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An Historical Survey on Light Technologies

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ABSTRACT Following the celebration of the International Year of Light and Light-based Technologies in 2015, this paper presents a survey of the exploitation of light throughout our history. Human beings started using light far into the Stone Age, in order to meet immediate needs, and widened its used when ancient civilizations developed. Other practical uses were conceived during the Middle Ages, some of which had a deep impact on social life. Nevertheless, it was after the Scientific Revolution and, to a wider extent, with the Industrial Revolution, that more devices were developed. The advancement of chemistry and electricity provided the ground and the tools for inventing a number of light-related devices, from photography to chemical and electrical lighting technologies. The deeper and broader scientific advancements of the 20th century, throughout wave and quanta paradigms and the research on the interactions with matter at the sub-atomic level, have provided the knowledge for a much broader exploitation of light in several different fields, leading to the present technological domains of optoelectronics and photoelectronics, including cinema, image processing, lasers, photovoltaic cells, and optical discs. The recent success of fiber optics, white LEDs, and holography, evidence how vastly and deeply the interaction between light and man is still growing.

INDEX TERMS Camera obscura, LED, light technologies, lighting, photography, CRT, photovoltaic devices, optoelectronics, photoelectronics.

A preliminary version of this paper was presented at the HISTECON 2015 Conference in Tel Aviv in August 2015, on the occasion of the International Year of Light and Light-based Technologies in 2015 [1]. The present paper constitutes a deepened and extended presentation of the subject.

I. EARLY USES

A. ILLUMINATING THE DARKNESS

The first use of a light other than sunlight was made by humans quite different from us. Paleontologists discovered that this happened 1.5–0.5 million years ago, far back in the Stone Age, when *Homo erectus* learned to conserve fire and used it for protection from cold and predators and for lighting the darkness of the night, thus promoting socialization among clan individuals gathered thereabout [2]. For reasons strictly related to his technology, based notably on stone, he is considered a human, not just a hominine, and the conservation of fire that he practiced so far ago constituted the light technology which endured for the vast majority of human history. Around 100–50 thousand years ago, *Homo sapiens* was capable of starting fire at will. Apart from bonfires, for thousands of years the only sources for lighting the dark of night were torches and lamps fed with fuels such as vegetable or animal oil (Fig. 1), which were used to illuminate dwellings and palaces of ancient and classical civilizations, allowing a rich social life after dusk [3].

FIGURE 1. The Lascaux Lamp is a stone-engraved oil lamp used about 17,300 years ago during the Upper Paleolithic by men inhabiting the Lascaux Cave in Southern France, famous for its magnificent wall paintings. (Photo by Sémhur on Wikimedia Commons).

Cheap tallow candles had been broadly used since Roman times, and became an important source of light in the Middle Ages, in spite of their terrible smell. In China, candles made from whale fat were employed from the third century BC, and fragrant beeswax candles are supposed to have been made for the Chinese elite since the Tang Dynasty in the seventh century AD. An advanced lighting system that consisted of natural gas collected in wells and carried indoors through bamboo piping was used in restricted areas of China in the mid fourth century AD [4]. The use of whale oil had a major boost from the sixteenth century, when it became a lucrative fuel that pushed European nations to ruthless whaling in the northern Atlantic, often in harsh competition. This activity continued, even expanding into other oceans, well into the nineteenth century, as Melville's Moby Dick recounts [5].

B. EARLY OPTICAL INSTRUMENTATION

As far as we know, lenses were the first optical tools. The polished-crystal Nimrud lens (38 mm in diameter), now at the British Museum in London, was made by Assyrians in the Near East in the late eighth century BC, and magnifying meniscal lenses are described in Egyptian hieroglyphs of the fifth century BC. About at the same time, Chinese scholar and philosopher Mozi (or Mo Tzu, ca. 470–ca. 391 BC) observed that what we now call a pinhole *camera obscura*flips images upside down, deducing that light travels along straight lines (Fig. 2) [6]. In the following century in Ancient Greece, the same observation was made by the mathematician Euclid (ca. 367–283 BC), who reported it in *Optics*, the first systematic investigation on light, whereas Aristotle (384–322 BC) used a *camera obscura* in observing a solar eclipse.

FIGURE 2. **The image of the New Royal Palace at Prague Castle (size approx. 4 × 2 m) created on an attic wall by a hole in the tile roofing. The inversion of the image was initially observed inside a dark room (*camera obscura*, in Latin), provided by a small hole in a wall (Photo by Gampe on Wikimedia Commons).**

Practical uses of sunlight other than lighting were first reported by Greek authors. According to historian Polybius, Aeneas Tacticus, a military engineer of the fourth century BC and the earliest Greek writers on the art of war, invented a vision-related system for military communications, the so-called hydraulic telegraph, capable of transmitting pre-defined messages at a distance. Burning mirrors, typically made of bronze, have been traditionally attributed to Archimedes (ca. 287 BC – ca. 212 BC) at the time of the Second Punic War (214–2 BC). Even if it is questioned whether they could actually set fire to Roman triremes, the fact that Theophrastus had already described them some 90 years before [7], as also did Ibn Sahl in the tenth century AD and other authors, is a clue that they could really work. Such devices were made of bronze, not of glass. Higher fusion temperatures allowed the production of early transparent glass and the invention of glassblowing in Roman Syria around 20 BC, which opened the door to new uses of light and allowed the production of ampoules which, filled with water, were used by Roman scholars in early systematic investigations of magnification and light reflection. However, optical technology was still very rudimentary, and it took several centuries to develop them into useful technologies, other than the earliest glass windows and cheap housewares flanking terracotta [8]. In fact, the Alexandrine astronomer Claudius Ptolemy (AD 90–168), who wrote of reflection, refraction, and colors in his Optics [6], resorted to naked-eye observations to develop his geocentric universe model, which dominated for fifteen centuries, until the Scientific Revolution.

C. MEDIEVAL NON-LIGHTING DEVICES

Centuries later, Muslim scholars al-Kindi (Latinized Alkindus, ca. AD 801–873) and Ibn Sahl (ca. AD 940–1000) in Baghdad used curved mirrors and lenses to study the reflection of light, and to anticipate Snell's refraction law of 1621. Al-Haytham (Latinized Alhazen, AD 965–1039) ground lenses and curved mirrors and made a pinhole *camera obscura*, which he used in his investigations, and suggested its use in the observation of solar eclipses. He was the first to provide a clear explanation of the device's operation and his *Book of Optics* (*Kitab al-Manazir* in the original Arabic), a treatise in seven volumes written between 1011 and 1021, remains a milestone in optics [9].

Almost at the same time, the effect of the *camera obscura* was also studied in China. Duan Chengshi (d. 863) mentioned the image inversion effect in *Miscellaneous Morsels from Youyang* around 840 AD during the Tang Dynasty, and Shen Kuo (1031–1095) was the first to approach it with geometrical and quantitative concepts in *Dream Pool Essays* written in 1088 AD, under the Song Dynasty.

It the Near East, Al-Haytham's book was influential to many Arabic scholars and, after a Latin translation during the twelfth century, to Western science, at a time when it was starting to revive [10]. Roger Bacon (ca. 1214–1292), an English Franciscan who studied light, reflection, and lenses, used a *camera obscura* to observe solar eclipses. German Dominican friar Theodoric of Freiberg (ca. 1250–ca. 1310) and Persian Kamāl al-Dīn al-Fārisī (1267–1319) independently performed experiments with glass globes filled with water to simulate water droplets suspended in air to deduce that refraction of sunlight in raindrops is the effect responsible for the shape and colors of the rainbow, thus anticipating Newton's results of 1666 [11].

Glass-making advanced in the western world in the in the eleventh century, with the the substitution of soda with more accessible potash in Northern Europe and early slabs obtained from blown glass in Germany. In the twelfth century, stained glass was produced, notably enriching gothic cathedrals such as Saint Denis and Chartres. Eyeglasses for presbyopia were invented in northern Italy around 1290 and soon developed in Venice, producing a major social impact because they allowed the extension of the productive life of elder people [12] (Fig. 3). In the fourteenth century, Venice started producing early European glass mirrors, and improved transparent glass windows. Eyeglasses made with concave lenses, for myopia, were introduced in the fifteenth century by Nikolaus von Kues Krebs (Nicholas of Cusa, 1401–1464), a German clergyman and scientist who was one of the major scholars of the time, and had an important political role in the Roman Catholic Church.

FIGURE 3. First depiction of glasses, used by Cardinal Hugh of Provence. Detail of a fresco by Tommaso da Modena in the Dominican Chapter of the church of St. Nicholas in Treviso (Italy), 1352. (Photo by the author).

