From Symbol to Substance: the Technologies of Light

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Every day you play with the light of the universe
Pablo Neruda[*]

There has never been a time when the nature of light has not been at the leading edge of science, technology and art. We 'play' with it for so many reasons – to encode information, to bedazzle the senses, to probe the universe, to evoke the presence of the divine. These are not, as they might seem, separate issues, which is one reason why the scientific study and use of light comes laden with cultural and symbolic signification. At the same time, those scientific explorations – both fundamental and applied – have prescribed the boundaries of light as an artistic medium. As our ability to produce and manipulate light has evolved, artists have embraced the possibilities on offer, so that light art is, among other things, always a conversation with technology.

Sacred Light

The theological virtues of light pervaded its early scientific study. Early Christianity was imbued with a metaphysics of light stemming from the tradition of Neoplatonism, according to which radiance was a symbol of God's presence. When men spoke truth, they were 'lucid'; when they understood it, they were 'illuminated'. This reverence for light motivated the thirteenth-century proto-scientists Robert Grosseteste, Bishop of Lincoln, and his disciple Roger Bacon to study optics at the University of Oxford. 'Physical light is the best, the most delectable, the most beautiful of all the bodies that exist,' wrote Grosseteste.[1] That was not mere genuflection; Grosseteste was the first to propose that the rainbow's arc – an eternal source of wonder, a symbol of the Virgin and the post-diluvian renewal of life – results from the refraction of light by clouds. His hypothesis wasn't quite right, but it helped to locate the answer to this age-old question in optical science.

Light had not shaken off its religious connotations when the great scientists of the seventeenth century, such as Isaac Newton, Robert Boyle and Robert Hooke, began to study it. In popular culture light was as much demonic as it was divine, to be feared as well as revered. Things that glitter and glow in the dark are the stuff of folklore. Boyle's servants summoned him in terror to investigate a side of meat hanging in his pantry, gleaming with luminescent bacteria. Phosphorus, discovered around 1669, was attributed miraculous healing powers because of its spontaneous glow, the result of chemical reactions with air. When phosphorus was demonstrated to Boyle at his house in 1677 by writing, in a darkened room, the word 'DOMINI' with a finger dipped in the liquid

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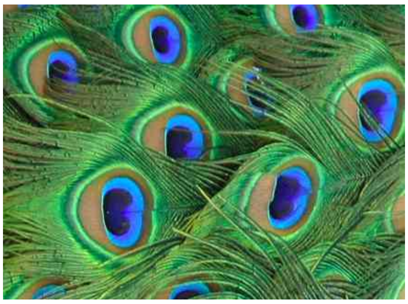
[*] Poem XIV, Twenty Love Poems and a Song of Despair, transl. W. S. Merwin, Penguin, Harmondsworth, 1969.

element, you can sense Boyle's awe at this 'mixture of strangeness, beauty and frightfulness'.[2] His colleague John Beale worried that studying it would 'raise stories of Ghosts in my house'.[3]

Light and Colour

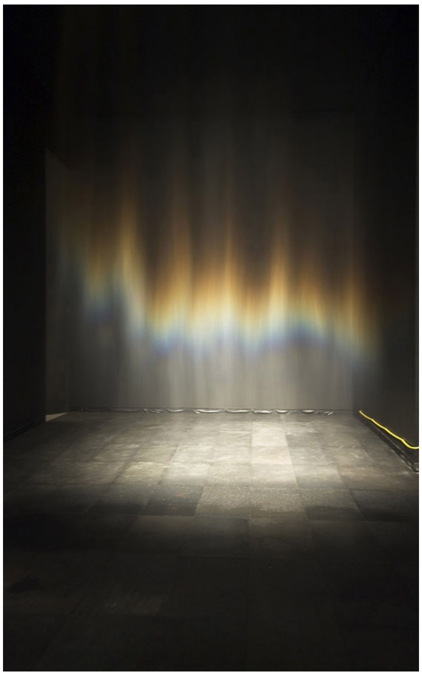
Boyle's assistant, Robert Hooke, a less pious man, was more interested in the technologies of light and optics. Hooke wanted to know what light is, and his answer clashed with Newton's. For Newton, light was 'corpuscular' – a stream of little particles. Hooke insisted that it must be a wave, a vibration of some all-pervading substance called 'the ether'. As Hooke very nearly understood, the interference of light waves may explain the iridescence of peacock feathers (in which the interfering rays bounces off microscopic stacked layers of reflective material) and of oil slicks on water.



