The Art and Science of Light: An Illustrated Retrospective

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More than 100 years have passed since Wilhelm Roentgen's discovery of x-rays, a form of electromagnetic radiation with wavelengths shorter than visible light. Roentgen's work was the continuation of other scientists' study of the properties of light waves. Subsequent research into particle theory by Albert Einstein and others led to the physics principles that not only laid the groundwork for state-of-the-art medical imaging but also changed the understanding of our universe, from atoms to black holes. Because light is the visual medium of radiologic science, technologists must develop an artistic eye. This retrospective pays homage to those who advanced the scientific theory of light and contributed to the foundation of modern medical imaging:

- Wilhelm Roentgen – x-rays (1895).
- Albert Einstein – photoelectric effect (1905).
- Niels Bohr – quantum theory and the atom (1922).
- Werner Heisenberg – uncertainty principle (1932).
- Christian Doppler – Doppler effect (1842).
- Rembrandt van Rijn and Johannes Vermeer – old masters in painting light (1600s).

Wilhelm Conrad Roentgen

Roentgen discovered the rays that behave in ways both similar to and strikingly different from visible light. He coined the term "x-rays" because to him they were a great mystery, and in algebra, "x" represents an unknown quantity that is replaced by the solution. In his seminal 1896 article, he described the unique characteristics of x-rays that are still accurate today, including that they[1]:

- Transmit in complete darkness.
- Are invisible to the human eye.
- Originate from a cathode ray tube.
- Penetrate black paper that blocks visible light.
- Light up barium platinocyanide-coated paper.
- Expose photographic covered plates.
- Diminish at a distance but fluoresce at 2 m.
- Have an intensity that follows an inverse square law.
- Make wood, water, and human flesh appear transparent, but metal and bone remain opaque. The transparency of intervening objects depends on their molecular density and thickness.
- Are not reflected by mirrors nor deflected by glass prisms.
- Travel at a constant speed—the speed of light.
- Share some properties with visible light.

Shortly after Roentgen published his article, x-rays were identified as a continuum of the electromagnetic spectrum of light. In 1901, Roentgen received the first Nobel Prize awarded in physics (see **Figure 1**). As a tribute to Roentgen's original description, the high-energy waves still are called x-rays, even though they are no longer mysterious.

Albert Einstein

Einstein was preoccupied with the unique qualities of light his entire career. Although he is best known for his theories of relativity, his Nobel Prize was awarded primarily for his explanation of the photoelectric effect, which revealed that x-rays were a form of light that traveled in quanta, or packets of energy. Einstein's persistent curiosity about the peculiar nature of light resulted in the special theory of relativity, an idea conceived while riding his bicycle toward a lamp light. He reasoned that unlike moving Newtonian objects whose speeds are summed or subtracted, the speed of light is constant for all observers. Relativity would explain everything, from the tiniest subatomic particles to galaxy-devouring black holes.

Max Planck's Light Bulbs

> *Planck's scientific work often is described as theoretical studies in black-body radiation, but his commissioned job was finding out how to get the most visible light from light bulbs using the least amount of energy. He used statistical analysis to match observations that atoms do not emit light energy in continuous waves but rather in discrete packets of energy (E) as determined by a discrete integer (n) multiplied by Planck's constant (h) multiplied by their frequency (v), the equation being $E = nhv$. This first step led to the quantum theory, and it was the first indication that classical Newtonian physics could no longer explain everything; an altogether new form of physics was required.*