D. EARLY MODERN AGE DEVICES

During the Renaissance, the *camera obscura* was accurately described by Leonardo da Vinci (1452–1519) in *Codex Atlanticus* (around 1515), and was used by German artist and theorist Albrecht Dürer (1471–1528) and Dutch polymath Gemma Frisius (1508–1555). Italian polymath Gerolamo Cardano (Cardan, 1501–1576) provided it with a biconvex lens in place of the pinhole, and Venetian Scientist Daniele Barbaro (1514–1570) complemented it with a diaphragm. The latter described the device in *The Practice of Perspective* (*La pratica della prospettiva*, in Italian, 1569), in the framework of studies on perspective, which was then booming in figurative arts. Another Italian, Ignazio Danti (1536–1586) added a concave mirror to flip the reversed image in 1573. Soon afterwards, the Neapolitan polymath Giambattista della Porta (1535–1615) made the *camera obscura* popular with *Natural Magic* (*Magia Naturalis*, in original Latin, 1584) to the point that it became a common tool of many artists for achieving precise pictorial compositions. Most likely, they included the Dutch master Johannes Vermeer (1632–1675) (Fig. 4) and, for sure, the Italian Giovanni Antonio Canal (Canaletto, 1697–1768), whose original device is preserved at Museo Correr in Venice, whereas the device of the English Joshua Reynolds (1723–1792) is now at the Science Museum in London. The pinhole *camera obscura* was also studied and used by German Johannes Kepler (1571–1630) in the framework of his investigations on eclipses, the intensity of light, parallax, and the apparent size of far bodies, and also in land surveying, as advised by Friedrich Risner (1533–1580) and Athanasius Kircher (1601–1680). A reflex device, provided with a flat mirror at 45° that deflected the image upwards, was presented by J. C. Sturm (1635–1703) in 1676 and compact portable *camerae obscurae* were conceived by Johann Zahn (1641–1707) of Germany, who described them in *Oculus Artificialis* (1685), together with other optical instruments.

FIGURE 4. Art critics argue that the exceptional accuracy of proportions of paintings like *The Astronomer* by Johannes Vermeer, ca.1668, have been achieved thanks to a *camera obscura*. (Photo in public domain - Wikimedia Commons).

Developments in lens technology led to the invention of the microscope (1595) and the refractor telescope (1608), which enabled key discoveries of the Scientific Revolution. Both these compound instruments were reputedly developed in the Netherlands, resorting to combinations of lenses, by Zacharias Janssen (ca.1580–1638), the latter being also attributed to German-born Hans Lippershey (1570–1619) and Jacob Metius (1571–1624). However, these instruments have an Italian origin, attested by *Photismi de lumine et umbra* (1521) and *Diaphana* (1552) by Francesco Maurolico (1494–1575), and *De reflectiones optices* (1589) by Giovanni Battista Della Porta. As a matter of fact, the manufacturing of lenses was introduced in the Netherlands by Italian craftsmen who emigrated there around 1590, and a 1634 document reports that the first Dutch telescope was built in 1604, imitating an Italian model of 1590. By using a self-made telescope, Galileo Galilei (1564–1642) revolutionized astronomy starting in 1609. Although his observations had been anticipated by some months in England by Thomas Harriot (1560–1621), it was for Galileo's instrument that the name was coined in 1611. Early microscopes paved the way for the investigation of the extremely small world, and it was again for Galileo's perfected self-made instrument that the name was coined in 1624.

Some forty years later, in 1666, Isaac Newton (1642–1727) carried out experiments with prisms which allowed him to discover the spectrum of sunlight. After investigating the chromatic aberration of lenses, he conceived the reflecting telescope (1668), first reporting his results in 1672 and finally publishing them in *Opticks* in 1704. The instrument was perfected by James Short (1710–1768) in 1740, by adopting a parabolic mirror so as to focus all rays on one point. A long series of successive developments, of which a description is out of the scope of this paper, led to extremely complex optical instruments, such as the Hubble Space Telescope, launched in 1990.

II. INDUSTRIAL CHEMISTRY AND LIGHT

A. GAS LIGHTING

During the Industrial Revolution, coal was the strategic energy resource not only for providing mechanical energy through the steam engine, but also in iron and steel making, that required a pretreatment for converting coal into coke [13]. A by-product of the process, coal gas, opened the door to the development of industrial lighting [14]. The first experimental gas-light plant was installed by Jean-Pierre Minkelers (1748–1824) in his laboratory at the Collège du Faucon of the University of Leuven in 1784. A few years later, Philippe Lebon (1767–1804) developed experiments with wood gas in France between 1792 and 1801, but his demonstrations did not capture the attention of the revolutionary government, at that time more interested in warfare technologies. One of these was the optical telegraph, invented by Claude Chappe (1763–1805) in 1792. It was based on devices dubbed semaphores (i.e. sign bearers, from Greek roots), provided with articulated arms to be shaped according to the letters to be conveyed. These semaphores were installed on towers built within visual distance of each other to receive and retransmit the message. It was the first modern telecommunication system, and provided a strategic advantage during the Napoleonic Wars.

FIGURE 5. A satirical cartoon with passengers watching the early public gas lighting in London, 1807. It proves the sensation produced by the system. (Photo in public domain - Wikimedia Commons).

The first British gas plant, that used coal gas, was built by William Murdoch (1754–1839) for lighting his house in 1792. Ten years later, he and Samuel Clegg (1781–1861) installed a gas light plant in the Boulton-Watt foundry where they worked. They found a competitor in Fredrick Winsor, a German-born Englishman (originally Winzer, 1763–1830), who in 1804 installed the first gas lighting of a public building in the Lyceum Theatre in London [15]. The system became public three years later, with the plant installed by Winsor in Pall Mall, central London (Fig. 5). In 1812, Winsor and Clegg formed a company that started developing the first commercial lighting network in London two years later. Designed using the model of water supply, it featured a centralized large coal-gas generator, with pipe distribution to supply the consumers' gas-flame lamps, which provided the light of about 15 candles, feeble only by present standards. The piping in London soon spread to 42 km, and in a matter of a few decades gas lighting bloomed in several cities in Europe (in France, Belgium, Germany, Russia, ...) and America, for both private and street uses, because of its competitive cost that allowed savings of about 75% compared to oil lamps and candles. For more than a century these plants were fed by coal gas, and natural gas came into use only later. Low-cost artificial light had a significant impact on social life and industrial organization. It made the city streets much safer at night, allowing nightlife and social and cultural events to flourish. It also made viable much longer work hours in offices and factories in the wintertime, allowing a production increase. On the other hand, in spite of various technological improvements, some risks of explosion due to the piping technology of the time remained and toxicity from combustion products persisted in indoor use, together with

FIGURE 6. A pubic lighting system consisting of lamps with six gas mantles is still visible in present-day Lübeck, Germany. (Photo by the author).

FIGURE 7. The Branobel Company of the Nobel brothers owned the oil derricks in the Balachany field (near Baku, Azerbaijan, end of the nineteenth century). At that time, drilling was mainly devoted to producing kerosene for lighting, and the size of the plants suggest the economical relevance of the enterprise. (Photo courtesy of Tekniska Museet on Wikimedia Commons).

soot deposits. They were partially reduced by the commercial version of the laboratory Bunsen burner, introduced around the middle of the century, that allowed better gas combustion. A major advancement consisted of the gas mantle, invented in 1885–1991 by Austrian chemist Carl Auer von Welsbach (1858–1929), Bunsen's student, which consisted of a metal nitrates net that catalyzes gas combustion, allowing a white light of about 100 candles, much brighter than free flame. It gained widespread success for street lighting in the early nineteenth century (Fig. 6), but at that time, electric light had already begun its relentless spread. The mantle is still used in camping lanterns. Gas grids were profitable in cities where many consumers could be reached with relatively short piping. In rural areas and small towns, candles and much cheaper oil lamps remained the most viable sources of light, and in the first half of the nineteenth century whale oil was still vital for fueling them.

B. KEROSENE

The industry of crude-oil extraction grew quickly after the invention of the processes for deriving kerosene (paraffin, in British English) from petroleum in 1853–1855 and early successful drillings in Europe and America (Baku in Azerbaijan, Galicia in Poland, Hannover in Germany, Ontario in Canada, France, Romania, Titusville in Pennsylvania, . . .) in the period 1846–1859 [16]. Ten million 360-pound barrels per year were extracted in Pennsylvanian by 1874, although the main world producer was the area of Baku. The Nobel brothers amassed a fortune with their Branobel Company, which drilled there and produced kerosene using the continuous cracking patented by Alfred in 1881 (Fig. 7). They were not the only people to become rich on oil. John Davison Rockefeller (1839–1937) founded Standard Oil in 1870 and, thanks to the booming market and unconventional management methods, he became the richest man in the world in a matter of few years. Behind this success was the substitution of whale oil with cheaper kerosene for lighting, not the sale of gasoline (petrol in British English). There was basically no market for it because the internal combustion engine with a carburetor had not yet come to an industrial reality. Gasoline was deemed a dangerous by-product usually released into rivers.

Besides gas and kerosene, chemistry produced other lighting technologies during the nineteenth century, which found some success in specific niches, including limelight, which enjoyed widespread use in theater stage lighting, and acetylene lamps, which were employed in the later years of the century in domestic lighting, in lighthouses, and in car and bicycle headlights.