The colours in the peacock's tail are caused by light reflected from microscopic stacks of reflective material in the feather barbs.

How light makes colour was Newton's forte. In *Opticks* (1704) he gave the first complete account of how the rainbow is made, explaining not only its arc shape – a slice of a cone of light reflected from raindrops onto the observer, as René Descartes had already adduced – but also its chromatic bands. As light enters and exits a raindrop, it is refracted: the ray's path is altered. When light is refracted through different angles, the rainbow spectrum that sunlight contains is teased out into its component colours. That same distillation of light, albeit from an artificial source, is effected in Olafur Eliasson's 1993 work, *Beauty*, in which a bright light shone on a fine mist falling from sprinklers elicits a fugitive rainbow.

In the seventeenth century, Isaac Newton provided the first complete theory of how the rainbow is formed.



Olafur Eliasson, *Beauty* (1993).

Newton asserted that the arc has seven fundamental colours: red, orange, yellow, green, blue, indigo, violet. This tenet, still recited by schoolchildren, is sheer numerology: Newton believed that the rainbow was seven-hued by spurious analogy with the seven notes of the musical scale. Scientists today usually recognise just six colours, indigo and violet being merged as purple.

Here, then, was something new about light: its 'whiteness' is condensation of all the colours of the rainbow. Newton proved that fact in a celebrated experiment in 1665, when he demonstrated that sunlight separated by a prism into a multi-coloured spectrum can be recombined by a second prism and lens to create pure white illumination. But didn't this contradict everything artists knew about colour from mixing paints? The reason for the discrepancy is that mixing coloured light *adds* colours (and brightness) to the rays – it is called additive mixing. But mixing pigments *subtracts* colours, because each pigment absorbs parts of the light reflected from the mixture. This subtractive mixing inevitably diminishes the brightness of the reflected rays.

Before any of this was understood, Newton's theory of light and colour seemed strange, even absurd. Johann Wolfgang von Goethe rejected it, proposing instead a muddled theory of colour, which made yellow and blue the 'primaries' from which all other colours are composed. Goethe's ideas have always exerted a peculiar attraction for artists – J.M.W. Turner, a 'light mystic' of almost Neoplatonic proportions, produced a startling vision of the post-diluvian world based on these ideas in 1843. But there is little in Goethe's theory for the scientist.

J. M. W. Turner, *Light and Colour (Goethe's Theory) - The Morning After the Deluge* (1843)

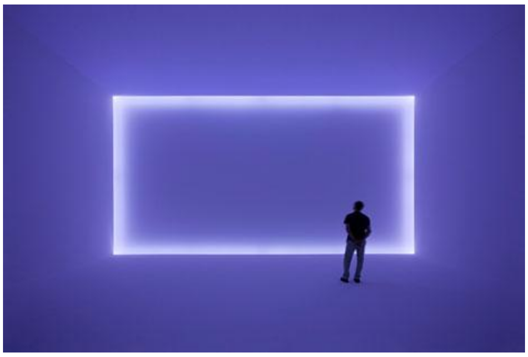
The ambiguities and effects produced by additive mixing of light are apparent in several works by Dan Flavin in which differently coloured fluorescent tubes are placed side by side, modulating one another's appearance. The effect is striking in his *Untitled (to Don Judd, Colorist*) (1987), where vertical quartets of white, red, yellow, blue and green light are topped with horizontal white tubes: the white seems to bleach the blue and green tubes in particular, except where the light bounces off the dark floor and regains its chromatic intensity. Judd also combines yellow and pink additively to make a delicately graded salmon/peach hue in *Untitled (to the 'innovator' of Wheeling Peachblow)* (1966–8).

Don Flavin, *Untitled (to Don Judd, Colorist*) (1987).

