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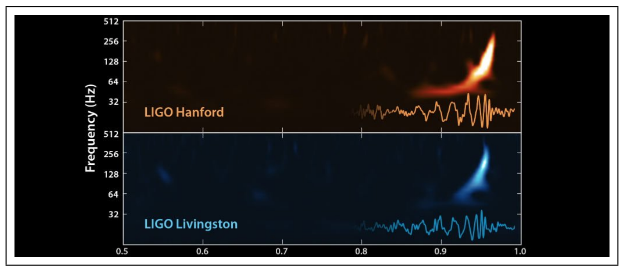
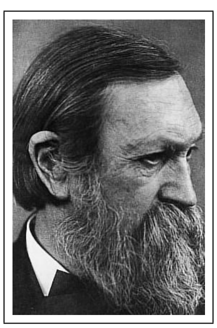
Cover article



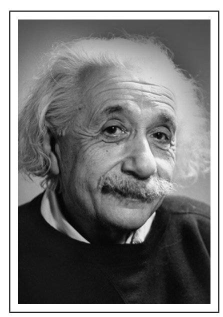
A century after Einstein predicted the possibility of waves in space-time continuum, mankind has been successful in detecting such a wave. It was a remarkable feat in experimental science as it required the detection of change in length less than the diameter of an atomic nucleus. The authors, members of the international team that achieved this feat, describes the discovery.

General Article

Series Article



What is the correct way of doing science? In answering this question, and philosophical viewpoint called positivism developed in continuation of the empiricist tradition, which dominated the scientific landscape towards the end of the 19th century. This article discusses this viewpoint, and its impact on the development of science.



Organizational News

Gravitational waves: Einstein's whispers from the cosmos

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Arunava Mukherjee*

Ah, gravitational waves, that enigmatic prediction of Einstein's theory of general relativity. Once purely a source of theoretical debate, they are now humanity's latest way of learning about the universe. The first success of using gravitational waves as a cosmic messenger came from the Laser Interferometer Gravitational-Wave Observatory (LIGO), which has successfully detected gravitational waves from the coalescence of a binary black hole system [1]. This signal is known as GW150914, since the waves passed through Earth on September 14th, 2015.

The direct detection of gravitational waves is very exciting from the point of view of fundamental physics. However, LIGO is not just a highly sensitive *detector*. It is an entirely new type of *observatory*—this binary black hole coalescence is only the first of many that LIGO is expected to detect. These observations, as well as observations of other astronomical events, will give us a wealth of completely new information about the universe: from tests of strong-field gravity to more standard astrophysical matters, like the evolution of binary stars.

In the following article, we will give a brief introduction to gravitational waves, discuss LIGO's initial discovery, and put it in the context of what we can expect from gravitational wave observations in the future. Further information about GW150914 is available on the LIGO Open Science Centre (LOSC) webpage [2].

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History

Any relativistic theory of gravity will predict the existence of gravitational waves—a way to transmit information about changes in the gravitational field from one point in spacetime to another. Einstein first derived the basic properties of gravitational waves in general relativity in 1916. Gravitational waves then became the subject of considerable theoretical debate for the first half of the 20th century. For instance, are they real, physical effects, or just some sort of artefact of the coordinate system one is using? Now the physicality of gravitational waves is a settled matter due to better theoretical understanding and experimental results. Daniel Kennefick's book gives an excellent account of this history [3].

The first attempt to detect gravitational waves came from Joseph Weber in the 1960s, but with technology (large metal bars) and data analysis techniques that are not as sophisticated as those we now employ. Weber claimed to detect signals, but other researchers were unable to reproduce these results.

The first observational evidence for the existence of gravitational waves came in the late 1970s from radio observations of binary pulsars,[1] where one can precisely measure the masses of the stars and orbital period of the binary by timing the pulsar, as was first done by Joseph Taylor and Joel Weisberg using the pulsar discovered by Taylor and Russell Hulse. One finds excellent agreement with the decrease in the period that general relativity predicts will be caused by the emission of gravitational waves. This measurement has since been joined by a number of similar ones, all of which are in agreement with general relativity.

The 1970s also saw the first proposals for interferometric gravitational-wave detectors like LIGO, which were designed to be able to detect the weak signals one expects from astrophysical sources. The LIGO observatories were inaugurated in 1999. While the initial detectors did not prove to be sensitive enough to detect gravitational waves, this was consistent with astrophysical expectations. In 2015, the first upgrade to the more sensitive Advanced LIGO detectors was completed, and the instruments detected gravitational waves almost immediately.