C. PHOTOGRAPHY

In the nineteenth century, progress in chemistry made possible the recording of images captured with the *camera obscura*, transforming it into a camera. After photosensitive salts were produced, Joseph Niépce (Nicephore, 1765–1833) obtained the first photographic image in 1822, with an exposure time of about eight hours. Seven years later he formed a company with another Frenchman, Louis-Jacques-Mande Daguerre (1787–1851) [17]. In 1831, the latter produced a more advanced photographic emulsion, based on iodized silver and capable of much shorter exposure times, namely 20–30 minutes, and then developed final treatments with sodium chloride (1837) and sodium thiosulfate (1839) to fix the image, thus creating the photographic process suitable for practical use that was dubbed the daguerreotype (Fig. 8). The word photography was coined about at the same time, merging two Greek roots meaning writing with light. Each image, impressed on a glass plate coated with the photosensitive emulsion, was unique, as in the case of painted pictures. Although those early emulsions required very long exposures and only allowed black-and-white images of a poor

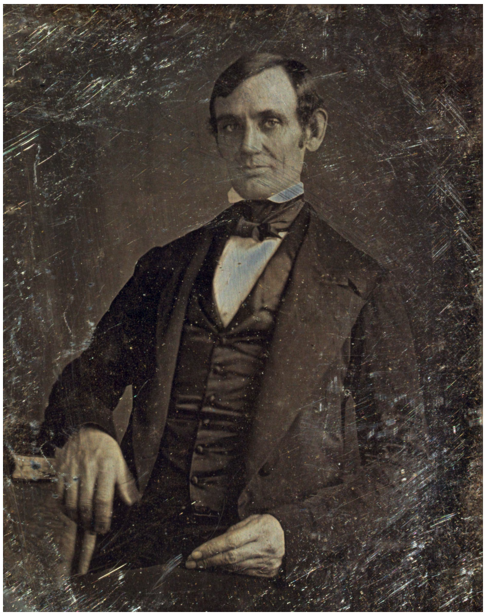

FIGURE 8. Daguerreotype of Abraham Lincoln shot by Nicholas H. Shepard in 1846, when he was a congressman-elect from Illinois. This is his first authenticated image. (Photo in public domain - Wikimedia Commons).

quality, still they constituted a revolutionary way of representing reality. In fact, the daguerreotype was sensationally presented at a joint meeting of the Académie des Science and the Académie des Beaux-Arts of Paris in 1839. The research carried out at the same time in England by Henry Fox Talbot (1800–1877) resulted in the negative emulsion with positive printing, which allowed multiple copies to be made [18].

As a new and powerful means for representing observable reality, photography furthered a critical revision in the visual arts, directing them towards new forms of expression capable of representing what was not transferable to photographic images, and eventually evolving into revolutionary art movements like impressionism, expressionism, and cubism. None initially guessed the future fundamental role of photography in the press, science, industry, advertising, and commerce. In 1888, George Eastman (1854–1932) founded the Eastman Kodak Company in the US for producing cameras, and the following year he patented the first photographic film, made of a ribbon of celluloid (ca. 0.2 mm thin) coated with a photographic emulsion, which allowed the shooting of several images in sequence, getting rid of awkward glass plates. The photographic film pushed photography into maturity, and shortly thereafter was used in the early movies, furthering the birth of cinema, the most important visual art of the twentieth century from a cultural, social, and economic point of view. At the end of the nineteenth century, emulsions required exposure as short as a thousandth of a second, allowing snapshots and reportage pictures, while the Kodak Brownie camera, marketed in 1900 at just one dollar ($28 of today), made photography a mass product for leisure.

III. LIGHT GOES ELECTRIC

A. ARC LIGHTING

If chemistry provided coal gas and kerosene lighting, it was electricity, the other main technology of the second Industrial Revolution, that attacked their domain. Just after the invention of the electrochemical cell by Italian Alessandro Volta (1745–1827) in 1800, the possibility of producing light using a persistent electric arc was tested by Russian physicist Vasilij Vladimirovič Petrov (1761–1834), who produced the first persistent arc as soon as 1802 by using the largest battery then in existence, made of 4,200 cells [19], [20]. Seven years later, the eminent English chemist Humphry Davy (1778–1829) gave the first public demonstration, making use of a huge battery of 2,000 cells capable of producing a 10-cm arc. It took some decades to develop the effect into a viable technology. An arc lamp used two aligned carbon electrodes that had to be touching to establish the electric current, and then separated to create the arc. A very intense light was obtained when the electrodes were kept at a proper distance, together with a strong heat that caused the erosion of the two electrodes. The consequent gap expansion had to be compensated for, in order to avoid stretching and extinguishing the arc. An arc lamp with a gear for regulating the carbon distance was first patented in Great Britain in 1845 by Thomas Wright [21]. The next year, another Briton, William Staite (d. 1854), made a lamp with automatic regulation driven by an electromagnet fed with the arc current, and improved it during the following years (Fig. 9). A better model was developed by V.L.M. Serrin in France in 1858, and other automatically-regulated arc lamps were proposed by Charles F. Brush (1849–1929) in the US in 1877, and František Křižík (1847–1941) in Bohemia in 1881, among others. Brush became the main American producer, while R.E.B. Crompton (1845–1940) established Crompton & Co. in 1878, which became the leading British manufacturer of arc lights (and generators).

The first public building equipped with electric arc lamps was the Opéra Theatre in Paris in 1846, that was powered by a battery of 360 relatively cheap zinc-carbon cells, the model invented by German chemist Robert Bunsen (1811–1899) in 1841. Despite that, it remained very expensive to supply arc lamps with disposable electrochemical cells, due to the high power needed. Prospects changed when effective electromechanical generators became available, after the middle of the century [22]. Prof. Frederick Hale Holmes (1830–1875) put into service the first electric lighthouse at South Foreland, near Dover (UK) in 1858, developing an idea of Michael Faraday. It was provided with an arc lamp fed by a 36-magnet generator capable of 1.5 kW at 600 rpm, derived from an early Alliance alternator, that was powered by a steam engine and equipped with a rectifying device. Though not completely reliable and quite inefficient and expensive, it was one of the first electromechanical generators capable of practical operation at relatively high levels of power, and demonstrated the potentials of electric lighting. The first lighthouse specifically designed and built for electric current was the

Souter Lighthouse (South Shiled, UK) in 1871. Thereafter, several other lighthouses were electrified based on its model.

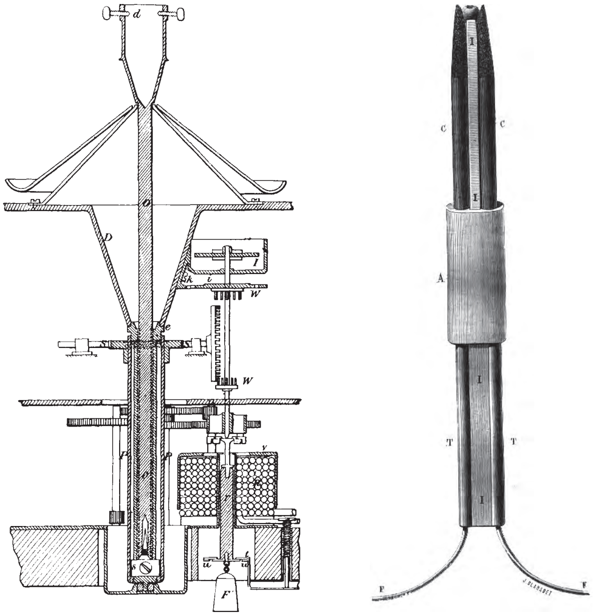

FIGURE 9. **The self-regulating arc lamp proposed by William Edwards Staite and William Petrie in 1847, and the much simpler Jablochkov candle of 1876. (Photo in public domain - Wikimedia Commons).**