Deconstructing Light

After Newton, the common belief was that light is a substance. At the start of the nineteenth century the English polymath Thomas Young begged to differ, showing that a wave theory was needed to explain light's interference effects. Waves are excited whenever a body becomes luminous: for example, when the tungsten filament of a light bulb is heated by electrical current passing through. As James Clerk Maxwell showed several decades later, the waves are vibrations of electrical and magnetic fields: they are electromagnetic waves. The wavelength of light – the number of waves per millimetre, say – determines its colour. As Young correctly estimated, the wavelength of violet light is around 400 nanometres (that is, 400 thousand-millionths of a metre), and that of red light is around 700. Young pointed out that there was no reason for the waves to cease at these visible extremes. Ultraviolet light – known in Young's time as 'blackening rays' (we still speak today of 'black light') – has wavelengths shorter than violet; and infrared light, which we cannot see but can feel as heat, has wavelengths longer than red.

Ultraviolet light may be rendered 'visible' when it stimulates fluorescence, whereby it is absorbed by a material and re-emitted at a slightly longer wavelength, typically in the violet part of the spectrum. The result is that only the fluorescent medium is rendered visible, and moreover often with a flat, ghostly appearance that disturbs perceptions of distance and contour. Douglas Wheeler makes use of ultraviolet neon tubes (described below) to 'dissolve' the edges of a wall-mounted acrylic panel, transforming it into a light installation.



Douglas Wheeler, *DW 68 VEN MCASD 11* (1968/2011).

There was no obvious upper or lower limit to the wavelengths of Young's light: that which we see is merely an arbitrary slice of a continuous spectrum, to which our eyes happen to be sensitive. At wavelengths shorter than ultraviolet, there are X-rays and then gamma rays; the long-wavelength end of the spectrum extends to microwaves and radio waves, with wavelengths measuring perhaps several kilometres. Scientific instruments such as astronomical telescopes can reveal this otherwise invisible universe.

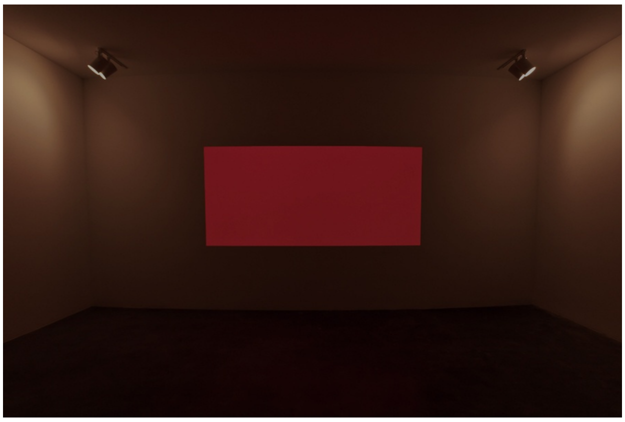
In 1905, Albert Einstein asserted that light is *quantised*: it comes in little packets (quanta) of energy, called photons. When an object glows, it emits a stream of these 'pieces of light'. Photons (unlike Newton's corpuscles) have no mass, but they have energy, which is proportional to their frequency: blue photons are more energetic than red ones. The quantum view of light doesn't replace Young's waves with particles. Instead, it says that light can display both wave-like *and* particle-like behaviour, depending on how you observe it. This 'wave-particle duality', which applies also to fundamental particles such as electrons, is easily misconstrued. It doesn't mean that light is sometimes a wave and sometimes a particle: it's always just light, but we can sometimes better understand what light does by considering it as a particle (photon), and other times by considering it as a wave.

Seeing Light

Goethe's notion of what light is might have been incorrect, but a more fruitful aspect of his work was the recognition that colour is a phenomenon not simply of light but of perception too: it arises from the way light impinges on the visual sense, which is capable of conjuring results that could not be guessed by focusing on Newton's 'light corpuscles' alone. The quirks of our visual system can, for example, make us see light that isn't really there, evoking yellow from red and green light, say. In daylight, colour is decoded by the light-sensitive cone cells in our retina, of which there are three types, with a strongest sensitivity to red, green or blue-violet light. The neural signals from these three types of receptors are combined before being interpreted by the brain as a particular colour. That's why red and green light mix additively to make yellow: red+green and yellow both elicit the same neural response from the cone cells.

