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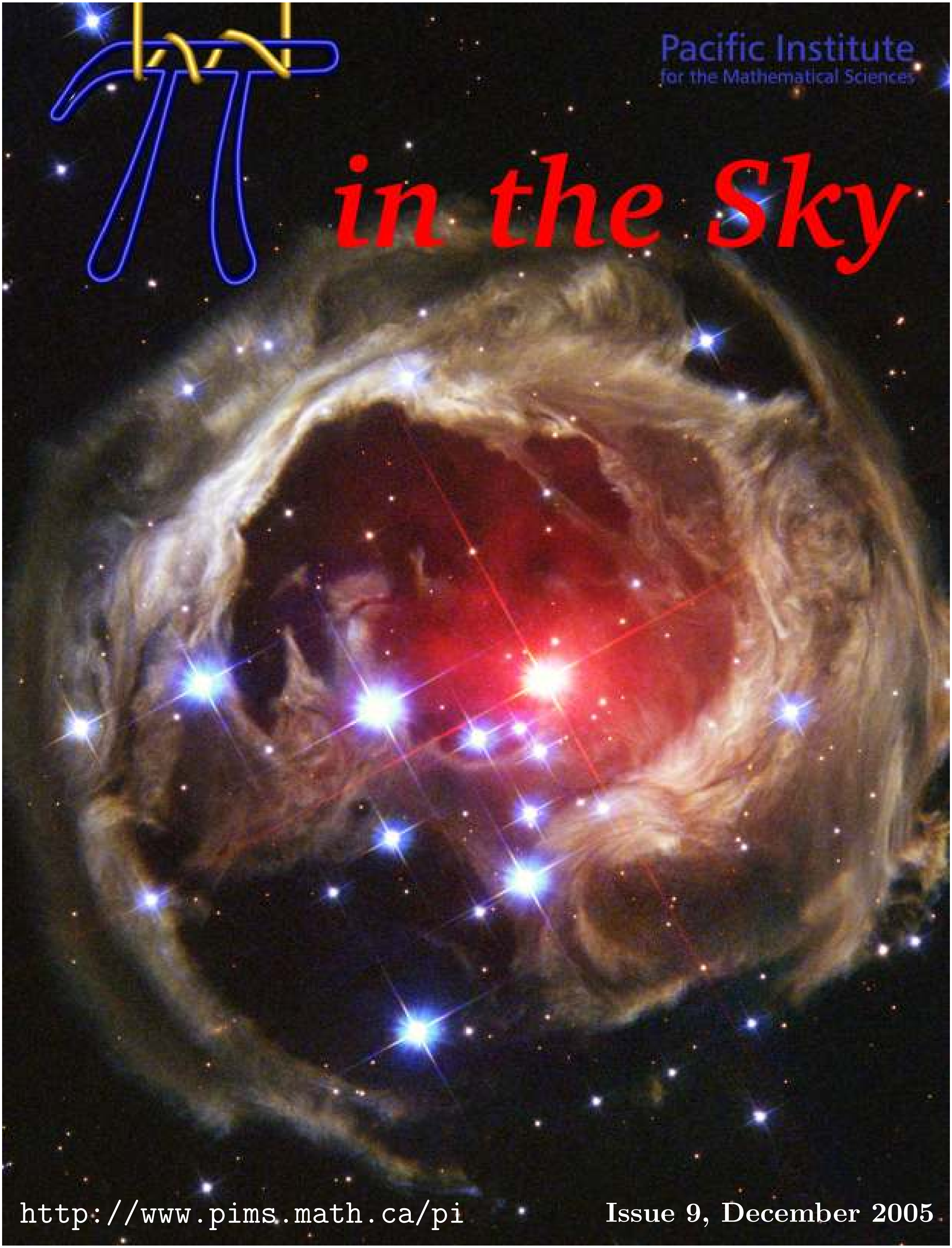
π in the Sky



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The Art of Physics: Visualizing the Universe, Seeing the Unseen

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In 1905, Albert Einstein penned three watershed articles that engendered a revolution in physics, and laid the foundations for Relativity and Quantum Mechanics.