In the 1870s, after 40 years of developments, companies such as Siemens (Germany, 1867), Gramme (France, 1869), and Brush (US, 1878) started producing efficient dynamos, capable of supplying cheap industrial electrical power. Early plants where commissioned in France in 1875, when a factory in Mulhouse (Alsace) was equipped with four Gramme dynamos for powering four Serrin arc lamps, and a chocolate factory in Noisiel-sur-Marne was provided with similar equipment [23]. Other French factories soon followed, while the Gare du Nord and the Grands Magasins in Paris were the first public buildings illuminated with arc lamps. In 1876, Pawel Jablochkov Nikolayevich (1847–1894, also transliterated from Cyrillic as Yablochkov), a Russian telegraph engineer just arrived in Paris, developed a simple and economic arc lamp. Dubbed the Jablochkov candle, it featured a very simple design with two parallel carbon rods set side by side, so as to maintain constant the arc length while consuming, with no need for automatic adjustment (Fig. 9) [24]. A layer of plaster of Paris was placed between the rods, and a thin graphite link connected their tops, intended to fuse when the lamp was switched on, thus starting the arc. Even if it could be operated only once and had to be replaced every time the light was turned on, it was very competitive both as an investment and in running costs (it gave some hundred candles of light operating at about 9 amps, half that of other arc lamps). It definitely launched arc light in Europe. In 1878, Gramme developed an efficient alternator whose alternating current ensured equal consumption of the two carbon rods. It triggered the emergence of AC current applications. The same year, a Gramme alternator powered eight Jablochkov candles in the Grands Magasins du Louvre in Paris and similar systems were implemented in Avenue de l'Opéra and the Place de l'Opéra on the occasion of the 1878 Paris Exposition, where the Jablochkov candle and other arc lamps were exhibited. Arc lamps based on French technology began to spread in Britain in the same year. Plants with Jablochkov candles were installed in London's West India Dock, Billingsgate Market, Holburn Viaduct, and the Thames Embankment. The first electric street lighting system, provided with arc lamps and powered by an early water-wheel-driven Siemens generator, was put into service in Godalming (UK) in 1881, and it was soon replicated in Brighton (UK). The first American arc-lighting was installed in the Wanamaker department store, Philadelphia, in 1878 by Charles Francis Brush (1849–1929), who had started to develop his system based on European technology (namely, devices by Gramme, Pacinotti, and Jablochkov). One year later, Brush put into service in San Francisco the first commercial system selling electric lighting from arc lamps to several customers. The main North American cities (New York, Boston, Philadelphia, Baltimore, Montreal, Buffalo, San Francisco, Cleveland, . . .) were equipped with public lighting systems with arc lamps, made mainly by Brush by 1881 [25]. In subsequent years, arc-light installations spread in Europe and in America. In order to exploit the blooming market, the American Electric Company was founded by British-born American electrician Elihu Thomson (1853–1937) and Edward J. Houston (1847–1914) in 1880 (renamed Thomson-Huston ElecV sources.

B. INCANDESCENT BULBS

A major limitation of arc lamps consisted in their harsh light, which was successful in the open air (parks, squares, streets, . . .) and in large buildings such as mills, factories, large stores, churches, hotels, depots, and stations, but resulted completely unsuitable for the small rooms of offices and dwellings, where they were unable to compete with gas light. A potential solution for such uses was supposed to stem from the incandescence produced by the electric current flowing in a platinum strip, which also was first observed by Humphry Davy in 1801, while experimenting with electrochemical cells. Nevertheless, all attempts to produce a practical incandescent lamp remained frustrated for several years, in spite of the patent registered by Irish politician Frederick De Moleyns (1804–1854) as early as 1841. None of the tested metal filaments and carbonized organic strips proved to be suitable, since the former quickly melted and the latter emitted particles that blacked the interior of the enclosing glass bulb. Both effects led to a very short useful life of the lamps, and were ascribable to the poor vacuum created inside the bulb containing the incandescent element. Nor was the use of platinum filaments practicable, due to the unaffordable cost of the metal.

The development of technology often proceeds through combinations and occasional mutations originated from

FIGURE 10. **An Edison's incandescent bulb from 1879 (Photo of Gregory Moine on Flickr).**

stochastic external factors, in a process that resembles biological evolution [26], and this was what happened for incandescent lighting. In this case, the evolutionary factor consisted of the mercurial air pump invented by German chemist Hermann Sprengel (1834–1906) in 1865. This simple and robust device was capable of reducing the pressure in a chamber to one millionth of an atmosphere, allowing eliminating almost all the oxygen responsible for combustion from the glass bulbs where the filaments were housed. Thanks to the Sprengel pump, Englishman Joseph Wilson Swan (1828–1914), who had been experimenting incandescent lighting since 1848, demonstrated the first viable bulb early in 1879. It was provided with a carbonized paper filament, capable of prolonged operation and further improvements allowed his bulbs to reach many weeks of operation in 1880. In America, Thomas A. Edison (1847–1931) led an impressive experimental campaign in which he tested more than 6,000 filaments, of both inorganic and organic materials collected in different continents. He was able to produce a bulb made with a carbonized cotton thread that lasted 14 hours before burning, of which he gave a spectacular demonstration in the Menlo Park Laboratory in late 1879. He made a much more durable model (1,200 hours) based on a stronger carbonized bamboo fiber in 1880 (Fig. 10). Also, St. George Lane-Fox (1856–1932), an Englishman, and Hiram S. Maxim (1840–1916), an American who moved to the UK in 1881, made their own bulbs. The inventions of these four men were compared at the 1881 International Exhibition of Electricity in Paris, and Edison's bulb proved to be the more efficient (3.3 lumens per watt, in modern units). Furthermore, it featured a high resistance and operated at a low current, which enabled the running of more lamps connected in parallel. Other incandescent lamps were developed in the following years, including the very efficient and durable carbon/platinum bulb of Italian Alessandro Cruto (1847–1908) in 1880. As early as 1880–1881, Swan used his bulbs to light his house in Gateshead-on-Tyne and the residence of Lord Armstrong, a wealthy industrialist from Northumberland, which was powered by the first British hydro-generator. In 1881, 1,194 of Swan's lamps made the Savoy Theatre in London the first public building with incandescent lighting. Initially, Edison followed the same policy for lighting the residence of John Pierpont Morgan in 5th Avenue, New York City. The famous financier was an enthusiast of the plant, and supported Edison by backing the *Edison Electric Light Company*, founded in 1878, together with the Vanderbilt family. Today, we tend to attribute the incandescent bulb to the ingenuity of Edison, forgetting all other inventors. The reason is that he made a decisive step ahead. At that time, anyone who wanted electric lighting had to buy a whole plant, including the generator. Edison had it in mind to attack the market of gas lighting and conceived to play on the same ground, by selling bulbs and power, not power stations (indeed, Brush put into practice a similar concept in his 1879 arc-light plant in San Francisco) [27]. After founding the *Edison Illuminating Company* in 1880, Edison designed the commercial distribution of electricity to end-users from a centralized 110-V DC power station, which gained a great success at the 1881 Paris Exhibition. Early plants were put into service in Holborn Viaduct, London, (including 2,000 lamps) and Pearl Street, New York, (supplying 80 customers), in January and September 1882, respectively [28]. Litigation between Edison and Swan on invention priority was stopped in 1883, and a commercial agreement was set for market exploitation [29]. It was not Edison's only litigation about incandescent bulbs. The 1886–1891 *War of Currents* against Westinghouse's AC system was much harsher [30]. AC plants, initially intended for lighting, were extended to power uses after the commercialization of Tesla's induction motor in 1891. Transformers provided easy voltage changes in AC systems allowing for much longer line extensions and more flexible operations than Edison's DC system, as the name then given, *universal system*, recalls. When AC was prevailing, in 1892, the Edison General Company, which had been started in 1889 by consolidating Edison's lighting companies, merged with Thomson-Houston Electric Company, a producer of AC systems, creating the General Electric Company (GE) which became by far the largest producer in America, where the annual production of lamps had grown from 70,000 in 1883 to 7,500,000 in 1891. At the expiration of Edison's basic patent in 1893, more manufacturers entered the market, notably Philips in Holland, founded in 1891, causing a dramatic fourfold drop in bulb prices. When the invention of the gas mantle gave a new commercial advantage to the gas industry, electric lighting companies responded with more research and development. In 1898, GE acquired the rights to a highly efficient evacuation method for mass production by mean of the so-called getters, patented in 1896 by Italian inventor Arturo Malignani (1865–1939), which allowed the manufacture of economic bulbs with lifetimes of 800 hours, and the GE Research Laboratory was established in 1900, and was devoted to pure research. There, the GEM (General Electric Metallized) bulb was developed in 1904, which ensured an efficiency of 4.8 lumens per watt (23% higher than carbonized filaments). Several researches were carried out in those years, and earlier in Europe, on new thin metal filaments with higher melting points, which ensured a more brilliant light and higher efficiency. Carl Auer von Welsbach developed the osmium filament (which melts at 3033°C, but is rare and expensive) by using a sintering process in 1902. An alloy of osmium and tungsten (wolfram in German) was also produced and market-tested under the name Osram, which was kept when that material was given up. Siemens and Halske developed tantalum filament bulbs in 1905, which had some success for a few years. Tungsten is a material of choice for filaments, in virtue of its very high melting point (3422°C) and affordability, but it is also challenging because of its brittleness. Hungarian Sándor Just (1874–1937) and Croatian Franjo Hanaman (1878–1941) first patented a method for producing tungsten filaments in Vienna in 1904. It resorted to a complex sintering process and was marketed by a Hungarian company that same year. Subsequent agreement and patents led other European producers (Auergeselleschaft, the General Electric Company of the UK—not related to GE, Philips, Osram Geselleschaft, ...) to commercialize tungsten bulbs with increasing success, thanks to an efficiency of around 12 lumens per watt (three times more than carbon filaments). In the US, William David Coolidge (1873–1975) obtained an alternative and competitive technology for producing such filaments, consisting of the ductile tungsten produced by purifying tungsten oxide, in 1907 [31], whereas Irwing Langmuir (1881–1957) introduced the inert-gas bulb (initially nitrogen and later argon) in 1913. Both these engineers worked at GE, and their achievements ensured a dramatic increase in the efficiency of the incandescent bulb and its definitive supremacy over gaslight, with a huge gain for GE. Later Langmuir, left free to follow his interests in the GE Research Laboratory, developed fundamental investigations on surface chemistry, which gained him the 1932 Nobel Prize in chemistry [32]. For his part, Coolidge used the tungsten filament to develop the hot cathode x-ray tube, a major achievement in radiology.