Goethe recognised that spectral colours can be grouped into complementary pairs – red/green, yellow/purple, blue/orange – and that strong colours can stimulate the appearance of a surrounding aura of the complementary, noting that after staring at a bright colour for a long time one may see an after-image in the complementary colour when one looks away. This effect is elicited in Ann Veronica Janssens' work *Donut* (2003), in which concentric rings of strongly coloured light are projected onto a wall and rapidly alternated with moments of darkness, stimulating coloured 'phantom' images of the shapes in the viewer's perceptual field when no light is projected. The eye also adjusts our perception of colour to accommodate changes in overall light intensity – an effect called colour constancy, which has the evolutionary rationale of ensuring that hues don't seem to alter in confusing ways as the sun slips behind cloud. James Turrell's *Space Division Constructions* series, begun in 1976, exploit this feature of vision to produce 'screens' of coloured light intersecting a space apparently enclosed by white walls, whose 'whiteness' is sustained by colour constancy.

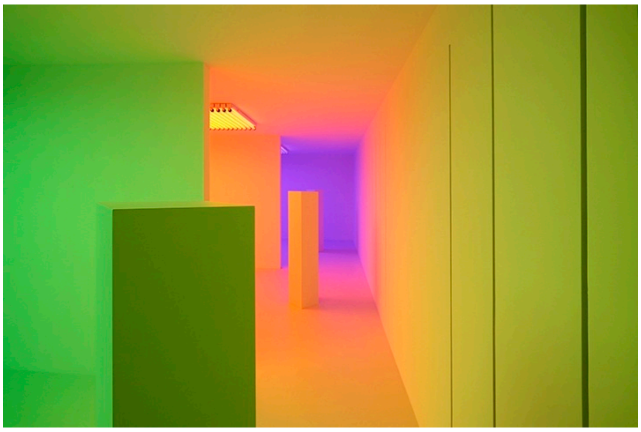
Ann Veronica Janssens, *Donut* (2003).



James Turrell, *Present Tense* (1991), a ‘space division’ work.

In very dim light the cone cells don’t register the illumination very strongly, and instead our visual sense switches over to using rod cells, which are more light-sensitive but don’t convey any sense of colour, which is why objects seem to lose their colour in darkened environments. Also, rod cells are rather more sensitive to blue than to red light, making greenish and bluish objects, such as foliage, relatively more visible at night. This shift in colour sensitivity happens at dusk as rods take over from cones, and is known (after its discoverer) as the Purkinje shift. Turrell’s *Dark Spaces*, made in the 1980s, exploit this adaptation of colour vision. Installed in very dim environments, they require viewers to sit for several minutes while adaptation to the dark takes place, so that if they are patient and attentive they can begin to make out the faint projected light. The intensity is sometimes so low that one can’t be sure if what is seen is real or just a trick of the retina: the light acquires what Turrell called a ‘questionable existence’.[4]

Turrell, who has studied perceptual psychology, has also exploited a visuosensory phenomenon called the Ganzfeld effect, in which the brain responds to the lack of stimulus from a highly uniform visual field by amplifying random ‘neural noise’, producing hallucinations – or alternatively, by creating a sensation of ‘blackness’ or blindness. Both consequences have been reported by Arctic explorers in dazzling white snowscapes. Turrell’s ‘Ganzfeld’ works saturate a space with coloured light that reflects off pure white surfaces, causing a disorientation of perceptions of space and scale. This optical effect is also manipulated by Carlos Cruz-Diez in his *Chromosaturation* installations, in which visitors walk through three adjoining chambers, each flooded with red, green or blue light. Coloured light merges at the boundaries of the chambers, summoning a range of hues through additive mixing. Alternatively, Cruz-Diez presents the viewer with simultaneous, sharply contrasting colours at different points in the environment, so that complementary colours may enhance one another’s vibrancy – an effect that painters have exploited instinctively since the Renaissance.



Carlos Cruz-Diez, a *Chromosaturation* installation.

Making Light

It's sobering to realise that the scientists of Newton's generation had a sophisticated understanding of optics – they knew the laws governing the reflection and refraction of light, and could use lenses and prisms to manipulate it – but still had to work in the evenings by candlelight and oil lamp. Not until the advent of gas lighting in the early nineteenth century was there more than the feeblest relief from night's gloom, and only after electrification in the latter part of that century was there an alternative to the glow of the naked flame.

