Part I

Illumination: The History and Future of Physical Science and Technology

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A short history of light in the Western world[1]

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Omnis cognitio lux est.
A. Kircher, Ars Magna *(1671), p. 800.*

God looked at the first light and saw that it was good. Humankind has generally agreed. Light is associated with promising beginnings, the dawn, birth, daylight, the nourishment of body and soul, clarity of thought, transparency in purpose, and honesty in action. Its absence signifies the darkness over the deep, dungeons, the underworld, murkiness in reasoning, stealth, and death. Light enables work, promotes safety, and cures ills; darkness is the domain of bats and criminals. Artificial lighting, which prolongs the day, ranks with agriculture at the top of the benign inventions of humankind.

We must not allow the sublimity of the subject to blunt our scientific objectivity. The appearance of comets on dark nights used to terrify multitudes; flashes of lightning still do, and rightly so. Staring at the Sun will blind you; baking in its rays can give you cancer. A laser can destroy as well as save your vision. Too much light ruins a dinner party. Furthermore, as we know from myth and scripture, humankind bought what illumination it has acquired at the cost of terrific pain and suffering. Prometheus paid for his gift of fire with his liver. The entire human race paid for the instruction of Adam and Eve by the forfeiture of paradise.

Further to its dark side, light gives rise to controversies. Physicists have quarreled about it for ages. Aristotle said that light is "the activity of what is transparent so far forth as it has in it the determinative power of becoming transparent," which is anything but transparent [1]. The atomists believed that light consists of particles, the stoics that it consists of waves. The scientific revolutionaries of the seventeenth century agreed no better. Descartes considered light a pressure in an ether when he did not describe it as a stream of billiard balls. Huygens made light a longitudinal wave. Newton's light particles, like Newton himself, were subject to periodic fits. Then came Young and Fresnel, with transverse waves in an ether as rigid as steel; Maxwell, with electromagnetic waves in a mechanical ether; Lorentz, with electromagnetic waves in a non-mechanical ether; Einstein, with particle-waves; and

[1] This is a revised version of an after-dinner talk on the first evening of the *Amazing Light* symposium in honor of Charles Townes (http://www.metanexus.net/fqx/townes/). The editors have allowed me to retain the tone of the talk, but not the many accompanying slides; in compensation, I have added references to their sources and to direct quotations.

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Bohr, with a relationship with a detector, wavelike or particle-like at the discretion of the experimenter.

Since the record shows so clearly that we cannot depend on physicists to give us the true character of light, I will follow the safer method of historians. They still believe in cause and effect and aim at something beyond truth – that is, *lux veritatis*, "the light of truth" [2]. So much is easy to work out. It is harder to say when the history of light began. Up-to-date cosmologists now place its birth date at 13.7 billion years BCE, but they keep changing their minds. Anyway, it is too long a time to cover in a chapter. We can easily cut it down by a factor of three million by using the date proposed by Archbishop James Ussher in the seventeenth century and retained long past its sell-by date by contemporary creationists. On this reckoning, God ushered in the world (that is the very word Archbishop Ussher used, apparently confusing himself with his creator) and light on October 21, 4004 BCE at six o'clock in the evening [3].

Even on Ussher's abbreviated scale, I do not have enough time to give a full account of light and its interactions with humankind. That is no problem: the historian is used to boiling down oceans of detail to a few exemplary liters. In the history of light that we are about to imbibe, the labels on the liters are (1) God's sign, (2) Fate's herald, (3) Cosmology's witness, (4) Europe's servant, and (5) Townes's slave.

1.1 God's sign

The oldest certain event in the history of light occurred in its 1,656th year. God had just drowned everything. The ark lay beached on Mount Ararat. God took pity on the wet remnants of the human race and promised not to drown it again. Here is how light came in:

> I do set my bow in the cloud, and it shall be for a token of a covenant between me and the earth. And it shall come to pass, when I bring a cloud over the earth, that the bow shall be seen in the cloud . . . I will look upon it, that I may remember the everlasting covenant between God and every living creature of all flesh that is upon the earth [4].