The physical nature of gravitational waves

Gravitational waves are in many ways a direct analogue of electromagnetic radiation, though the information they can provide about astrophysical sources is more like what we gain from sound in our day-to-day life. They also have some features that are purely their own. Like electromagnetic radiation, they travel at the speed of light and are transverse waves, only acting perpendicular to the direction of propagation. They also carry energy and momentum and have two polarisations, like electromagnetic radiation, but there the similarities end: Fig. 1 shows the two polarisations of a gravitational wave through their effects on a ring of freely-falling test masses. These consist of stretch in one direction with a compensating squeeze in the perpendicular direction (and are thus given the names plus and cross, denoted by $+$ and $\times$), while the linear polarisation states of electromagnetic radiation move charges back and forth in a line. The magnitude of this squeezing and stretching is proportional to the size of the ring, and is thus measured by the *strain* $h = \{\text{change in separation}\}/\{\text{separation}\}$. (Note that the strain illustrated here is enormously larger than any gravitational wave strain that could realistically be observed on Earth.)

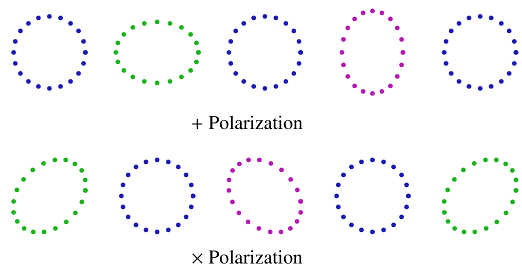

Figure 1: An illustration of the effects of the two gravitational wave polarisation states on a ring of freely falling test masses. Each row shows one polarisation state, with the effects over one cycle laid out horizontally. The relative phase (in a given column) corresponds to e.g. a binary viewed perpendicular to its orbital plane.

Additionally, unlike electromagnetic radiation, gravitational waves from even very strong sources are extremely weak—alternatively, one can think of this as implying that spacetime is very stiff: Even

[1] Pulsars are rotating neutron stars that emit a beam of radiation that regularly sweeps by the Earth as they rotate. They can rotate very rapidly (up to hundreds of times per second) and are excellent clocks.

very small amplitude gravitational waves carry enormous amounts of energy. For instance, the binary black hole coalescence that created GW150914 emitted the equivalent of 3 solar masses of energy[2], much of it in a fraction of a second during the most dynamical part of its coalescence, leading to an energy flux at Earth greater than that from the full Moon, despite being around a billion light-years away. However, these gravitational waves had a peak strain of 10^{-21}, which would correspond to changing the distance between the Sun and the Earth by less than the diameter of an atom.

Gravitational waves also interact very weakly with matter, so they carry information directly from their astrophysical sources to our detectors, without the scattering and absorption that afflicts electromagnetic radiation. However, like sound, they are emitted at wavelengths that are similar to the size of their source, and thus cannot be used to form an image of the source.

The quadrupole formula first written down by Einstein in 1916 gives a reliable guide to the order of magnitude of the gravitational radiation emitted by a given source, even in the strong-field regime—here we give it in the order-of-magnitude form

$$h \sim \frac{G}{c^4}\frac{\{\text{mass}\}\{\text{nonaxisymmetric velocity}\}^2}{\{\text{distance to source}\}}$$

(here G and c are Newton's gravitational constant and the speed of light, respectively). Note that the amplitude of the radiation falls off as the inverse of the distance to the source and is quite small (at reasonable distances) for even massive and highly relativistic sources, due to the factor of G/c^4. Specifically, if one considers a binary of two ~ 30 solar mass black holes at a distance of ~ 1 billion light-years, orbiting at $\sim 0.5c$, the speed of the binary that created GW150914 right before its coalescence, the resulting strain at Earth is $\sim 10^{-21}$, which is indeed the maximum strain observed by LIGO.

[2]This corresponds to $\sim 5 \times 10^{47}$ J, using Einstein's famous relation $E = mc^2$.

How does LIGO work?

Gravitational waves stretch and compress the space between freely falling test particles in a plane perpendicular to their direction of propagation. In an interferometric detector like LIGO, large mirrors serve as these "test particles"—mirrors are placed at the end of two arms at right angles to each other (Fig. 2), and the modulation of the differential optical path length in the two arms is measured by changes in the interference pattern, quite analogous to the iconic Michelson-Morley experiment of the late nineteenth century.