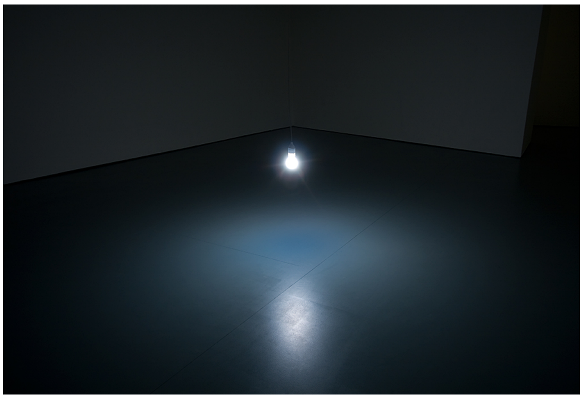
Science was more the beneficiary than the begetter of these new light technologies. Thomas Edison's carbon-filament incandescent bulbs, filed for patent in 1879, were the result not of theory but merely trial-and-error testing of different materials. There were plenty of electrically powered incandescent lamps before then, some also using carbon filaments, but the key to commercial success lay with finding the optimal design and making the device affordable and convenient.

One of Thomas Edison's earliest incandescent bulbs.

Incandescent tungsten-filament lamps were improved in the early twentieth century by adding a halogen element, usually bromine or iodine, to the chamber, which allows tungsten evaporated from the hot filament to be re-deposited back onto it, enabling it to last longer. Most bright film, stage and projection lighting uses tungsten halogen bulbs. The greater robustness of these filaments allows halogen bulbs to withstand the strong forces of acceleration that they experience in Conrad Shawcross's dynamic lightworks, such as *Loop System Quintet* (2005). Here, single bulbs are attached to articulated arms, which rotate at high speed, tracing out apparently solid trails of light.

Conrad Shawcross, *Loop System Quintet* (2005).

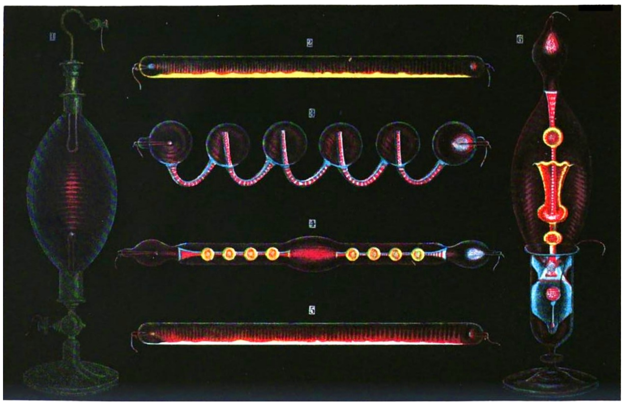
Incandescent bulbs have been stripped of their banal familiarity when reconfigured for artistic purposes. By modifying the filament to tune the colour spectrum of the light, and applying a special coating to the glass, engineers at Osram were able to reproduce the light spectrum of moonlight for Katie Paterson's *Light Bulb to Simulate Moonlight* (2008). And the wasteful heat of their glowing filaments – one reason for their disappearance in this age of energy efficiency – is an intrinsic aspect of the viewing experience for Cerith Wyn Evans' *S=U=P=E=R=S=T=R=U=C=T=U=R=E* 'Trace me back to some loud, shallow, chill, underlying motive's overspill…' (2010): dazzling columns made of long glass tubes threaded from end to end with a hot filament.



Katie Paterson, *Light Bulb to Simulate Moonlight* (2008).

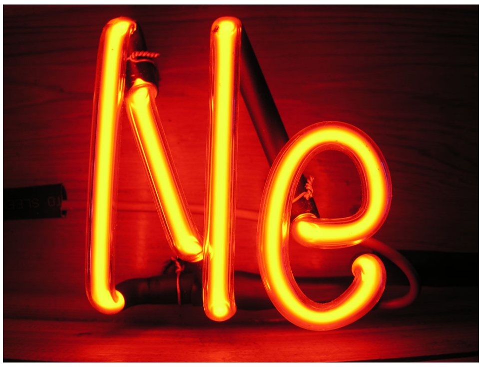
Cerith Wyn Evans, *S=U=P=E=R=S=T=R=U=C=T=U=R=E* (2010).