The awe tinged with fear inspired by the rainbow shines forth from many depictions of it in religious art. Christ often appears sitting on a rainbow while dropping the damned into the fiery pit. According to the Archangel Michael, the covenant certified by the "bow/Conspicuous with three listed colors gay" referred only to destruction by water. God reserved the right to annihilate again, by fire:

> Day and night,
> Seedtime and harvest, heat and hoary frost
> Shall hold their course, till fire purge all things new,
> Both heav'n and earth, wherein the just shall dwell [5].

The great west window of Fairford Church in Gloucestershire, the only parish church in England with all its medieval stained glass still intact, gives a good idea of the purging presaged by Michael. A red-hot Earth serves as Christ's footstool. He sits on a bow with three arches colored blue, orange, blue, an indication that something unusual is at hand.

The rainbow appears as an ambiguous sign, convex to the blessed above, concave to the damned below, a symbol of the good and evil that brand the human condition [6–9].

A few bold and, some think, insensitive souls divined in the apparently capricious bow some indications of law and order. These souls belonged to geometers. According to John Ruskin, the effete Victorian art historian, anyone who could calculate a rainbow could not appreciate it: "I much question whether anyone who knows optics, however religious he may be, can feel an equal pleasure or reverence which an unlettered peasant may feel at the sight of a rainbow" [10]. He was not the first such questioner. "There was an awful rainbow once in heaven," wrote Keats, but it appears no more. Physicists have seen to that:

> We know her woof, her texture; she is given
> In the dull catalogue of common things.
> Philosophy will clip an Angel's wings,
> Conquer all mysteries by rule and line,
> Empty the haunted air, and gnomèd mine –
> Unweave a rainbow [11].

There are various ways to experience the sublime, however. François d'Aguilon, the author of one of the very first optical treatises, which had the distinction of plates designed by Peter Paul Rubens, made a beautiful parallel between ways of receiving light and ways of knowing God. The blessed can experience his overwhelming light directly; those favored by grace can see Him reflected in His works; while most peasants, geometers, and art critics must be content with broken images, as if produced by refraction, and "the light of nature alone" [12].

The foremost of those who worked by the unaided light of nature was Aristotle. He knew that the Sun, the observer, and the center of the bow lie on a straight line, and that the bow's center can never be above the horizon [13]. Scholastic philosophers inspired by him, and by the metaphysics of the light that lit up their cathedrals, developed these hints. Among them was the Franciscan monk Roger Bacon. Following some sublime remarks about light and the covenant and many digs at fellow philosophers, he confided to his famous *Opus Maius* the uplifting observation that the maximum height of the rainbow above the horizon is 42 degrees [14–16]. Would it be too much to say that his combination of reverence, assertiveness, and inquisitiveness has characterized much of the life of science? Or that apparently trivial facts, which at first fit nowhere within received wisdom, may be keys to new kingdoms? That was the case with Bacon's 42 degrees.

Isaac Newton first saw the light in December 1642. Note the ominous recurrence of the number 42. Thirty years later he explained the colors of the rainbow. The famous lines of Alexander Pope,

> Nature and Nature's laws lay hid in night
> God said, Let Newton be! And all was light [17],

agreed perfectly with Newton's own estimate of his achievements. He rated his discovery that white light is not pure but a mixture of lights of different colors as "the oddest if not the most considerable detection which hath hitherto been made in the operations of

Nature" [18]. The detection gave the longed-for explanation of the order of the colors of the bow. Newton had not discovered its geometry, however, namely the tracing of rays through droplets that refract, reflect, and focus sunlight into rainbows. That had been worked out shortly before Newton's birth by the author of Cartesian geometry, the "very Secretary of nature," René Descartes, before whom all other philosophers were "mere shrimps and fumblers" [19]. Descartes had derived Bacon's 42 degrees using only Snell's law and the value of the index of refraction of water [20].