In commemoration of this "Miraculous Year," the United Nations declared 2005 the International Year of Physics. Throughout the year, the worldwide physics community organized events to mark the pioneering contributions of Einstein, by highlighting the vitality of physics, and bringing the excitement of discovery to the public. At the University of Victoria, this physics-fest has been marked by lectures and a special exhibition, "The Art of Physics: Visualizing the Universe, Seeing the Unseen." (An online version can be explored at http://maltwood.uvic.ca/physics/.)

Organized jointly by particle physicist, Dr. Margret Fincke-Keeler, who studies the basic building blocks of matter and the forces that hold them together, and one of us (A. Babul), a cosmologist who studies the origin, evolution and ultimate fate of the Universe, this exhibition draws together a series of striking visual images and video installations from areas as diverse as stellar astronomy and medical physics. The images were contributed by scientists and institutions from around the world. The aim of the exhibition is two-fold: first to highlight the relatively unknown, though central, role of visualization in science and second, to draw attention to the deep connection between art and the aesthetics of scientific imagery. The images provide a rare glimpse into the arcana of the scientists' efforts to render the physical world comprehensible.

Of the 33 images, about half feature cosmic phenomena. Visual imagery has always been integral to astronomy. Early on, the images seen through telescopes were sketched on paper. Later photographic film was used, and nowadays, the images are recorded in digital format, allowing them to be easily manipulated. Many of the images shown are not as they would appear to the eye. Instead, they are comprised of different data digitally combined to provide insight about processes underlying the phenomena.

On the theoretical side, contemporary astrophysicists take advantage of powerful supercomputers to understand how the universe, having emerged from the fires of the Big Bang in an exceedingly smooth and homogeneous state, has evolved into today's richly structured system where galaxies trace out web-like chains woven about giant voids millions of light-years across. Astrophysicists use sophisticated image analysis and visualization tools to turn billions of bytes generated by the supercomputers into meaningful information.

Visualization is also central to particle physics. Particle physicists use it to make sense of the interactions between tiny ghost-like particles that are too small to be directly seen. In close analogy with woodsmen who can identify animals

Stellar Sprite In The Eagle Nebula: Appearing like a winged fairy-tale creature poised on a pedestal, this object is actually a billowing tower of cold gas and dust rising from a stellar nursery called the Eagle Nebula. A torrent of energy in the form of ultraviolet light from young stars is eroding the pillar, sculpting fantasy-like landscapes in the gas. The starlight is also responsible for illuminating the tower's rough surface. The column is silhouetted against the background glow of more distant gas. The colours in the image are artificial in that they have been chosen to enhance specific features of interest to astronomers and astrophysicists. Photo kindly provided by NASA/ESA, Space Telescope Science Institute, and the Hubble Heritage Team.

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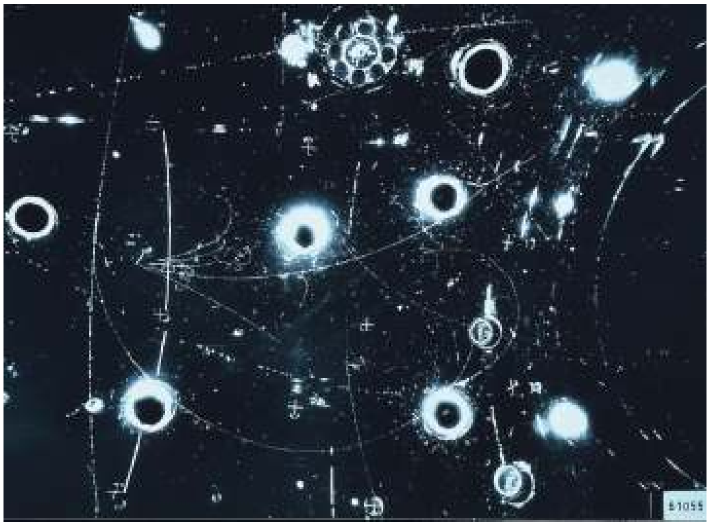


Gargamelle Event: Bubbles forming in the wake of charged subatomic particles streaking through a CERN bubble chamber called "Gargamelle." The bubble chambers are filled with a superheated liquid. The wakes induced by the particles cause cavitation. The resulting lines of bubbles can then be photographed and analyzed. This image is the first observation of "neutral currents" in the Gargamelle chamber where a neutrino interacts with a nucleon and emerges as a neutrino. Photo kindly provided by CERN, Geneva, Switzerland.

by their tracks, particle physicists are able to deduce the presence of different particles and elucidate their properties by the "tracks" they create as they pass through sensitive detectors. The resulting images are invaluable jigsaw pieces in the grand puzzle of matter and energy.