C. ADVANCED INCANDESCENT LAMPS

Halogen lamps were developed starting in the 1960s. They use any halogens (iodine, bromine, chlorine, and fluorine) in a bulb of a small size, so as to counteract the evaporation of the tungsten filament operating at high temperatures (250°C or higher) in order to produce a higher efficiency (up to 21 lumens per watt). However, they require a quartz or hard glass housing to resist such temperatures without softening. Tungsten halogen lamps using fluorine appeared in the 1970s, and became available in the 1990s for domestic use, in both mains- and 12-volt-fed versions, suitable for spotlights. Bulbs of very small sizes allow the use of expensive xenon and krypton, and have found a niche market in headlamps for high-level cars.

D. DISCHARGE LAMPS

The gas-discharge tube was invented by Heinrich Geissler (1815–1879) in Germany in 1857. It was of the low-pressure cold-cathode high-voltage type, and was first publicly demonstrated at Queen Victoria's diamond jubilee in 1897. In the earliest three decades of the twentieth century, several commercially viable discharge lamps were derived from Geissler's tube [33]. The Moore lamp, developed by American inventor Daniel McFarlan Moore (1869–1936) in 1896, and marketed in 1904, featured a special valve which automatically restored the gas (nitrogen, carbon dioxide) into the tube as it became exhausted. The Aarons tube, the first mercury vapor lamp, was invented by German physicist and activist Martin Leo Arons (1860–1919) in 1892, and was later marketed by AEG. In America, Peter Cooper Hewitt (1861–1921) made a mercury vapor lamp in 1901. It was much more efficient than incandescent bulbs, but presented a poorer chromatic rendition that made it suitable for limited uses. The fluorescent lamp was derived by coating the inside of the glass housing with a fluorescing powder acting as a frequency converter, so as to produce a more pleasing light. Edmund Germer (1901–1987) patented this innovation in Germany in 1926, and GE acquired its rights in 1939, when also other companies started production, initially with cold-cathode high-voltage models. The high-pressure mercury-vapor lamp was incidentally conceived by Hungarian physicist and engineer Dénes Gabor (later a British citizen, 1900–1979) while at Siemens and Halske in 1927. Later developed by more than one company, in a few years these lamps spread as street lighting, due to their high efficiency (42 lumens per watt), in spite of their low chromatic performance. They were first used commercially in England in 1932. The neon lamp, another discharge lamp derived from the Geissler tube, was invented by French chemist George Claude (1870–1960) in 1909, exploiting the neon that he obtained as a byproduct from the air liquefaction process he had invented. A few years later neon signs became extremely popular, particularly in the US where they were introduced in 1923, making Claude a wealthy man.

The low-pressure sodium-vapor lamp is another discharge lamp, which is started by vaporizing this highly reactive metal by means of an auxiliary neon discharge. Early sodium-vapor lamps were produced by Philips in 1932, resorting to sodium-resistant glass. They had unparalleled efficiency (up to 200 lumens per watt, i.e. twenty times higher than incandescent bulbs), but their monochromatic yellow light was suitable for outdoor use only. When these lamps were perfected in the 1930s, electrification had reached rural areas in Europe and in North America, leading to the definitive substitution of kerosene lamps with electric light.

Developments continued in the following decades, especially after World War Two, when florescent lamps reached full commercial exploitation. The high-pressure sodium-vapor lamp was introduced in the 1970s, and was almost as efficient as the low-pressure version, but had a much better chromatic rendition even though it produced a salmon-pink light. The compact florescent lamp, with the same base as the incandescent bulb, was launched by Philips in 1980.

FIGURE 11. **New York skyline with One World Trade Center, marked by innumerable electric lights, in 2017 (Photo in public domain - Wikimedia Commons).**

The more recent technology for lighting consists of LEDs, which is dealt with later. Artificial light has dramatically changed our way of life from two hundred years ago, and now all of these different electric lamps contribute to lighting our houses, workplaces, streets, and buildings, providing our cities with one of their more distinctive features (Fig. 11). We must not forget that, at the same time, electricity has allowed us to bring light to very challenging places, like mines or the interior of the human body for inspections and surgery. Finally, it must be pointed out some "minor" lamps have not been considered here, such as the Nernst lamp of 1898, which attained some success before being surpassed by the tungsten filament bulb, the acetylene lamp, which also had some success in the early twentieth century, and some modern lamps, e.g. the induction lamp and the sulfur lamp.

IV. POWER FROM LIGHT – PHOTOVOLTAIC CELLS

Light-converters are able of transforming light radiation into electricity. American Charles Edgar Fritts (1850–1903) made the first working archetype of a solar cell in 1883, that consisted of a layer of selenium covered with a thin film of gold and had an efficiency of less than 1%, totally unsuitable for practical exploitation [34]. Nevertheless, the device's potential was authoritatively acknowledged by Werner von Siemens [35]. Viable light-converters based on semiconductors, stemmed from the pioneering work of Russell Ohl (1898–1987) at Bell Labs in 1941 [36] and, more prominently, of Gerald L. Pearson (1905–1987) in 1954, whose team, working under William Shockley, developed the first photovoltaic cells capable of generating appreciable levels of electricity [37]. Initially the efficiency was very low (4.5%–6%), but the following improvements allowed the production of the photovoltaic (PV) generators used by NASA to power satellites (since Vanguard in 1958 and Explorer 6 in 1959) and interplanetary probes, and they are still now the main power source for such applications because of their superior power-to-weight ratio. Early space applications promoted the development of cells with higher efficiencies and lower costs, thus paving the way to modern PV conversion. Solar cell development, as well as lasers and LEDs, have greatly benefitted from the pioneering theoretical studies on heterostructures which gained Russian Zhores Alferov (b. 1930) and German-born American Herbert Kroemer (1928) the 2000 Nobel Prize in physics [38].

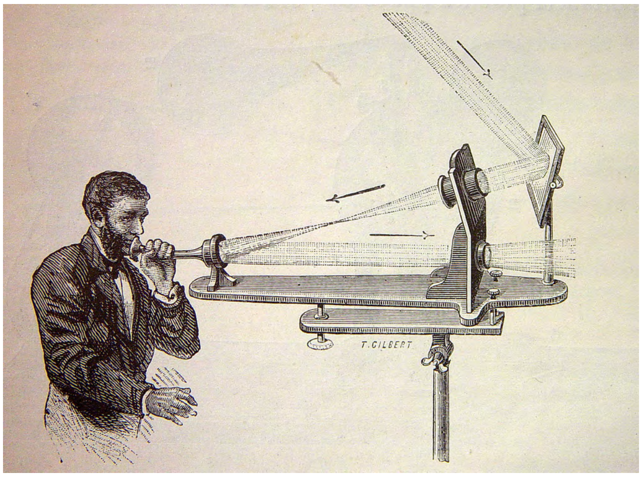

FIGURE 12. **A. G. Bell's *photophone* of 1880 used the light-sensitive property of selenium to transmit sound using a beam of light. (Photo in public domain - Wikimedia Commons).**

V. PROCESSING IMAGES

A. PHOTOSENSORS

An important part of the light technologies of the twentieth century stemmed from the light-sensitive property of selenium. An early development, in 1880, consisted of the *photophone*, made by Alexander Graham Bell (1847–1922), who was assisted by Charles Sumner Tainter (1854–1940) in the research into transmitting sound over a beam of light (Fig. 12) [39]. In spite of the four patents registered, they obtained poor practical results. At that time, early ideas on the transduction of images into electric signals emerged, as recalled further on when dealing with television. Among the several physicists who researched photoelectric effects, German Julius Elster (1854–1920) and Hans Friedrich Geitel (1855–1923) observed in 1893 that the resistance of a junction varies with incident light, for which they are credited with the invention of a viable photocell [40]. Different types of selenium photocells were in production some decades later, particularly in light meters for cameras

FIGURE 13. **The Super Kodak Six-20 was a highly sophisticated and very expensive still camera marketed in 1938 that established a technological benchmark in the camera market. It featured a special Kodak anastigmat f3.5 lens and was the first camera with a coupled selenium-based electric-eye for autoexposure, fully automatic for eight shutter speeds between 1/25 and 1/200 s. (Photo by Jason Schneider, courtesy of The Enthusiast Network/ Shutterbug Magazine).**

such as the high-level Super Kodak Six-20 of 1938, which sold for $225 ($3,794 today, Fig. 13).