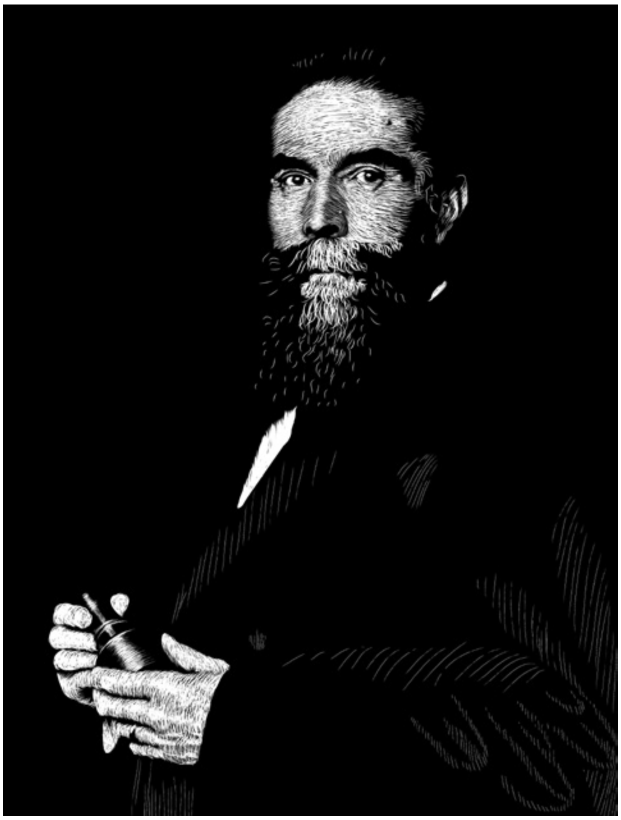

Figure 1. *Digital portrait by the author of Wilhelm Roentgen holding a cathode ray tube. Artwork comprised of thousands of hand-drawn lines using a graphics tablet, stylus, and Xara software. Drawing based on a public domain photograph.*

The photoelectric effect explained that the incident light that ejects electrons from atoms can be understood only if light consisted of quantized packets of energy ($h\nu$), rather than as a continuous wave. Electrons are not ejected until a minimum amount of light energy (threshold frequency) is reached, and the number of electrons ejected depends on how many light photons were involved (intensity). The maximum kinetic energy of the ejected electron (K_{max}) is determined by Planck's constant (h) multiplied by the frequency of the incident photon (ν) minus the threshold frequency (ν_o), that is, $K_{max} = h(\nu - \nu_o)$.

The photoelectric effect explains one way x-rays interact with human tissue and how technical radiographic settings work. When preparing to take a radiograph, setting the kilovoltage potential determines the energy of the x-ray beam and penetration, and setting the milliamperes determines exposure and exposure time. Both kilovoltage and milliamperes contribute to image quality and contrast. Therefore, understanding the nature of light is key to producing radiographs of diagnostic quality.

The Speed of Light

Other types of waves require a static medium. Sonar, for example, requires water, and sound requires air. It was once believed that light waves required a medium of "ether," which was invisible and undetectable. The concept of ether was highly problematic because it meant there was an absolute reference in the universe: an invisible "stage" for all interaction. This concept of absolute reference was rejected long ago by Galileo and later by Ernst Mach; both said that all motion is relative and cannot be detected unless referenced by an outside point of view.[2] In a break from classic Newtonian physics in which velocities are summed or subtracted, Einstein theorized that light coming from (or observed by) a moving traveler has the same velocity from any reference point, an idea confirmed by the Michelson-Morley experiment in 1887.[3] Einstein once said, "For the rest of my life I will reflect on what light is" (see **Figure 2**).[4]

The constant speed of light changed the way the universe was perceived. Not only could the all-permeating ether finally be discarded, but the measurements once thought to be the concrete foundations of Newtonian physics (time, distance, and mass) were now subject to change. Einstein's relativity makes the science fiction adventures of galaxy-hopping space travel in *Star Trek* and *Star Wars* a mere fantasy. The vast distances and the universal speed limit of light make intergalactic travel too impractical. If a hypothetical space craft approaches the speed of light, time slows, length compresses, the mass of the space craft increases, and impossibly high amounts of energy are required. At a certain point, the space craft stops accelerating, despite greater energy input.

A result of Einstein's special theory of relativity has been called the most famous equation in all of science: energy (E) equals mass (m) multiplied by the speed of light squared (c^2), that is $E = mc^2$. This simple equation, which states that energy and mass are interchangeable quantities, often is misinterpreted as the formula of the atomic bomb. The principle of the atomic bomb is bombardment of a uranium atom with a neutron that splits the uranium atom into 2 smaller atoms and more neutrons that trigger a fission chain reaction. Although tremendous energy is released, it is the energy of internuclear binding forces, and there is no appreciable change in mass.

A much better demonstration of $E = mc^2$ is in explaining the physics of the positron emission tomography scanner, in which a positron and electron annihilate each other and convert their masses into pure light energy, consisting of photons traveling in opposite directions. This light is detected and calculated as a 3-D image of the patient. Although most radiologic technologists do not think about the relativity theory in their daily practice, it is the foundation of some radiologic images.

Einstein expanded his ideas with his general theory of relativity, which explained the phenomenon of gravity as a distortion of the space-time continuum and predicted monstrous black holes where gravity is so great even light cannot escape. Relativity explains the tiniest and the most immense objects in the universe.