These discoveries of the optical operations of the Deity were recorded in an up-to-date version of the Bible published in the 1730s. This was the work of the Swiss-German naturalist Johann Jacob Scheuchzer, and it taught the latest knowledge of nature via a thousand magnificent illustrations dispersed through three folio volumes. The opening spread, to accompany the text "Let there be light," illustrates the latest Copernican cosmology and several discarded world systems. The works of the fourth day, when the Sun and Moon were ushered in, give the theory of eclipses and lunar phases. Scheuchzer devoted two dozen plates to Noah's adventures. They begin with a possible naturalistic origin of the flood in an encounter with a comet, end with the rainbow (Fig. 1.1), and include a course on fossils as "vestiges of the deluge" [21].

Scheuchzer took the idea of a collision with a comet, whose wet tail soaked the Earth after its hard head had broken open the barriers to the waters in the abyss, from Newton's successor at Cambridge, William Whiston. It was one of four consequential cometary encounters in Whiston's cosmology. The first occurred when God bound a comet into tight solar orbit and so created the Earth; the second tilted the Earth's axis as a punishment for Adam's meal of enlightenment; the third caused the Flood; and a fourth will eventually strike the Earth head on, burn it to a crisp, and send it into a very eccentric orbit. In its travels it will experience blazing heat and unspeakable cold, making it a perfect hell [22].[2]

To Whiston and Scheuchzer, religion and science properly construed not only did not oppose but actually reinforced each other. Scheuchzer undertook the immense expense and labor of his *Physica Sacra* to spread these tidings to his conservative fellow citizens in Zurich and even beyond. Many people down to our time have found their religion and their science to be mutually supportive. A notable example was that one-man university, Father Guillaume Pouget, of the order of Lazarists. He taught exegesis, apologetics, history, Hebrew, mathematics, and physics at about the time of the discovery of relativity. Once, while serving mass, the pious Pouget stopped, awestruck by a shaft of light. An acolyte later asked him whether he had stopped because he had seen God. Not quite, Pouget replied: "[T]he sun was falling on the paten and I caught myself calculating the angle of reflection" [23].

The grand and awesome rainbow is but one of the marvelous apparitions formed by the play of light in the atmosphere. Perhaps the oldest, which dates from the Fourth Day of Creation, is sunset. Somewhat later came the aurora borealis; its study has produced not only feelings of the sublime, but also much valuable information about the solar wind and the Earth's magnetic field. I would not be doing light justice without mentioning that it

[2] The book was dedicated to Newton.