Science also benefited from the invention of the gas-discharge tube, the forerunner of the neon light. When an electrical discharge is passed through a gas (such as mercury or sodium vapour), electrons in the current may collide with gas molecules and excite them into emitting light of a colour characteristic of the elements in the gas. In the 1850s the German scientific-instrument maker Heinrich Geissler invented tubes that exploited this effect, producing richly coloured light sources that were sold for demonstrations to universities and schools. In some cases – for example, with argon gas and mercury vapour – the emitted light lies outside the visible range in the ultraviolet zone. Filling the tube with a liquid that fluoresces under ultraviolet irradiation, or coating the walls with a phosphor material that does the same, allows this 'black light' to be converted to a form visible to the human eye: this is a fluorescent tube. The latter approach was developed by the French physicist Edmond Becquerel to study fluorescence. The colour of the light can then be selected by choosing an appropriate phosphor.



Some of Heinrich Geissler's gas discharge tubes.

At the end of the nineteenth century the advantages of using so-called inert gases – helium and argon, but especially neon – in gas-discharge tubes become apparent. Neon was discovered in 1898 by William Ramsay and Morris Travers in London. Using gas-discharge tubes to study its properties, Travers wrote that 'the blaze of crimson light' from a neon tube 'was a sight to dwell upon and never forget'.[5] That was precisely what recommended this gorgeous orange-red glow for advertising signs and displays. The trouble was that neon was rare. Only when the liquefaction of air became an industrial affair, first by French inventor Georges Claude's company Air Liquide in 1902, did neon become readily available as a by-product. Claude (the 'French Edison') unveiled his large neon tubes in 1910. Three years later they were being used in advertising and signage, and in 1919 they lit up the entrance to the Paris Opera.



A neon discharge tube.

When Dan Flavin began to use fluorescent tubes in the 1960s, their commercial, ready-made aesthetic was part of the appeal, just as painters such as Frank Stella took to using industrial paints: the choice was a political statement, a challenge to authority and, given the standardisation of commercial products and the 'cool' quality of the fluorescent light, a depersonalisation of the artistic gesture. Flavin worked primarily with fluorescent tubes because he wanted a choice of colours – but he simply took these 'off the self' from what was available. That ready-made philosophy means that most of Flavin's works are composed of linear tubes, whereas the neon tubes used for commercial signage are typically customised: bent to form letters or images. Several artists who work with neon tubes – Joseph Kosuth, Bruce Nauman, Glenn Ligon, Tracey Emin, Cerith Wyn Evans – adopt the message along with the medium, spelling out glowing slogans that subvert, echo or even exploit the intimate association with advertising.

Quantum Light

The advent of light-emitting diodes (LEDs) in the 1950s and then the laser in the 1960s marked the capacity of advanced science at last to contribute substantially to the art of illumination. These devices can be understood, and thus designed, only using quantum physics, but the principles are not so different from the gas-discharge tube: electrical current stimulates the emission of light, with a wavelength (colour) determined by the chemical nature of the emitting fabric. In the late 1950s scientists discovered that the semiconductor gallium phosphide, laced with other elements, can be used in red-light LEDs – initially called 'crystal lamps' because the glowing component was crystalline. Tinkering with the chemical composition yielded green and yellow devices in the 1970s, while strong blue-light LEDs, made from gallium nitride, did not appear until the 1990s. LEDs not only may last longer than incandescent bulbs but use much less power – a valuable asset in just about any application.

Blue-light gallium nitride LEDs.

When LEDs became widely used in advertising billboards in the 1970s, artist Jenny Holzer appropriated the idiom in artworks that undermined the commercial-propagandist function of the medium: for example, in her use of a huge LED sign in New York's Times Square to broadcast the message 'PROTECT ME FROM WHAT I WANT'. Scrolling messages on LED displays have remained a signature feature of her work, but as LED technology shifted from bulb-like capsule units to miniaturised, flat devices, she made more use of bespoke polychromatic arrays that adapt to the surrounding architecture and bend in sculptural ways.