The exhibition also includes visualizations of "atoms" in different arrangements from the world of solid-state physics. Until the invention of the scanning tunnelling microscope two decades ago, the very idea of trapping, imaging and moving about individual atoms was a "pipe dream." This scanner maps out corrugations on a surface due to individual atoms via a finely sharpened, atom-wide tip. The atoms are detected by tiny electrons that fly off the probe and "tunnel" into the electron shells of individual atoms. The resulting measurements are given a visual form using digital image processing. Today, these stunning images are considered contemporary scientific visual icons, in the same category as images taken by NASA's Hubble Space Telescope. They not only provide new insights that promise breakthrough technological applications but also present beautiful evidence of the validity of the theory of quantum mechanics.

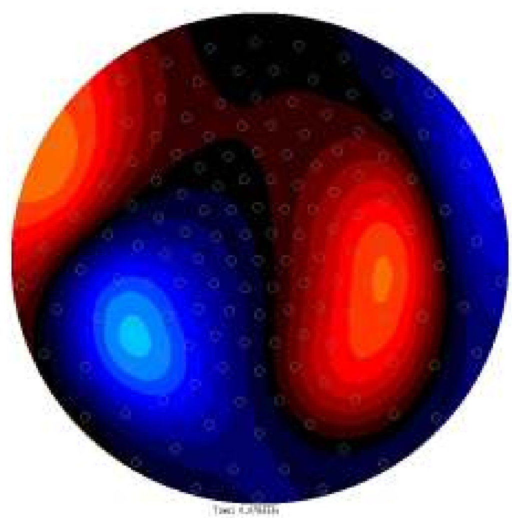
Finally, the exhibition hosts several instalments contributed by medical physicists. Medical physics—dating back to the discovery that X-rays could be used to view the insides of the human body—has been firmly rooted in the art and science of scientific imagery. And while X-ray imaging is still the basis for many diagnostic approaches, the replacement of the film by electronic detectors and the ability to manipulate the data digitally has led to a host of techniques, including the ability to generate three-dimensional views of the human organs without resorting to surgery. Moreover, sophisticated instruments, such as the functional MRI and the Magnetoencephalograph, are opening new vistas into previously inaccessible regions like the brain. It is now possible to collect remarkably accurate spatial and temporal information about neural activity in the brain in a non-invasive fashion, literally making it possible to image "thinking." The exhibition includes a video clip of brain activity associated with, appropriately enough, "seeing."

In short, the exhibition, with its array of visually stunning images and video installations, offers a unique opportunity to be awed by the beauty and harmony in areas of nature not normally associated with sense experience. Additionally, it also provides a glimpse into the world of scientific research, highlighting how heavily scientists rely on creative scientific visualization to uncover and understand the subtle mechanisms that underlie the workings of nature.

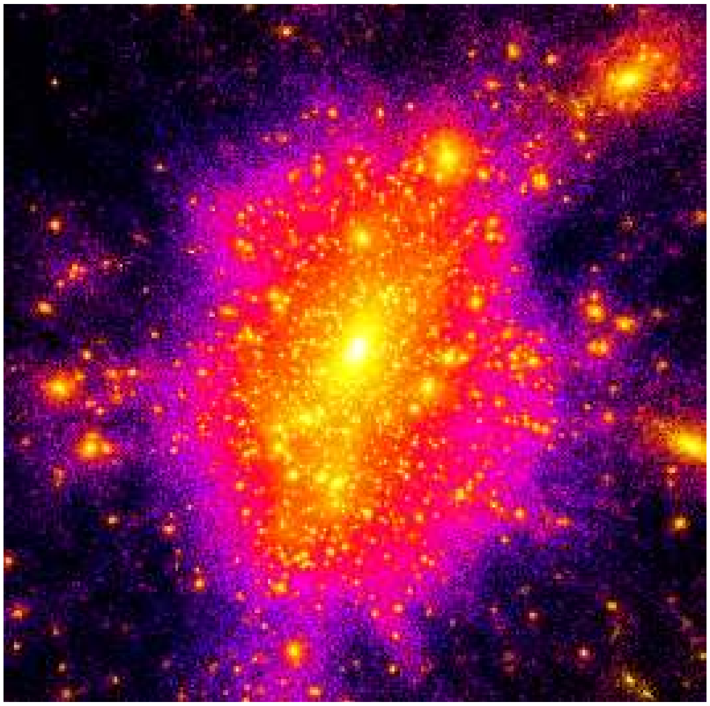
Scientific Imagery, Intuition, and Insight

