether it is Galen's anatomical sketches, or early x-ray images, or a CAT scan of our own head, the human form seems endlessly fascinating. But the body is decidedly three dimensional while each of these rendering techniques yields a two dimensional image. How much information is lost? You don't have to be an anatomist or computer scientist to realize that the answer must be "a whole lot." Researchers at Sandia National Laboratory and the Baylor University Medical Center have used massive parallel supercomputers to turn two dimensional MRI images into three dimensional views and the results are startling—the detection of breast tumors that were "invisible" to x-ray mammography. But why stop with the human breast? The Visible Human project seeks nothing less than a four trillion byte image library that will provide three dimensional numerical coordinates from which *both internal and external structures can be depicted, rotated, viewed from any angle and reversibly "dissected." Early* *scientists built physical models. Later scientists employed conceptual models. Today, scientists in fields as diverse as psychology, crystallography and medicine are employing computer models to help them better understand the natural world*[3].

Modern day neo-Luddites scoff at the idea that *see-duction* is a new way of knowing. "After all," they argue, "scientists have always used the processes of visualization, simulation, and modeling. The computer is just a tool." The trouble with this "argument" is that it totally fails to understand the power of revolutionary tools. Thirty years ago, Marshall McLuhan observed that we shape our tools and thereafter our tools shape us. The computer, the first meta-tool—or tool with no specified, overt purpose—and its human masters are engaged in an endless bootstrapping cycle of shaping both us and our machines. Truly revolutionary tools pass through three stages: First, they simply enable us to perform the same old tasks with greater efficiency (quantitative phase). Second, with enough speed and efficiency, the old task mutates into something inventive and unexpected (qualitative phase). Finally, we find ourselves using the tool to perform totally new and unforeseen tasks. In effect, the tool has shaped us so that we think in terms that would have been impossible without it (revolutionary phase). No one who looks at the work of Bill Thurston or Edward Lorenz or any of the hundreds of other scientists using the computer to help themselves see, can argue that it's simply business as usual. Today, *see-duction* is in its infancy, somewhere between the quantitative and qualitative phases; tomorrow, it will enable us to think in new ways and usher in a third scientific revolution.

FROM ART TO SCIENCE

Who is the greatest scientist of all time? Twentieth century denizens might choose Albert Einstein or Watson and Crick. Those with a longer view might select Charles Darwin or Isaac Newton. Still others might argue that since all science is based on mathematics, the greatest scientist has to be mathematician. They might choose Muhammad al-Khwarizmi or Rene Descartes. But each of these great scientists, as Newton so aptly pointed out, was only able to proceed because he already stood on the shoulders of giants—the shoulders of the inventors of the scientific method. Pythagoras, Plato, and Aristotle (and later, Euclid) who invented deduction; Brunelleschi, Alberti, and Leonardo (and later, Galileo and Bacon) the inventors of induction. But notice that those individuals we recognize as scientists were already building on the work of philosophers and artists. Revolution in scientific method has always required a synthesis of Snow's two cultures. Breaking the scientific paradigm (as Kuhn so ably documents) has always required forces outside the scientific community. The same is true today. *See-duction* is the work of artists as much as it is the work of scientists:

Tony Robbin[4] *is an artist with a simple, if incomprehensible, mission—to see and paint the fourth dimension. In 1975, Englebert Shucking, a physicist at NYU, told Robbin that he had seen the fourth dimension. Shucking said little else, but it was enough to send Robbin on his mission. Four years later, Robbin visited Tom Banchoff, a professor of mathematics at Brown University, and saw his first computer-generated graphics of a hypercube rotating in space. Today, Robbin has programmed his own computer to allow him to see the fourth dimension. He has sold his large, 4-D paintings to private collectors and corporations such as General Electric and AT&T. What's the attraction? Isn't a fourth spatial dimension some kind of conjurer's trick? Not according to Robbin: "Physics has confirmed what we really knew all along: three dimensional space is an arbitrary convention. In the future there will be many works by many artists based on visual experience of the fourth dimension. With new works of art and new computers, the tools are already available to us for learning to see the fourth spatial dimension that is all around us and hidden from our view for only a moment. When the fourth dimension becomes part of our intuition, our understanding will soar." For Robbin, visualizing the fourth dimension is analogous to the work of the Renaissance masters—it is the portal to knowledge.*

Donna Cox is an artist with an unusual institutional home—the National Center for Supercomputing Applications at the University of Illinois. Her job, to steal a title from Ed Tufte's[5] *classic book, is envisioning information. Whether it's the "Motion Analysis of Kink Instabilities in Supersonic Flow," "Plastic Injection Molding," or "Numerical Relativity: Black Hole Space Times," her task is making sure that the graphic displays of the supercomputers (with artist's names like Klimt, Courbet, and Mondrian) convey the maximum amount of information possible. But what rules are to be followed? How can dry equations be turned into meaningful pictures? Tufte closes* Envisioning Information *with a lament: "The essential dilemma of* *narrative designs is how to reduce the magnificent four-dimensional reality of time and three-space into little marks on paper flatlands. Perhaps one day high-resolution computer visualizations, which combine slightly abstracted representations along with a dynamic and animated flatland, will lighten the laborious complexity of encodings -- and yet still capture some worthwhile part of the subtlety of the human itinerary." Cox, and the scores of other artists who work at the National Computing Centers and proprietary computing firms around the world, have already taken the first step in that human itinerary. If a picture is worth a thousand words, how much information can be contained in the six minute computer simulation of a thunderstorm? The answer may just be the hundreds of lives that can be saved if such simulations enable us to better forecast the weather.*