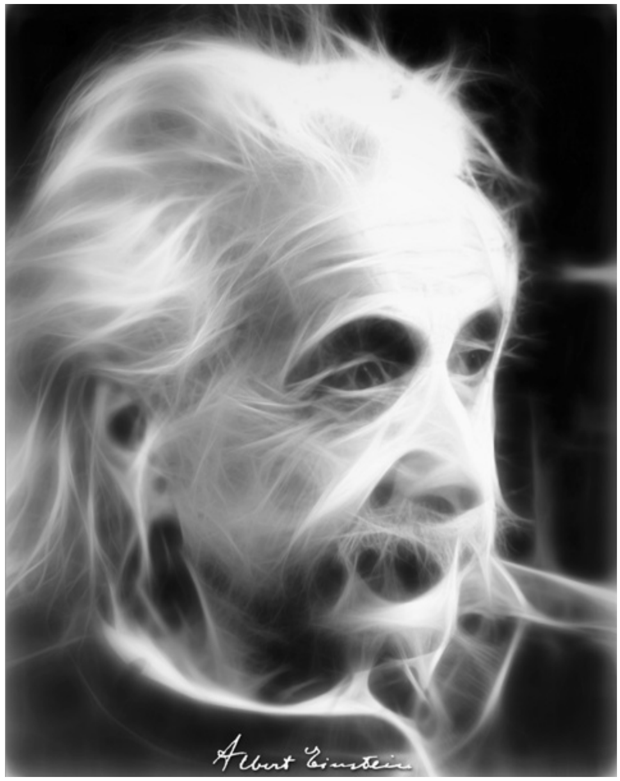

Figure 2. *Portrait of Albert Einstein, whose theories of relativity are based on the unique properties of light. Matter distorts the space-time continuum and can bend the path of light. Digital art image by Andrej Hromin of Rijeka, Croatia. Reprinted with permission from the artist.*

Niels Bohr

The model of the atom proposed by Bohr explained Planck's quanta of energy emission and Einstein's photoelectric effect but, in doing so, rejected the Newtonian model of the atom. The Rutherford model of electrons orbiting the central nucleus was inadequate because a charged particle changing direction in an orbit would lose energy and fall into the nucleus. Bohr's model had to explain atomic light interaction, chemical reactions, and the inherent stability of atoms. A carbon atom can undergo countless chemical reactions yet remains a carbon atom. As Bohr further investigated the atom, the idea of separate properties of light being a wave and electrons being particles was no longer valid. With the photoelectric effect, Einstein showed that light could be a photon particle. Louis de Broglie then showed that particles could be waves. Both photons and electrons had a particle-wave duality. The electron therefore could exist as a standing wave around the nucleus, absorb and emit quanta of light energy, and yet remain stable. The paradoxes that resulted from Bohr's quantum theory altered the foundations of science.

The archetypical test of the quantum theory is a simple demonstration with light. According to Feynman, the classic double-slit experiment:

> *has in it the heart of quantum mechanics. In reality, it contains the only mystery. We cannot make the mystery go away by 'explaining' how it works…In telling you how it works we will have told you about the basic peculiarities of all quantum mechanics.*[5]

With the double-slit experiment, if photons are shot through a single slit toward a screen, they create an expected diffraction pattern.[5] If the photons are then shot through 2 parallel slits, they create an interference pattern as the peaks and troughs of the light waves cancel or build on each other. However, if the photons are shot only one at a time, they create an interference pattern as if the one photon simultaneously went through both slits.

The same experiment can be performed by shooting electrons (or other particles). With one slit open, a line of particles is detected on the screen. With two slits open, the electrons show an interference pattern. If both slits are kept open and a detector that can see which slit the electron passes through is introduced, the interference wave pattern collapses and 2 lines appear on the screen. The mere act of observation somehow alters the experiment.