Though often mistakenly taken to mean merely the design of presentation graphics, the phrase "scientific visualization" has a much broader definition. It is the art of transforming the abstract, be it in the form of reams of meticulous measurements or streams of computer-generated numbers, into geometric or symbolic representations. Visualization, to quote from the 1987 National Science Foundation (USA) panel report on Visualization in Scientific Computing, *"offers a method for seeing the unseen. It enriches the process of scientific discovery and fosters profound and unexpected insights."* Or, in the words of the theoretical chemist Primas, *"There is no insight without internal images!"* (Primas, as quoted by Euler 2001). Insight here, as Euler elaborates, refers to the ability to see a problem or a natural phenomenon clearly in one's mind, and understand its essence intuitively in spite of the fact that it cannot be directly perceived.

From this perspective, scientific imagery is especially important today as scientists probe levels of reality that cannot be directly accessed by human senses. Moreover, real processes in nature are complex, with the underlying organizing principles shrouded in a confusing cacophony of details. Through scientific imagery, scientists can de-emphasize, or even abstract away, the non-essential aspects of a phenomenon, so they can explore it more easily and ultimately "see" through to its essence.



Brain-seeing: A two-dimensional projection showing magnetic field patterns on the surface of a human brain during a task involving "seeing." This image was taken using a Magnetoencephalograph (MEG). As the brain takes in and processes inputs, waves of electrical impulses associated with nerve activity ripple about. These electrical impulses give rise to minute magnetic fields. The MEG utilizes exquisitely sensitive superconducting quantum interference devices, cooled to −269 degrees Celsius, to pick up these tiny magnetic fields literally through the skull and the scalp, allowing for non-invasive study of a live brain in action. Photo kindly provided by T. Cheung and N. Virji-Babul, Down Syndrome Research Foundation (DSRF).



Virtual Cluster of Galaxies: An image showing the distribution of "unseen" dark matter in a numerically simulated cluster of galaxies. Clusters of galaxies are among the most gravitationally bound systems in the universe. They are populated by swarms of hundreds of galaxies and are filled with very hot X-ray emitting gas. To understand how such structures have arisen, cosmologists use powerful supercomputers to simulate the evolution of the universe over its 14 billion year history. Photo kindly provided by T. R. Quinn, *N*-Body Shop, Astronomy Dept., U. Washington.

Cosmic Tadpoles: This impressionistic image details the outcome of collisions between streamers of gas in the Helix Nebula, the closest planetary nebula to the sun. Astronomers have dubbed the tadpole-like objects in these images "cometary knots" because their glowing heads and gossamer tails resemble comets, and there are thousands of such knots. Each gaseous head is at least twice the size of our solar system; each tail stretches 100 billion miles, about 1000 times the Earth's distance to the Sun. Photo kindly provided by NASA, ESA, STScI, NOAO, the Hubble Helix Nebula Team, M. Meixner (STScI), and T. A. Rector (NRAO).

Recent findings in neuroscience and psychology may explain why imagery plays such a fundamental role. The human brain processes visual information much more efficiently than textual, numerical or even diagrammatic data. It is primed for accepting visual inputs. It devotes a significant fraction of its resources to the processing of these inputs, transforming them into mental representations that allow for easy recognition of patterns and anomalies otherwise concealed in a jumble of numbers. It is especially fine-tuned for identifying the unexpected. Increasingly research into the role of visual imagery in science suggests that there is a close connection between the creation and manipulation of visual imagery, cognition, and "creative thinking."

The use of scientific imagery is a centuries old tradition. From Ptolemy to Tusi, Copernicus to Kepler, Newton to Feynman, imagery has been at the root of historical breakthroughs. Even Einstein, the man whose monumental insights of a century ago are the focus of this International Year of Physics, relied heavily on visuals. His biography and personal letters indicate that visualizations were the foundation of many of his ideas, including his greatest legacy: the Theory of General Relativity.