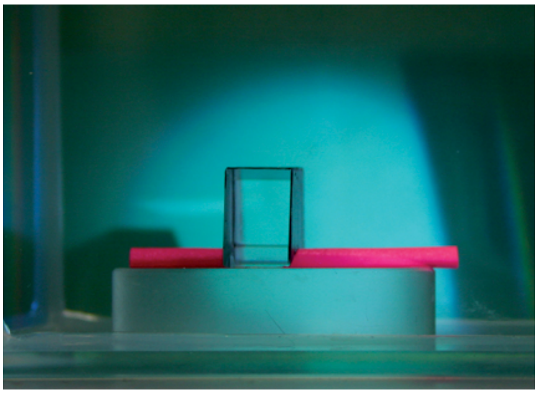
Jenny Holzer, *Monument* (2008).

The direct conversion of electricity to light in LEDs and lasers, without the intervention of heat, allows light technology to be miniaturised. Because they are small, robust, can be switched on and off almost instantly, and can be tailored to specific colours, LEDs have transformed display technology. The crystalline semiconductors in these devices can be expensive and brittle, and require high-tech processing methods. But over the past two decades LEDs have also been made from electrically conducting plastics that will emit light, which are flexible, cheap and easy to manufacture using printing technology. Plastic LED screens are now being commercialised for laptops and televisions, and their low cost, low power consumption and bendiness are sure to stimulate new uses: light-emitting textiles, paper-like screens with moving images, expansion into art, design and architecture.

The rapid electronic switching of LEDs and lasers also means that binary information – the currency of information technology – can be encoded in pulses of light, rather than the electrical pulses of silicon microelectronics. This is a major motivation for the recent growth of photonic technology, which introduces new methods of controlling and manipulating light. For example, photonic crystals – 'mirrors' made from tiny arrays of reflective objects, such as stacked microscopic beads, honeycombs of holes, or alternating layers of two materials – can contain light almost perfectly, leading to tightly-curved light channels and leak-proof optical fibres. Many of these tricks for controlling light are already used by nature: in, for instance, the brilliantly reflective wings of the Blue Morpho butterfly or indeed the peacock feathers that fascinated Robert Hooke. The uses of highly reflective and iridescent pigments with such layered microstructures have so far been confined to applications such as car paints; artists are just beginning to understand how to use these materials to guide light and blend colours.

The wing scales of the Blue Morpho butterfly contain microscopic structures that reflect blue light.

The new technologies of light go much further. It is now possible to subvert the laws of optics themselves: for example, artificial materials that can refract light 'the wrong way' or that can guide light rays along artfully curved paths that skirt an object – like river water running round a protruding rock – in effect rendering the object invisible. These 'invisibility cloaks' were first made for operating at microwave frequencies; now they work for visible light too. Even light itself is not immune to reinvention: quantum engineering that reconfigures the way light is absorbed and re-emitted as it travels through a transparent substance can effectively slow down light to a crawl, and even bring it to an apparent standstill – and even more extraordinary, can make it seem to exit a material before it even enters. Whether these tricks will find practical uses – storing information in arrested light pulses, for example – remains to be seen.



An ‘invisibility cloak’ made from a crystal of calcite, which hides a section of the roll of pink paper.

Trick of the Light

Art has always been beholden to technology to a greater extent than is commonly acknowledged, whether it be the glassmaking expertise that contributed to the manufacture of Egyptian faience, the pigment-making alchemy of the Middle Ages, or the invention of photography or of acrylic resins. In most such instances, the technologies themselves had other motivations; artists see opportunities that scientists and inventors rarely imagine, happily appropriating technical innovation, but also subverting and redirecting it. The technologies of light are no exception, and that is why advanced photonic engineering will surely enter the gallery.

But there are additional dimensions to this relationship. For one, light has a symbolic cultural resonance that science has not eroded, that indeed it even enhances as it offers new possibilities for luminal play and new insights into the nature of light itself. Through relativity, light becomes the determinant of time. Quantum engineering imbues light with information and meaning and makes old certainties – the path of a light ray – contingent. Moreover, light is not just about electromagnetism and photons, but about perception and illusion. There are many tricks of light, and they force us to question the relationship between the world that impinges on the senses and the world that the senses reconstruct from that stimulus. There is a science of *effect* that light mediates. And this is a part of what makes it, and has always made it, such a powerful medium for the artist.

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