In 1938, Chester F. Carlson (1906–1968) exploited the photoconductive properties of selenium in conceiving electrophotography, i.e. the dry copy process, but its development was very slow [41]. Only in 1959 Haloid-Xerox (a small company that eventually become the Xerox Corporation) built on Carlson's idea to produce the Xerox 914 (from a Greek root meaning dry), the first commercial dry copier.

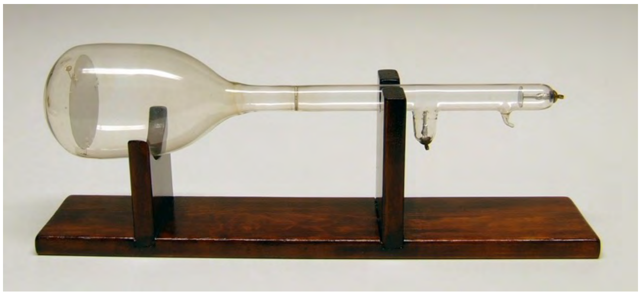

FIGURE 14. **The Braun tube of 1897 was the forerunner of the CRT, used for over one century in TV sets and oscilloscopes (Photo courtesy of Henk Dijkstra at www.crtsite.com).**

B. CRT

The first cathode ray tube (*CRT*) was the Braun tube, made by German physicist Karl Ferdinand Braun (1850–1918) in 1897, by providing the Crookes tube of 1879 with a phosphor-coated screen, where the cathode rays impacted after being emitted from a cold cathode and undergoing a deviation proportional to the variable voltage to be detected (Fig. 14). Braun did not patent the invention, and published the construction details so as to allow everyone to use it [42]. Jonathan Zenneck (1871–1959) is credited for developing the cathode ray oscilloscope from the Braun tube in 1899, when he was an assistant to Braun, by adding a second deflection at right angles to the first, and proportional to time, which allowed two-dimensional viewing of a waveform [43].

In the 1920s, the hot-cathode CRT was introduced at Western Electric and the oscilloscope gained increasing success as a very versatile laboratory instrument, allowing the measurement of a wide range of time-varying physical quantities by means of proper transducers. It also fostered the development of television, as we will soon see.

Frederik C. Williams (1911–1977) and Tom Kilburn (1921–2001) of Manchester University (UK) conceived a different use of the CRT in 1947, when they developed the Williams-Kilburn Tube, a cathode ray tube capable of storing computer data with access speeds comparable to that of electronic processing. They used it in Baby, the first small demonstrative fully-electronic stored-program computer (i.e. based on the von Neumann architecture) in 1948, and in the larger Manchester Mark 1 the year after.

C. TELEVISION

Paul Gottlieb Nipkow (1860–1940), a young German engineering student, conceived and patented the *Elektrisches Telescope* in 1884. It was a rudimentary television concept, based on a rotating disc provided with a spiraling series of holes (Nipkow disk), which scanned the images, and on a selenium photo-transducer, which converted the light of the image slices into electrical signals [44]. The first rudimentary transmission of live images was pioneered by Gearges Rignoux and A. Fournier in Paris in 1909. In order to reproduce the image signals created with a matrix of 8 × 8 selenium cells, their *telephoto* modulated the light of an arc lamp with a Kerr cell, and the light beam was then sent to a Weiller disk (a rotating drum with a series of mirrors placed on its edge) and reflected onto a screen. The system could actually transmit only simple and barely discernible alphabet letters. A pivotal figure of the electromechanical television was the Scottish John Logie Baird (1888–1946), whose system, dubbed *radiovision*, of 1924 could convert images into electrical signals by means of a Nipkow disk, a selenium cell, and a triode amplifier. The generated signals were then reconverted into images using a second Nipkow disk synchronized with the first one. It allowed the first broadcast of rudimentary moving images in 1926.

The concept of the electronic television emerged early in the twentieth century, but took some time to prevail. In 1907, Russian Boris Rosing (1869–1933) patented the *electric telescope*, that used a CRT to perform the reproduction of an image from an electrical signal, but initially he could only draw simple geometric shapes. The following year, the Scottish Alan Archibald Campbell Swinton (1863–1930) conceived the electronic scansion of images and the principle of the full electronic television. It consisted of two beams of cathode rays (at the transmitting and receiving stations)

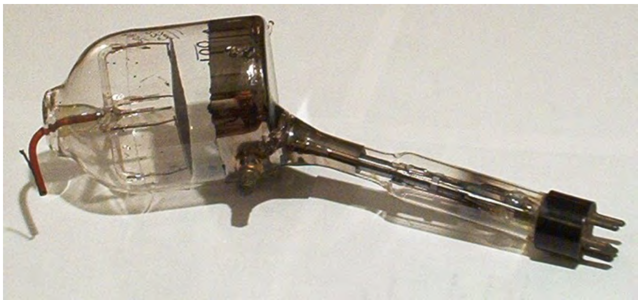

FIGURE 15. A 1932 Les Flory iconoscope, used in the electronic television for converting images into electrical signals. The device was invented by V.K. Zworykin in 1923 (Photo courtesy of Rob Flory at earthlink.net).

synchronously deflected by the varying fields of two electromagnets, aimed at overcoming the speed and resolution limitations of Nipkow's mechanical scanner [45]. On Christmas day of 1926, the Japanese Kenjiro Takayanagi (189–1990) demonstrated a television system that included a Nipkow disk in transmission and an electronic television receiver, based on a CRT, which remained long unknown to the western world. Building on the idea of the electric telescope, in 1923–28 the Russian-born American Vladimir K. Zworykin (1888–1982), a former student of Rosing in Saint Petersburg, developed the CRT into the *iconoscope*, an early electronic tube for converting images into electrical signals, and the archetype of the picture tubes long used in TV sets (Fig. 15). It eventually led to the RCA electronic television, about a decade later. The *image dissector* was an alternative video camera tube conceived by German Max Dieckmann (1882–1960) and Rudolf Hell (1901–2002) in 1925. It was also included in the first full electronic television systems built in 1927, and demonstrated in 1928 by young American Philo Taylor Farnsworth (1906–1971), who later won a long patent war against RCA and Zworykin that yielded him $1M. Similar developments of the electronic television were carried out in Germany by Manfred von Ardenne (1907–1997) at Loewe AG in the years 1931–33. The first commercial electronic television set was marketed by Telefunken in Germany in 1934. At that time, the electronic television had overcome the electromechanical system. Better vacuum video tubes came in the 1930s, starting with the *emitron* and the *super-emitron* (ten times more sensitive), developed in the UK in 1932 and 1934 by an EMI team lead by Russian-born British Isaac Shoenberg (1880–1963). In the same years the *superikonoscop* was developed in collaboration between Zworykin of RCA and the German company Telefunken. In the frame of the research into television at RCA, Albert Rose (1910–1990), assisted by Paul Weimer and Harold Law, developed the *orthicon* in 1939. It was an advanced tube provided with a photoemissive board for transducing images into electrical signals. In 1944, Rose and his team developed the *image orthicon*, which was kept secret and used in experimental bomb-guiding devices during World War Two. Released for commercial use in postwar period, it replaced the iconoscope in television cameras, because its superior sensitivity allowed shooting in low light. Image reproduction remained based on the CRT, which was evolving toward its maturity, and was ready to dominate the world of television sets and oscilloscopes for several decades, while such market opportunities fostered further R&D. The color television, with color TV sets, appeared in the 1950s, with early experimental broadcasts by CBS in the US in 1951 and RCA's NTSC standard adopted in 1953 and becoming operative one year later. In Europe, the French SECAM, adopted in France and in the USSR, and the PAL of Telefunken, adopted in the rest of the continent, started color broadcasts in 1967.

D. MODERN IMAGE TRANSDUCERS

Today, CRTs have almost completely disappeared, surpassed by more advanced technologies. Liquid crystals were observed for the first time in 1888 by Austrian Friedrich Reinitzer (1857–1927), but they were long considered a mere botanic curiosity [46]. The first prototypes of a liquid crystal display (LCD), of the dynamic scattering type and suitable as indicators, were developed by George H. Heilmeier (1936–2014) of RCA Laboratories [47]. The more efficient field-operated LCD (twisted nematic cell) was patented by Wolfgang Helfrich (b. 1932) and Martin Schadt (b. 1938) of the Swiss company Hoffmann-La Roche AG in 1970, and independently by James Fergason (1934–2008) in the US in 1971, who produced the first commercial LCD, marketed by the International Liquid Crystal Company (ILIXCO) which he founded that same year. More R&D carried on in different countries in the following twenty years, and allowed the development of the active-matrix addressed LCD in the early 1990s, notably by Hitachi and NEC, which paved the way for large-screen flat-panel displays for computer monitors and TV sets. More development came from Samsung's optical patterning technique, in 1996. Thanks to these innovations, the worldwide sales of LCD TV sets surpassed CRTs in 2007.