In the future, visualization will become even more important to the scientific endeavour. From a scientist's perspective, the march of progress—driven by the advance in technology—that has brought us to the current epoch of discovery and comprehension now threatens to overwhelm us with tsunamis of data. In the last two decades, the rate of scientific data generation has leapt from tens of megabits per day to just under a terabit per day, with no limits to growth in sight. This explosion reflects not only the improvement in the resolution of observations and numerical simulations, but also the increase in the dimensionality of the data. This colossal volume of data must be processed and catalogued. Most importantly, it must be explored, analyzed and understood.

Consequently, scientists are now compelled to transgress the imaginary boundary between the arts and sciences in order to foster transdisciplinary collaborations. Such collaborations, between scientists and visual artists—who have an intuitive understanding of colour, form, shape, and representation—will become increasingly vital in terms of giving complicated datasets meaningful visual form. Several astronomy departments in universities across North America have in-house visual artists. And many astronomy graduates have developed such strong skills in visualization that it is not uncommon for those who do not pursue the field professionally to be recruited by video and animation companies like DreamWorks.

Of course, while imagery and the design of creative representations of abstract phenomena is central to the scientific endeavour, it is only one part of the process. In the words of Primas, *"What is intuitively seen must be critically questioned and confirmed by rational reconstruction.... An adequate interplay between intuition and rational reconstruction is crucial not only for doing physics but also for learning physics."* (Primas, as quoted in Euler 2001).

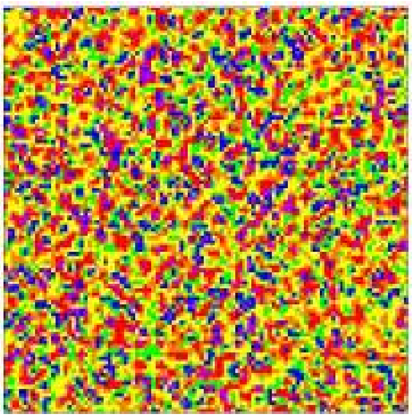
Scientific Imagery and Science Education

Given the fundamental role of scientific imagery, one would expect that the construction and manipulation of such imagery would be a crucial part of the science experience in the elementary and secondary years. This, unfortunately, does not appear to be so.

Various studies[1] have shown that today's science educa-

[1] OECD Programme for International Student Assessment [PISA]; Third International Mathematics and Science Study [TIMSS]; Connecting Research in Physics Education with Teacher Education: An International Commission on Physics Education (ICPE) Publication.

tion falls far short of teaching students how to look at nature with the passion of an explorer and how to make sense of what they discover. Instead, science education tends to focus on the transmission of established facts and principles, sometimes supplemented with simple mathematical exercises and demonstrative experiments. This goal is indeed attained, but at the expense of a much more important ideal of portraying science as a grand and dynamic, human endeavour to comprehend the natural world.



Noise II: Just like a television or radio, that emits static "noise," if not tuned to any station, a small amount of noise is always present in medical images. This picture depicts the intrinsic noise in a Computed Tomography (CT) scan image. Photo kindly provided by M. Hilts, BC Cancer Agency Vancouver Island Centre, and A. Jirasek, U. Victoria.

The purpose of teaching science ought to be to introduce students to the broad structures that gird scientific endeavour and to create opportunities for the students to experience the excitement of exploration and discovery that is at the root of science. Most importantly, the aim should be to teach the students how to convert their concrete observations into imagery that can be creatively manipulated to reveal the order and harmony underlying natural phenomena.