Instead of fighting the contradictions that arose in his work, Bohr embraced them as an indication that he was getting closer to the truth. His atomic model has since been superseded by more refined theories based on his ideas of complementarity. When he was to be rewarded the Order of the Elephant by the Danish king, Niels Bohr designed his own coat of arms that included the yin-yang symbol and the Latin motto, *contraria sunt complemeta*, which means "opposites are complementary."[6]

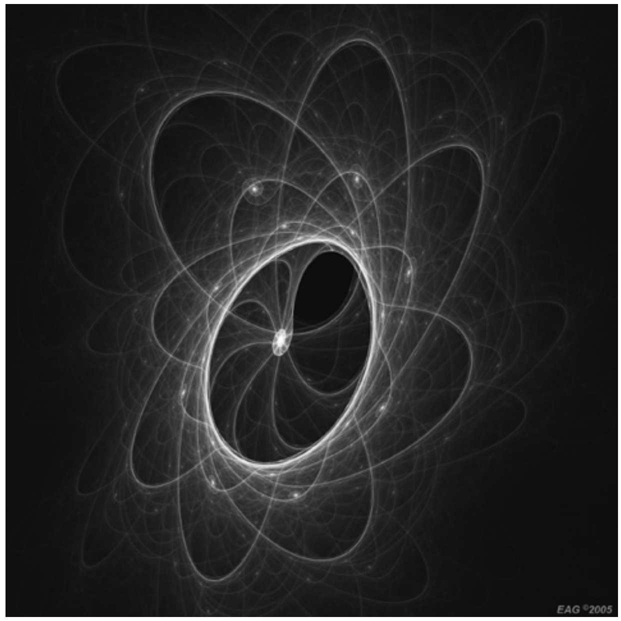

Figure 3. *Artist's conception of atomic probability waves. At the subatomic level, measurements become fuzzy and experiment design changes the results. Fractal art by Eric A Gehlin of Schaumburg, IL. Reprinted with permission from the artist.*

Werner Heisenberg

Heisenberg found that the method of investigation alters the result of an experiment. He explained this idea mathematically in his *uncertainty principle*, which remains a major tenet of quantum mechanics. The light used to measure particles imparts energy, altering the momentum or location of the particles, thus changing the results by the mere act of observation. An experiment can be designed to measure momentum or location precisely, but not both (the experimenter has to choose). Although this finding was unsettling for physicists who strive for precise measurements, at the atomic and subatomic levels, precision was impossible (see **Figure 3**). According to Heisenberg:

> *The violent reaction on the recent development of modern physics can only be understood when one realizes that here the foundations of physics have started moving; and that this motion has caused the feeling that the ground would be cut from science.*[7]

Einstein could not accept the imprecision of quantum mechanics for philosophical reasons, believing that it had to be incomplete. He spent many of his later years trying to find a grand unification theory that would improve upon quantum mechanics. Max Planck also had doubts about quantum theory, even though his work started the quantum revolution in physics.

Although we should not infer the uncertainty principle to hedge on macroscopic radiologic findings, radiologic technologists often must trade between image resolution and patient dose, thereby affecting the observed results. In the practice of screening for early cancer and disease, the x-rays and injected contrast media might "alter the experiment," thereby imparting their own health risks.

Christian Doppler

Doppler was a professor who studied mathematics, physics, and astronomy.[8] He published a paper on spinning binary star systems, noting that starlight shifts to the violet spectrum when a star is moving toward an observer on Earth, and that starlight shifts to the red when a star is moving away.[9] The explanation was that the wavelength of the light wave was compressed or elongated depending on the motion of the source relative to the observer. He applied this concept to sound waves and proved the same Doppler effect with a passing train that had on board a musical band playing a precise note. When the Doppler effect is applied to sound, it explains the tone of an approaching and departing train whistle; when applied to radar it predicts violent weather; when applied to ultrasound it determines the direction and velocity of blood flow; and when applied to distant starlight it explains our expanding (red shifted) universe (see **Figure 4**).

In radiology, the common use for the Doppler effect is with vascular ultrasonography. Using the Doppler effect, an ultrasonographer can evaluate and screen for the risk of stroke from carotid artery stenosis, renal arterial causes of hypertension, abdominal aortic aneurysms, peripheral vascular disease, deep vein thrombosis, portal vein thrombosis and varices, and postcatheterization pseudoaneurysms. Countless lives have been saved or improved because of a phenomenon originally seen in starlight.

A legacy from Doppler's work is the continued use of red and blue to show direction, but common

Figure 4. *Steam locomotive demonstrating the Doppler effect on sound waves. The Doppler effect can be applied to sound waves, ultrasound waves, radar waves, light waves, and distant star systems. Photography by Dusan Pavlicek of the Czech Technical University in Prague. Reprinted with permission from the artist.*

ultrasonography convention has the colors reversed, with red indicating blood flowing toward the transducer and blue indicating blood flowing away. That is probably because we associate red with being more immediate, when in fact light from a source going away is red shifted, with a longer wavelength and lower frequency.