Aaron is sui generis*—the world's first artist-computer (not an artist using a computer [a computer-artist], but a computer that is programmed to be an artist). Aaron is also the alter-ego of Harold Cohen*[6]*, a renowned abstract painter who gave up painting twenty years ago to enter into a strange, symbiotic relationship with a computer. What's the connection between art and computers? Between Harold and Aaron? For Cohen, art has always been about the representation of human knowledge; computer languages are also a form of representation—a set of rules, algorithms, and heuristics that encompass knowledge and might just lead to new knowledge. But could a computer program lead to the kinds of knowledge that an artist requires in order to create art? Harold has spent the last twenty years imbuing Aaron with all his painterly knowledge; Aaron's artwork speaks for itself. Cohen is emphatic that Aaron's work is not computer art: "The fact is that art is not, and never has been, concerned primarily with the making of beautiful or interesting patterns. The real power, the real magic, which remains still in the hands of the elite, rests not in the making of images, but in the conjuring of meaning." By creating a computer model of himself, Cohen has created a totally new method for cognitive scientists to study the ultimate question of knowledge: How do we mentally represent the world in order to create meaning?*

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This time, it's more than just the neo-Luddites who are scoffing. "How can math, and science, and computers have anything to do with artistic creation?" they complain. The essence of this plaint was anticipated almost fifty years ago by the Swiss sculptor Max Bill. After asserting his belief that "it is possible to evolve a new form of art in which the artist's work could be founded to quite a substantial degree on a mathematical line of approach to its content," Bill set forth what he believed would be the skeptical response to his manifesto: "It is objected that art has nothing to do with mathematics; that mathematics, besides being by its very nature as dry as dust and as unemotional, is a branch of speculative thought and as such in direct antithesis to those emotive values inherent in aesthetics; and finally that anything approaching ratiocination is repugnant, indeed positively injurious to art, which is purely a matter of feeling." The trouble with this "argument" is that it totally fails to understand art, science, and the longstanding, important relationship between them[7].

Far from being independent, these disciplines have always shared a five stage relationship as they engage in the same, vital, enterprise—observing and interpreting the universe and our place within it:

Shared tools Artists rely on scientific and mathematical tools to count, measure, design buildings, anneal glass and much more; scientists rely on artistic tools to model non-Euclidean spaces, create topological surfaces, enhance photos from space, and much more.

Mathematical foundations Neither art nor science could exist without a reliance on fundamental mathematical concepts. Perspective, proportion, and symmetry are just three mathematical ideas that are crucial to the practice of both art and science.

Mathematical inspiration There are no limits to what an artist may choose to depict, so it should not be surprising to discover that many artists have found inspiration in mathematical concepts and ideas: Phidias, Leonardo, Durer, Kandinsky, and Escher not only created works inspired by mathematics, they also wrote treatises explaining the role of science and mathematics to the arts. Today, the CyberArts movement, with its interest in chaos theory and fractals, is sometimes hardly distinguishable from the scientists working on those very subjects.

Epistemology Scientists and artists are seekers after the same thing: beautiful, elegant solutions. The famous British mathematician G.H. Hardy wrote that "the mathematician's patterns, like the painter's or poet's, must be beautiful." In his Messenger Lectures about the character of physical laws, Richard Feynman says, "[they] are simple, and therefore they are beautiful." Perhaps without realizing it, artists and scientists may be uniquely suited to judge the quality of each other's work.

Metaphysics Do science and mathematics tell us more about the inner workings of our own minds or the outer workings of the universe? Should artists be credited for inventing totally new ways of seeing (i.e. Cubism, 4D) or only with discovering preexisting modalities? Are the scientists' quarks and space-time wormholes really descriptions of our universe or simply current fictions that we use to explain our universe?

Such questions may ultimately have no answers, but this much is clear: artists, scientists, and mathematicians are engaged in the ultimate creative activity—creating something out of nothing. Today, and increasingly in the future, *see-duction* will contribute much to this creative quest.

See-duction is the second of a two part argument I have made regarding the relationship between art and mathematics. The first article, "The Art of Mathematics, The Mathematics of Art" appeared in Leonardo, *vol. 27, no. 1, 1994.*

REFERENCES

[1] Brent Collins has published a series of papers in *Leonardo* describing his mathematically based sculptures. Accepted for future publication in that journal is an article explaining his collaboration with Carlo Sequin, a computer scientist ant UC Berkeley.

[2] The *Not Knot* Video and booklet is available from Jones & Bartlett Publishers. There is also a wealth of information available on the University of Minnesota Geometry Center web site.

[3] In general, much of the most exciting *see-duction* work is being communicated through cyberspace. Two of the best sites are the University of Illinois' National Center for Supercomputing Applications (see especially the Renaissance Experimental Laboratory) and UC San Diego's Supercomputer Center.

[4] Tony Robbin explains his work in his book *Fourfield.* The book also comes with a computer program allowing the user to manipulate a hypercube in 4-space.

[5] Ed Tufte has self-published three classic books exploring the relationship between visualization and information. See *The Visual Display of Ouantitative Information*, *Envisioning Information*, and *The Brand New Visual Explanations.*

[6] Harold Cohen's story is told by Pamela McCorduck in *Aaron's Tale.*

[7] *The Visual Mind*, edited by Michele Emmer (MIT Press) is a first class collection of articles exploring the relationship between art and mathematics.