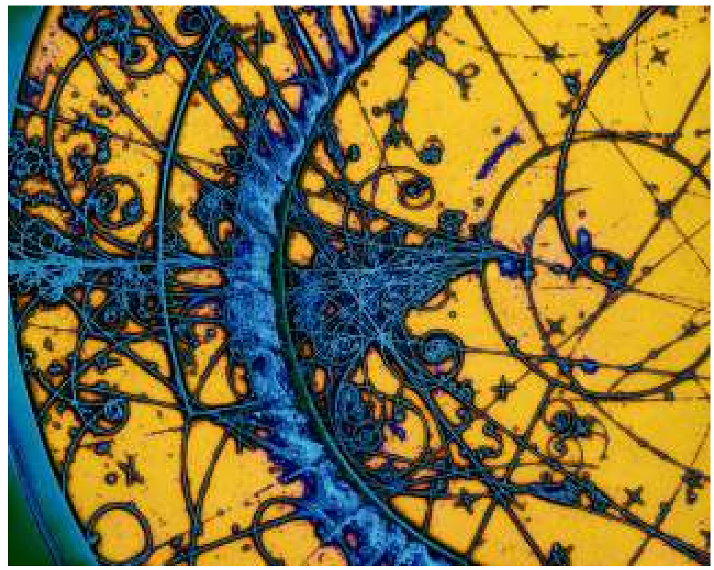
Both aspects are poignantly emphasized by Hirschbach, a Nobel Laureate in chemistry: *"In our science courses, the students typically have the impression—certainly in the elementary or beginning courses—that it's a question of mastering a body of knowledge that's all been developed by their ancestors.... Particularly...they get the impression that what matters is being right or wrong—in science above all.... I like to stress to my students that they're very much like the research scientists: that we don't know how to get the right answer; we're working in areas where we don't know what we're doing...I think any way we can encourage our students to see that, in science, it's not so important whether you are right or wrong...because the truth is going to wait for you."* (Hirschbach, as quoted in White and Gunstone 1998).

One consequence of limiting the teaching of science to the memorization of facts is that today's students are not able to operate between the concrete and the abstract with ease. They commonly confuse the symbols used to describe objects and the objects themselves. This hinders them from being able to translate their knowledge to different contexts and from using their knowledge creatively (Euler 2001). In other words, at the very time when our society is become increasingly knowledge-based, there is a growing concern that the present-day educational system does not provide for the level of scientific literacy and scientific skills necessary to meet the challenges of the future. Mechanically running through a series of prescribed problem solving steps does not engender insight and genuine understanding.

The studies mentioned previously have collectively identified a number of factors that are at the root of the problem. Many teachers have not had adequate exposure to science, and either lack the confidence to teach it or do not fully appreciate its very nature and goals (White and Gunstone 1998). Apprehensions and misperceptions have a direct impact on how teachers speak of science and the way they teach it.

Alternatively, teachers often cite the lack of easily accessible resources that would allow them to introduce science as an exploration. Today, the combination of easy access to computers, Internet connections that bring a growing number of online scientific archives within easy reach, and readily available data manipulation and imaging software, offers a unique opportunity to bring new dimension to science education.

Of course, technology, in and of itself, is not a panacea. The focus must be on teaching "formal thinking." The construction of symbolic descriptions, a process that is at the heart of the methodology of physics, is not a generic mode of mental activity. Euler (2001) argues that is the main stumbling block that makes the learning of physics a challenge.



Big European Bubble Chamber (BEBC)—Colour Treated Image: The European centre for subatomic research (CERN) often provides artists the opportunity to use the research environment as a stimulus for artistic endeavour. Depicted here is an artistically enhanced picture of particle tracks in the Big European Bubble Chamber (BEBC). Photo kindly provided by CERN, Geneva, Switzerland.

Visualization, however, is an exciting foil for introducing and incorporating formal thinking within science education. The ability to "see the data" and manipulate it visually carries an immediate appeal, a cache that tables and graphs simply do not have. Interactive visualization offers a unique opportunity to promote the active creation of mental images corresponding to the visual ones, to encourage the fostering of an intuitive understanding of the images, and to stimulate efforts at active mental transformations of these images to make "educated guesses" of what one would expect under different conditions. Inherent in the ability to experiment interactively with different visual renderings of data is the potential for seeing the data in new and unique ways. These are the very abilities that are critical for the successful doing of science.

More generally, the above skills are essential not only for budding scientists, but are a prerequisite for any form of advanced abstract thinking, be it deconstructing Shakespeare, searching for patterns and predictability in the stock market, critically analyzing the historical terrain of a people or events, taking advantage of the digital revolution to choreograph powerful new visual art installations, or designing the next hit software or hardware application.

Insightful, okay! But is it really Art?

The discussion of insight and understanding aside, the exhibition has been a resounding success. The general reaction is best summarized by the following quote: *"I just saw the 'Art of Physics' exhibition. It was quite a powerful and intriguing experience. I was caught between responding to the beauty of the images without thinking about them as information data, on the one hand, while responding just as strongly, on the other hand, to learning about what was actually being represented."*

This is not to say that there weren't any dissenting voices. Of these, the typical challenge was *"Is this really art? After all, aren't the images just showing natural phenomena?"* Well, yes and no!