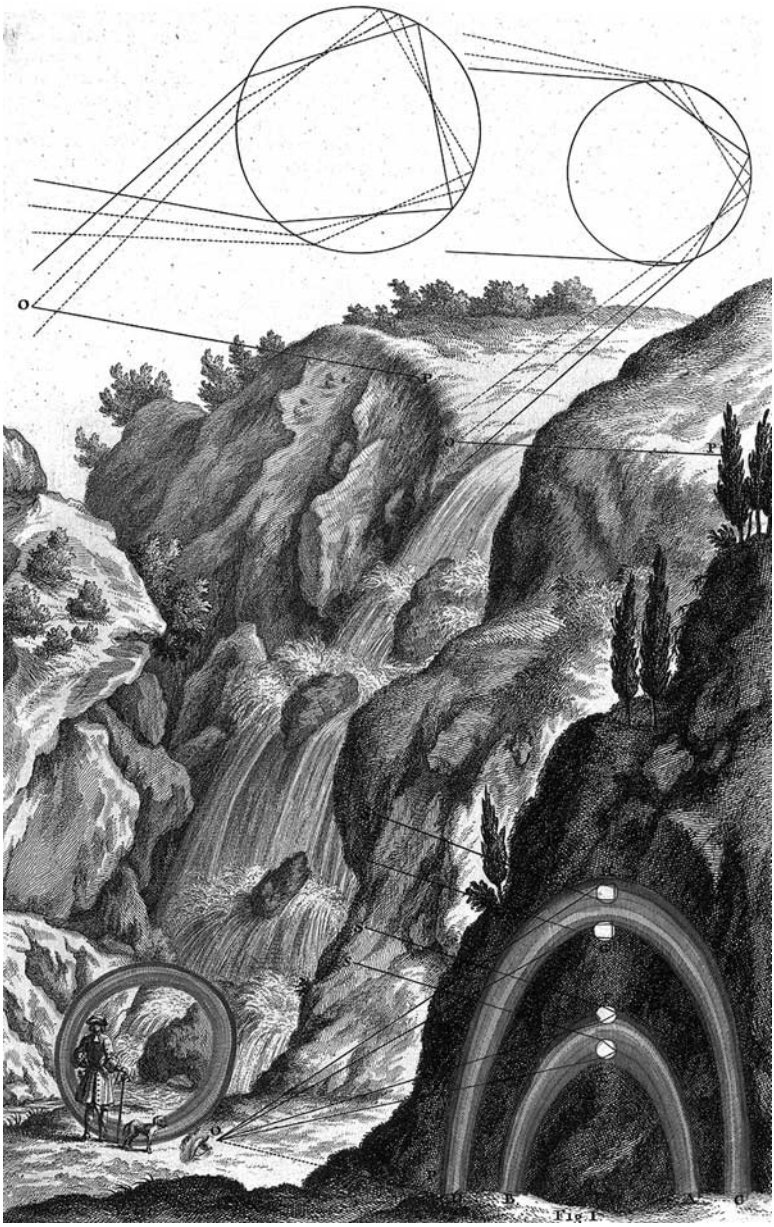

Fig. 1.1. The geometry of the covenant according to the optical theories of Descartes and Newton. Scheuchzer, *Physica Sacra*, Vol. 1 (1731), plate 66. Courtesy of the Beinecke Library, Yale University.

Fig. 1.2. The perplexed physicist. Albrecht Dürer, *Melencolia I* (1514). Private collection.

has a "lighter" side, as in mock Suns, halos, and the scary Brockengespenst, in which the observer's shadow, projected on a snow sheet, appears as a glorified ghost. According to a recent expert, no single intuitive theory of such glories exists: perhaps there is still some good physics to learn from the direct lights of nature [24].

1.2 Fate's herald

While light in the guise of a rainbow generally indicated good will, light in the guise of a comet almost always announced disaster. In Albrecht Dürer's famous *Melencolia*, the comet outshines the bow and lights an eerie scene cluttered with symbols of despondency (Fig. 1.2). The staring winged figure, compass listlessly in hand, has come upon a problem

that exceeds her angelic strength, perhaps in string theory, and she is peevish; behind her a small graduate student, unaware of the deep difficulties that have stumped his *Doktormutter*, cheerfully scribbles at his dissertation.

Inducing melancholy was feeble work for comets. More usually they heralded war, pestilence, and famine. A comet that appeared just before the Battle of Hastings, immortalized in the Bayeux tapestry, foretold the defeat of one of the armies. In the coy way of oracles, it did not identify which of them. An astrologer could be certain of success in foretelling a disaster (literally, a malevolent stellar influence) from the presence of a comet; indeed, the cornucopia of calamities in early modern Europe gave an *embarras de choix*.

During the unhappy century of the Protestant Reformation, in 1577 to be exact, a comet accurately foretold the collapse of an entire world system. This was the comfortable, reasonable, Aristotelian scholastic universe, in which the luminaries and the planets circle the central, stationary Earth. In this standard model of medieval times, the Moon and the heavens above it are made of a material and quality not found on our globe; here lies the region of generation and corruption, of irregular motion, of the four elements; there extends the firmament of perfection, of regular motion, of celestial light, and of the fifth element or quintessence. Since comets come and go, they must, in this model, spend their lives below the Moon. Indeed, they could appear uncomfortably close to Earth before city living and light pollution destroyed our intimacy with the night sky [25].

The comet of 1577 not only foretold, but also helped effect, the demise of the Aristotelian world system. Observations by Tycho Brahe and others, using the improved instruments of the time, indicated that it had no parallax and thus stood above the Moon, in the region of the stars and planets. That suggested that comets too might be recurrent, and no more menacing, astrologically speaking, than any other celestial body. By the end of the seventeenth century, cometary light no longer gave fright to people in countries where modern science had taken root. This pacification was not the work of science alone, however, but of science and its sometime partner the military. On the side of science stood Isaac Newton, Edmund Halley, and the excellent observations made all over Europe on the comet of 1682. With this information and Newton's equations, Halley confirmed that comets were recurrent visitors, not one-time messengers, to the solar system. He identified earlier appearances of the comet of 1682 and foretold the next, which took place as he prophesied [26].