Doppler's idea extends well beyond the sonography suite and even tells us about the origins of our universe. Edwin Hubble demonstrated that all objects observed in deep space are found to have Doppler red-shifted velocity relative to Earth and to each other. This Doppler red-shifted velocity is proportional to the object's distance from the Earth and all other interstellar bodies. This tells us that our universe is expanding and supports the theory that the universe was created by the Big Bang, which occurred about 13.7 billion years ago.[10]

Old Master Painters

Artists such as Rembrandt and Vermeer were adept at depicting light to create realistic 3-D images on 2-D canvases. These artists studied the interaction of light with their models and understood the human perception of subtle shading and light to make their artwork dramatic and convincing. Rembrandt's famous portraits and self-portraits displayed skill with light source placement, later duplicated by movie director Cecil B DeMille who coined the term "Rembrandt lighting."[11] A primary light source was placed high at a 45° angle to the face to best show high-contrast lighting and facial geometry. A second half-dimmed light was placed at mid-height and at 45° on the opposite side to reveal subtle tones on the less-well-lit side of the face. If the lighting was placed successfully, the less-well-lit cheek and area under the eye would show interesting half tones. This lighting technique still is used today by portrait photographers (see **Figure 5**).

Vermeer was skilled at depicting subjects in naturally lit interiors with a subtle photorealistic style that is considered uncanny even today. Some believe Vermeer used special optics and mirrors because much of his lighting was too subtle for the naked eye to detect.[12] For example, scientific analysis showed that his backgrounds depicted the inverse square law, with an exponential diffusion of light, which is difficult to capture when using only the artistic eye.

Experienced technologists use artistic vision when they create radiographs. By positioning and framing their subjects and by adjusting contrast and exposure, each image can be a work of art that not only is pleasing to the eye but also contains a wealth of diagnostic information (see **Figure 6**).

Light, as visual information, is portrayed in art. Light also is the medium for medical imaging, whether in the form of a backlit film, cathode ray tube monitor, liquid crystal display screen, or plasma monitor. The eye is our most complex and highly evolved sense organ, capable of detecting subtle changes in light and color, and transferring this information (via the optic nerves and optic tracts) to the visual cortex of our occipital lobes. However, what distinguishes artists and seasoned radiology professionals from other people is postprocessing (ie, the thinking that occurs after perceiving that visual data). Much of science and medicine is about logic, language, analysis, and categorization (left brain functions). However, visual processing (the artistic eye) is about conceptualization, spatial orientation, and pattern recognition (right brain functions). These

Figure 5. Self-Portrait *(1669) is an oil on canvas by Rembrandt, on display at the Mauritshuis museum in The Hague. Rembrandt was a master of lighting, shadow, color, and form. Public domain image.*

Figure 6. The Art of Painting *(1668) is an oil on canvas by Vermeer, on display at the Kunsthistorisches Museum in Vienna, Austria. The background wall demonstrates the inverse square law of light diffusion. This painting had special meaning to the artist and remained in his personal collection. Public domain image.*

right-brain skills are hard to teach and measure but are important in radiology.

With the rapid increases in digital image resolution and in the number of multiplanar images involved with each case, developing the right brain is crucial to make sense of this visual information overload, especially when the radiologist formulates an educated opinion on volumes of visual data. Knowingly or unknowingly, a seasoned radiologist develops the right brain through the experience of viewing thousands of medical images. This "artistic eye" can be further enhanced in radiologists and radiologic technologists who study and can appreciate the techniques used by great artists. Or better yet, they can train their right brains by creating original art themselves.[13]

Conclusion

Radiologists and radiologic technologists use light and artistic vision in their daily work. They sense subtle shades, recognize patterns, and use symmetry and balance to detect abnormalities. When this artistic skill is applied in combination with an appreciation for the underlying physics that creates the images, a thorough knowledge of human anatomy, and an understanding of the pathophysiology of disease, we can serve our patients by providing timely diagnoses and excellent medical care (see **Figure 7**).

Figure 7. The Anatomy Lesson of Dr. Nicolaes Tulp *(1632) is an oil on canvas by Rembrandt, on display at the Mauritshuis museum in The Hague, demonstrating mastery of light and the importance of continuing the tradition of medical investigation and education. Public domain image.*

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