While it is true that the images shown at the exhibition have their origins in measurements, they are far from being simple straightforward depictions. Typically, the phenomena cannot be "seen" and even when they can, the "seen" often masks the more important "unseen." The scientists' task is to consider all the available properties—whether it is something visible or just measurable, whether it is an observable or a more abstract deduced quantity—and seek to represent these creatively using colour, forms and shapes in juxtaposition in order to tease out clues about the underlying phenomena. In seeking the most meaningful representation, each scientist is guided by both his/her own individual sense of the aesthetics as well as the understanding that the construction must be consistent with the general framework of science.

Ghostly Reflections: In this image, the Hubble Space Telescope has caught the play of light reflecting off the ripples and wispy tendrils extending from a pitch black cloud of cold interstellar gas laced with dust, much like moonbeams reflecting off gentle waves on a dark ocean surface at night. The source of the light is the star Merope just outside the frame on the upper right. The colourful rays of light at the upper right, pointing back to the star, are an optical phenomenon produced within the telescope, and are not real. However, the remarkable parallel wisps extending from lower left to upper right are real features. They were caused by ripples on the cloud surface when the star began to shred the cloud. Photo kindly provided by NASA/ESA, STScI, the Hubble Heritage Team, G. Herbig and T. Simon (U. Hawaii).

In the words of Michelle Miller, an abstract artist living in Victoria (BC), *"This is no different than how I teach and what I look for in abstract art. I have a basis of rules that exist.... For instance, if I have some large shapes on the canvas...everything that happens around those shapes will change the way those shapes look. Every brush stroke influences every other brush stroke. It becomes a chain reaction. You cannot clearly anticipate all of the variables. Sometimes you need to look and 'listen' to what the painting is saying to you. By this, I mean relinquish control and just try to understand by observing what happens. If you have...a visual grasp on when things 'work', then you're on your way to the creation of something incredible."*

The problem of the creation of imagery in the physical sciences is very similar to that faced by artists in their work. Attempting to find appropriate symbols to represent concrete objects and natural phenomena in the physical world is no different from the problems an artist faces in choosing signs and symbols, colours and shape, form and allegories to represent his/her internal world. Although the two disciplines of art and science speak different languages, they have a similar aim: the investigation and representation of the world in which they live. From this perspective, imagery of the physical sciences truly straddles the boundary between Science and Art. It seeks to give expression to 'what is there' and 'what it might mean.' It seeks to unveil the aesthetics of the physical world. One can argue that a scientist is a medium through whom nature makes her works known.

While artists attempt to decipher their place in the world viewed from the prism of their experiences, the scientists attempt to decipher the underlying order and harmony of the physical world from the prism of their limited perspective. Both approaches reveal previously hidden relations, and both are investigations into the nature of reality that defines humanity.

References

[1] de Carvalho, A-M. and R. White 1998: *Introduction to Section D: Teachers' Attitudes and Practices* in reference [5] below.

[2] Euler, M., 2001: *Imagery and Formal Thinking: Approaches to Insight and Understanding in Physics Education.* International Research Group on Physics Teaching (GIREP) Seminar, University of Undine, Italy.

[3] *Knowledge and Skills for Life*, 2000 Ed. First Results from the OECD Programme for International Student Assessment (PISA). OECD, Paris.

[4] *Third International Mathematics and Science Study*, 1996 ff. TIMSS Monograph. Vancouver: Pacific Educational Program.[2]

[5] Tiberghien, A., E. L. Jossem and J. Barojas, Eds. 1998: *Connecting Research in Physics Education with Teacher Education.* International Commission on Physics Education.

[6] White, R. and R. Gunstone 1998: *Teacher's attitudes about physics classroom practice* in reference [5] above.

[2] Also see: Beaton, A.E., M. O. Martin, I. V. Mullis et al., 1996: *Science achievement in the middle school years: IEA's Third International Mathematics and Science Study (TIMSS)* and Beaton, A.E., I. V. Mullis et al., 1996: *Mathematics achievement in middle school years: IEA's Third International Mathematics and Science Study (TIMSS).* Both published by Chestnut Hill, Mass., TIMSS International Study Center, Boston College.