As they became naturalized in the heavens, comets and their co-inhabitants, the stars and planets, gradually lost their astrological significance. Here is where the military came in. The astrologers engaged on both sides of the big wars of the seventeenth century – the Thirty Years' War and the English Civil War – identified too strongly with their employers. Against best practice, they made the unforgivable error of specifying the victorious side in their prophecies. The failure of their predictions, together with the arguments of astronomers, destroyed confidence in astrology. The collapse was catastrophic – from the point of view of the astrologer [27].

Cometary astrology became a subject of fun, especially among political cartoonists. In a representative English example published during the Napoleonic wars, a comet rises

above France (identified by a frog in the landscape) and flies toward the resplendent Sun, containing the effulgent head of the great benefactor of America, George III. John Bull observes it all and mutters through his telescope

> Aye, aye, Master Comet – you may attempt your Periheliums or your Devilheliums for what I care but . . . you'll never reach the sun (pictured in Ref. [25], p. 147).

Here old John missed a metaphor by forgetting Newton's theory that the Sun maintained its light by swallowing comets.

When Halley's comet returned in 1835/36 for the second time after he had worked out its orbit, it was exploited as a symbol of faithfulness. Demoted to a valentine, it appeared frequently in love-ins with cupids (see Ref. [25], p. 187). Astronomical calculations and valentines have not pulled all the teeth from comets. Halley and Newton agreed with Whiston that comets participated in the Creation, caused the deluge, and will, in the grand final conflagration, smash and scorch the Earth. Meanwhile, the Berkeley method of extinguishing dinosaurs and photos of comets plunging into Jupiter have shown what collisions with interplanetary debris can accomplish, and the mass suicide of the cult of Heaven's Gate occasioned by the appearance of Comet Hale–Bopp in 1997 demonstrates that a bearded star need not hit us to precipitate a tragedy [28].

Before leaving scary lights in the sky almost tamed by science, I must mention lightning. The early modern defense against it was to ring church bells to break up thunderclouds. That was not wise: the ringing annihilated the ringers, not the clouds, because church towers in exposed positions often offered the best local path to ground via metal bells, wet ropes, and perspiring bell pullers [29]. Benjamin Franklin's proposal to deflect the ferocious light of lightning, the thunderbolts of the gods, with a puny spear or two mounted on a roof and wired to the ground, seemed preposterous to Europeans, as did the flying of kites to demonstrate the identity of electric sparks and lightning bolts. Cartoonists and couturiers introduced a lightning bonnet, trailing a wire to ground high-born ladies (Fig. 1.3(a)), and then, when gentlemen complained of being unprotected, a lightning umbrella with a spike and an earthed rib (Fig. 1.3(b); [30]).

By the early nineteenth century, the principle of lightning rods was widely understood and accepted, together with the implication that electricity plays a major part in the economy of nature. For much of the Age of Enlightenment, however, and in many parts of Europe, bell pullers died at the same rate after Franklin's invention as before. As I need not tell you, good scientific advice does not always prevail with the church or the state. Several thousand structures still suffer lightning damage every year in the United States [31].

1.3 Cosmology's witness

The rainbow, the comet, and lightning were romantic and noisy employments of light's adolescence. When it reached the age of 3,000 or so, it took up the more sedate occupation of informing the then new race of European astronomers about the firmament. As a

(a)

Fig. 1.3. Lightning fashion around 1780. From Figuier, *Merveilles*, Vol. 1 (1867), pp. 569 and 597.

consequence, the Greeks devised intricate geometrical schemes to describe the apparent motion of the planets and luminaries, without freeing themselves, however, from the all-too-human error of thinking that they occupied the center of the universe. Their astronomy and much of their philosophy disappeared from Europe with the collapse of the Western Roman Empire. Historians call the following centuries the Dark Ages.

The lights went on again in the twelfth century when the West recovered the learning of the ancients as improved by the Arabs and combined it with Christian faith in the vast