The concept of the plasma display was conceived in 1936 by Hungarian Kálmán Tihanyi (1897–1947), one of the inventors of the electronic television. Monochromatic plasma displays were first built by Donald L. Bitzer (b. 1934) and co-workers at the University of Illinois at Urbana–Champaign in 1964, and produced for the PLATO personal computers and high-profile niche displays. In the following years, bright plasma indicators gained success in calculators, cash registers, navigational instruments, etc. The first color plasma display, 21 inches in size, was jointly developed for Fujitsu by the University of Illinois at Urbana–Champaign and the NHK Science & Technical Research Laboratories of Japan. Fujitsu introduced a 42-inch display in 1995, while other producers developed more plasma displays for TV sets, leading them to compete with LCD in the sector of large-size flat sets.

The CCD (charge-coupled device) converts images into digital values instead of analog signals. It was invented by Willard Boyle (1924–2011) and George Smith (b. 1930) at Bell Labs in 1969 and gained them the 2009 Nobel Prize in physics [48]. Michael Francis Tompsett (b. 1939) designed and built the first ever video camera with a solid-state CCD sensor at Bell Labs in 1972 and Steven Sasson (b. 1950) made the first digital still camera by using a Fairchild 100 × 100 CCD at Kodak in 1975. In a tragic twist of fate, it was this device which almost brought about the bankruptcy of the giant of photographic films. CCDs are now main components in countless professional and leisure digital cameras, and are also used in highly advanced astronomical instruments, such as the Hubble Space Telescope and the Sloan Digital Sky Survey.

VI. LIGHT AND ICT

A. LEDs

Photonics and optoelectronics include generating, managing, and transmitting light-carried information, and the technologies upon which this is built are LEDs, lasers, and fiber optics. LEDs have a much longer story than one might think, since their principle was discovered in 1907 by British ‘‘Captain’’ Henry J. Round (1881–1966), an affiliate of Guglielmo Marconi and one of the wireless pioneers in the early twentieth century, when he observed the electroluminescence of a silicon-carbide junction [49], [50]. The first theoretical interpretation was proposed in 1922 by Russian Oleg V. Losev (1903–1942), who registered ten patents on it [51]. Losev was an ingenious inventor who anticipated solid-state electronics by two decades with his devices, but his work went unnoticed in the western world and was forgotten after his death, which occurred during the Battle of Stalingrad. Several years later, three Americans, James R. Biard (b. 1931), Gary Pittman (1930–2013), and Nick Holonyak (b. 1928), went in the same direction with much more success, thanks to a different social, economic, and political context. The first two, researchers at Texas Instruments Inc., developed the first diode emitting infrared (invisible) light using gallium arsenide (GaAs) in 1962. Holonyak made a diode capable of emitting visible light (red), namely the first LED (light emitting diode) suitable for practical use, while working at the GE Research Laboratory in that same year [52]. These early LEDs found limited use, being extremely costly. Mass production of low-brightness red LEDs based on gallium arsenide phosphide (GaAsP) started in 1968 and I personally still preserve my first-hand calculator, an HP21, provided with a display made with such indicators.

Costs dramatically dropped in the 1970s thanks to planar processing and new packaging techniques. The yellow LED was developed ten years later by M. George Craford (b. 1938), formerly Holonyak’s co-worker. The first high-brightness, high-efficiency LED, suitable for optical fiber, was made by Thomas P. Pearsall in 1976. A far more challenging target was the high-brightness blue LED, which was developed in 1989 after decades of research by Japanese Isamu Akasaki (b. 1929) and Hiroshi Amano (b. 1960), working on gallium nitride (GaN), and independently by Shuji Nakamura (b. 1954), working on InGaN, who shared the 2014 Nobel Prize in physics for it [53]. Their invention opened the door to the production of white-light LEDs, based on a phosphor coating of the LED emitter that converts a part of the blue emission into yellow (and later green and red) through fluorescence, so that the combination of blue and the other colors results in white light. Brightness increases (now over 300 lumens per watt) and cost reduction opened the door to the substitution of LEDs for incandescent light bulbs. The combination of red, green, and blue LEDs has also allowed the production of color displays, which are now a standard in billboards (hoardings in British English), commercial signs, stage lights, etc. (Fig. 16). Thanks to these developments, LEDs have gained the extraordinary success that is before our eyes.

FIGURE 16. Gigantic LED billboards in Shanghai in 2012. (Photo by the author).

B. LASERS

In a *laser* (Light Amplification by Stimulated Emission of Radiation, an effect introduced by Albert Einstein in 1914), atoms or molecules are stimulated to emit visible electromagnetic radiation through feedback and optical amplification. The concept of the laser originated from the researches developed by three physicists in 1952–3, namely Charles H. Townes (1915–2015) of Columbia University in the US, and Nikolay G. Basov (1922–2001) and Alexander M. Prokhorov (1916–2002) of the Lebedev Physical Institute in the USSR, who independently contributed to the principle and construction of the *maser* (Microwave Amplification by Stimulated Emission of Radiation) [54]. This device could feedback amplify the molecular activity, particularly of ammonia, to obtain a microwave oscillator, and could emit such microwaves exempt from noise, thanks to the working temperatures of close to absolute zero. The three scientists were rewarded with the 1964 Nobel Prize in physics, though after that early *lasers* were built. The idea of a *maser* working at a visible frequency was proposed by Townes and Arthur Schawlow (1921–1999) in 1958 [55], and started a race for the laser [56]. The winner, in July 1960, was Theodore H. Maiman (1927–2007), an American engineer of Hughes Aircraft Company, who succeeded in building the first commercial laser, capable of producing highly

FIGURE 17. **Theodore H. Maiman with the main components of the ruby laser. He preceded more credited physicists by developing the device at Hughes Aircraft Company in 1960. (Photo courtesy of HRL Laboratories, USA).**

concentrated beams of monochromatic light at a 0.69 μm wavelength. Amazingly, Maiman's optically pumped technology, based on millisecond pulses from a flash lamp and a ruby inserted into the helical lamp (Fig. 17), was much simpler than masers' [57]. Before the end of the year, two more lasers were working, including the helium-neon gas model capable of continuous wave (cw) operation made by Iranian-born American Ali Javan (b. 1926) and William R. Bennett (1930–2008).

A great deal of research was carried out by several researchers in the 1960s, resulting in different kinds of lasers and, also in this case, long lawsuits on priority and patents were fought. The Q-switched ruby lasers, introduced in 1961, allowed intensities of the focused pulses up to the MW/cm^2 level, capable of producing major interactions between light and matter. The laser-pumped laser was introduced by Keyes and Quist of Lincoln Labs in 1964. In the same year, the gas laser based on ionized argon, made by William Bridges of Hughes Research Labs, produced for the first time intense (visible) cw emission (13 wavelengths around blue and UV). Argon-ion lasers have been used as pumps for other laser, for surgery, and for laser light shows. The carbon dioxide laser was also developed in 1964 by Kumar Patel (b. 1938) of Bell Labs and, as the highest power cw laser (with a 10.6 μm infrared wave), is now widely used for power applications in industry, e.g. for robotized precision cutting [58], as well as focused welding and heat treatment, and also in surgery and military applications [59].

The neodymium-ion laser (1.06 μm) was introduced in 1961 by Elias Snitzer (1925–2012), who was in search of a cw laser at room temperature. He also pioneered the first glass laser that same year. Three years later, researchers at Bell Labs developed the Nd-doped crystal, namely calcium tungstate, as well as the Nd^{3+}–doped yttrium aluminum garnet (YAG), proposed by Joseph Geusic. Today, Nd-doped glass is the technology of choice for high-power pulsed lasers. The most powerful lasers built so far are at the National Ignition Facility at Lawrence Livermore National Laboratory (California), which uses its pulses to produce the implosion of a small tritium salt pellet, in experiments on inertial confinement nuclear fusion. It started operation in 2009. Its 192 Nd-doped phosphate glass lasers are designed to create 500-terawatt flashes lasting a few picoseconds (10^{-12} s). At the same time, new lasers capable of pulses on the femtosecond (10^{-15} s) and attosecond (10^{-18} s) timescale are opening amazing perspectives on cutting-edge research.

In 1962, Robert N. Hall (b. 1919) of GE Research Laboratory demonstrated the first semiconductor laser, earlier proposed by Basov and Java. It was based on a GaAs *p-n* junction working at liquid nitrogen temperature (77 K), and emitting pulses at the infrared 0.85 μm wavelength [60]. In 1970, continual-emission diode lasers based on heterojunction structures were developed by the Japanese Izuo Hayashi (1922–2005) and Morton Panish (1929) of Bell Labs, and independently by Russian Zhores Alferov (b. 1930), a co-recipient of the 2000 Nobel Prize in physics for his research on semiconductor heterostructures used in high-speed- and opto-electronics. Simple, reliable, and cheap, the semiconductor laser has found wide use in uncountable applications (readers and writers for optical discs, laser printers, optical fibers, industrial processes, scanners, readers of bar codes, pointers, surgery, ...). A laser printer uses a semiconductor (typically AlGaAs) laser beam to selectively activate the surface of an electrically-charged selenium-coated rotating drum, so that, due to photoconductivity, electrons are removed from the lightened areas. The toner particles are then attracted to the remaining charged areas and then transferred from the drum onto the paper, to be finally thermally fixed. The first laser printer, much faster than dot-matrix models, was developed by Gary K. Starkweather (b. 1938) at Xerox PARC in 1972, and in 1985 Canon put on the market the first laser copier.

C. OPTICAL DISCS

The first *optical disc*, written and read for storing analog video and audio contents, was produced in 1972, building on ideas independently conceived by American inventors David Paul Gregg (1923–2001) and James Russel (1931) some years before. It was put on the market as the *LaserDisc*, in the 30-cm diameter size and other formats by MCA (USA), Philips (NL), and Pioneer (J) in 1978–80 but, due to its high costs, it was never able to achieve widespread use (except in Southeast Asia), despite its superior audio and video quality. Philips and Sony jointly complemented its technologies with digital coding/decoding and digital processing of audio signals, thus developing the compact disc (*CD*), with a capacity of 700 MB in a diameter of 12 cm, a standard for all following digital discs [61]. It was launched in 1982 for digital audio recording, making rapidly obsolete the glorious vinyl records. A further three years later, in 1985, Microsoft developed it into the *CD-ROM*, for storing digital data with a capacity much greater than magnetic disks. Developed into a number of subsequent formats (*CD-R*, *CD-RW*, ...) it revolutionized the market for removable storage media, and pushed computers into multimedia. 200 billion CDs had been sold worldwide by 2007. The video compact disc (*VCD*, 800 MB), presented in 1993 by Philips, Sony, JVC, and Matsushita, was the first format for videos and quickly evolved into the *DVD* (digital versatile disc), jointly produced by Philips, Sony, Toshiba, and Panasonic in 1995 [62]. With a capacity of 4.7 GB, it can store an entire movie with many extra contents, but it was superseded by the Blu-ray (25–50 GB), marketed in 2003 and capable of storing high-definition movies and videos.

D. FIBER OPTICS

The canalization of light along a guide relies on the elimination of refraction when a given angle of incidence is exceeded, which produces the total reflection of rays at the guide walls and their confinement inside it. Although this possibility had been tested in 1840, it took more than eighty years to develop the first pioneering applications. Thin glass fibers capable of low attenuation (about 1 db/m) were studied from 1952 by various researchers, including British physicist Harold H. Hopkins (1918–1994) and Indian Narinder Singh Kapany (b. 1926), a student at Imperial College London, who coined the name "*fiber optics*" in 1955 [63]. Fibers of some tens of centimeters in length permitted early applications in optical reading and medical endoscopy, initially for diagnostics. The first semi-flexible optical fiber, patented by Basil Hirschowitz (1925–2013) and co-workers at the University of Michigan, was used in gastroscopy in 1956, while the first laparoscopic surgeries where performed in the years 1975–1981 by J.C. Tarasconi in Brazil and Kurt Semm (1927–2003) in Germany.

Japanese Jun-ichi Nishizawa (b. 1926) envisaged the use of optical fibers for data transmission at a distance in 1963, and Manfred Börner (1929–1996) made the first of such fibers at Telefunken laboratories in 1965 [64]. One year later, Sino-British-American Charles Kuen Kao (b. 1933) and George A. Hockham (1938–2013) in the UK defined the principles for attaining the very low attenuation (below 20 db/km) in supertransparent fibers needed for long-distance communication, in studies which gained Kao the 2009 Nobel Prize in physics (Fig. 18). A research team of American glassmaker Corning Glass Works achieved that goal in 1970 with a fiber capable of 17 db/km and obtained 4 db/km a few years later. Successive progress was astonishing, with 0.2 dB/km achieved in 1986. Meanwhile, early practical long lines where installed, starting with the 10-km fiber-optic communication line for telephonic service tested in April 1977 in Long Beach, California, by General Telephone and Electronics (GTE), preceding AT&T by less than a month. It operated at 6 Mbit/s, with signals generated by laser diodes. By 1987, second-generation fiber optics could operate at 1.7 Gbit/s with repeaters every 50 km, and one year later TAT-8, the first transatlantic optical cable, went into operation. In the late 1980s, third-generation fibers could transmit at 2.5 Gbit/s with repeaters every 100 km, but a new revolution started in 1992 with the fourth generation, based on optical amplification and wavelength-division multiplexing, which allowed performance to double every 6 months [65]. Today, practical transmission speeds can reach 10–40 Gbit/s and fibers capable of speeds greater by 1–2 orders of magnitude have been experimented with since 2013.

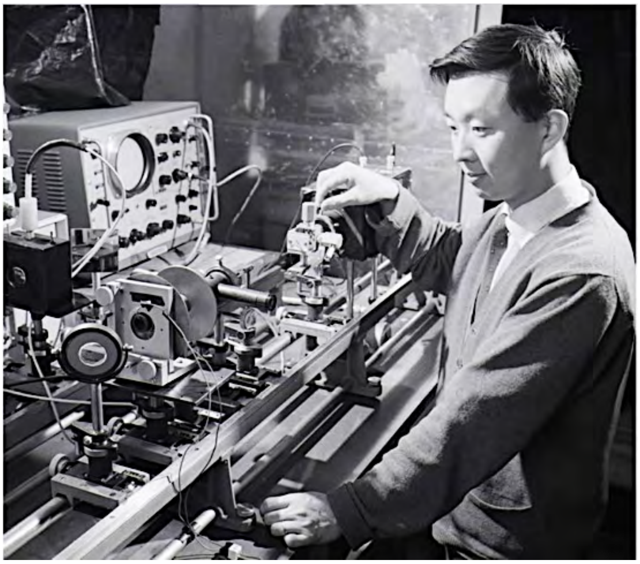

FIGURE 18. The young scientist Charles Kao doing an early experiment on optical fibers at the Standard Telecommunication Laboratories in Harlow, U.K., in 1965 (Photo courtesy of NTSE - Nano Technology Science Education – vlab.ntse_nanotech.eu).

Wavelength-division multiplexing (WDM) allows multiplying the number of optical carrier signals transmitted by a single fiber placing them on different wavelengths [66]. A great progress has been achieved with the Dense Wavelength Division Multiplexing (DWDM) technology that permits transmitting on the same fiber multiple optical signals at different wavelengths (i.e. colors). Transmission relies on frequency modulation, which result in carrying data independently on several wavelengths. Each wavelength is dubbed channel and has a frequency established by ITU-T standard and spaced from the nearby channel by a very precise gap (100 GHz/50 GHz). DWDM transforms a single optical fiber in multiple virtual channels, resulting in a huge increase of the amount of bandwidth available on a single fiber optic. Combined with optical amplifiers used as repeaters these fibers allow long distance broadband telecommunications. In particular, Erbium Doped Fiber Amplifiers (EDFAs), which are based on an erbium-doped silica optical fiber as a gain medium where optical amplification is produced by means of a laser pump light, are the most common high-gain devices used at this end. These DWDM optical lines with

EDFAs constitute Optical Transport Networks (OTNs). Such fiber optics networks, provided with few repeaters located at a great distance, have allowed broadband communication, supplanting telecommunication over copper wires, and much satellite communication. They allow advanced everyday internet services, such as video-on-demand, largely contributing to today's information society [67].

E. HOLOGRAPHY

Holography produces fully three-dimensional images by recording a light field with no use of lenses. It was conceived in 1947 by Dénes Gabor, then a researcher at British Thomson-Houston and the winner of the 1971 Nobel Prize in physics for holography [68]. It was soon exploited in art, with early exhibitions in 1968–70, and artworks by artists such as Salvador Dalí, and is now used in data storage (holographic memories store high-density data inside crystals or photopolymers), interferometry (e.g. in fluid flow analysis), sensors and biosensors, security (in currencies, credit cards, passports, ID cards, . . .), and other fields (Fig. 19) [69].

FIGURE 19. **Steve Jobs presenting an advanced holographic touch screen in 2011. (Photo by Verizon Ihologram).**

VII. FINAL REMARKS

This article can give only a very concise presentation of the vast R&D activities on light which have been carried out worldwide in the last two decades. Interested readers can find more information in the Final Report on the International Year of Light, downloadable at http://www.light2015.org/Home/About/IYL-Final-Report.html. Nevertheless, I believe that this presentation suffices to show how our use of light has evolved and expanded over time, with a tremendous boost over the last two centuries to a point where today light technologies, from lighting to power generation, information, and communication, pervade our lives and constitute pivotal tools of our society. If ancient men used it to reduce the darkness of their dwellings at night, over the last centuries we have learned how to use it to deeply improve our living habits and work conditions. A revolution stemmed from light in the last few decades, involving so many different technological fields which have merged in the optoelectronics and photonics domains. We now use widely its applications for leisure and entertainment in our free time, often without realizing that we are exploiting light. We cherish the hope that its uses can remain ethical, peaceful, and eco-sustainable, and perhaps this hope is based on more solid foundations than in the case of other technologies. We owe a great debt to the scientists and technicians who have inspired and allowed this evolution, some of whom have passed away in very recent years.

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