Simple as it might sound, the Advanced LIGO interferometer is able to measure strains of the order of 10^{-21}, that is $\sim 10^{-18}$ m of displacement across the arms of length 4 km—a displacement 1000 times tinier than the diameter of a proton. What makes this possible? The simple Michelson interferometer set-up is replaced by a Fabry-Perot cavity in each of the two arms, which acts to amplify the phase shift. Specifically, in these cavities, coherent light from an extremely stable laser bounces back and forth several hundred times as a phase shift builds up. In a 'lock' configuration when the instrument is adjusted so there is no light reaching the photodetector when the arm length is unchanged, the interferometer becomes extremely sensitive and can pick up even the tiniest of the displacements we mention.

It is important to remember that whatever signal we see is on top of a background of instrument noise. Instrument noise for advanced LIGO around the time of GW150914

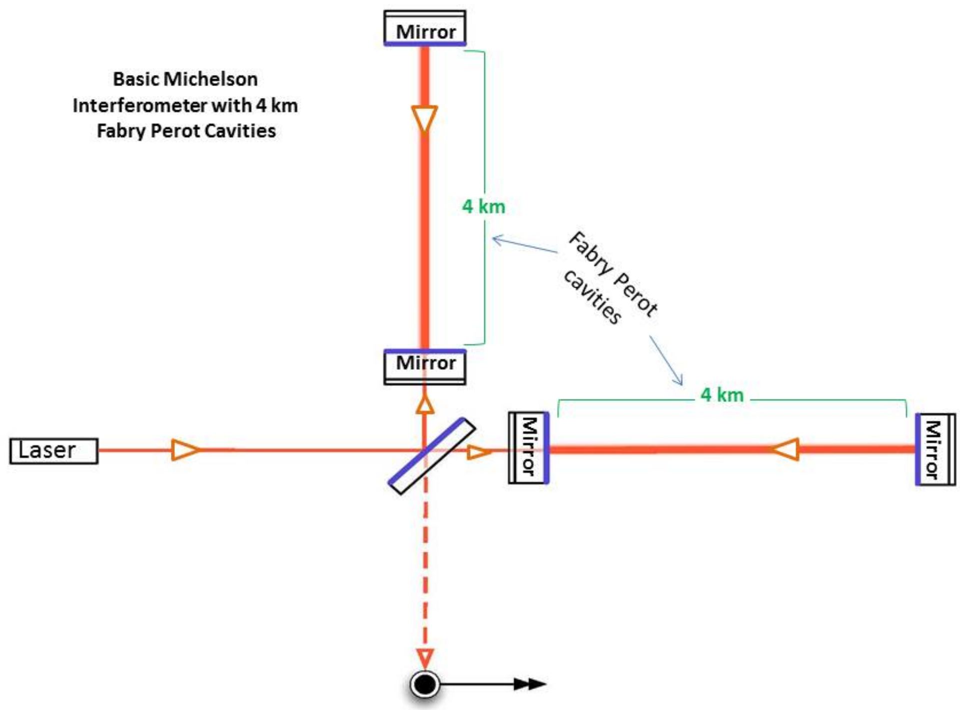

Figure 2: Schematic diagram of a basic Michelson interferometer with Fabry-Perot cavities. The central element is a beamsplitter, a half-silvered mirror that reflects half the light from the laser into the upper cavity and lefts the other half through into the cavity on the right. The black dot at the bottom denotes the photodetector that reads out the light that arrives there if the interferometer's arm length is changed, shifting it off the dark fringe. Courtesy Caltech/MIT/LIGO Laboratory.

is shown in Fig. 3. At low frequencies we have terrestrial noise of various kinds leading to mechanical oscillations of large amplitudes. At high frequencies we start getting dominated by quantum noise in the laser. However, between these two extremes, around 50–500 Hz, we have a "sweet spot", where the instrument noise is the lowest. We can expect to make detections of compact binary coalescences primarily in that range of frequencies.

An immense amount of technology and effort goes in to reducing the noise at various frequencies:

- Quantum shot noise (i.e. noise due to counting discrete photons) at high frequencies can be reduced by using higher power lasers, increasing the number of photons.
- Thermal noise at intermediate frequencies is controlled by various means, including using a large beam size to spread out the heating over the mirror and specially designed coatings on the mirror itself.

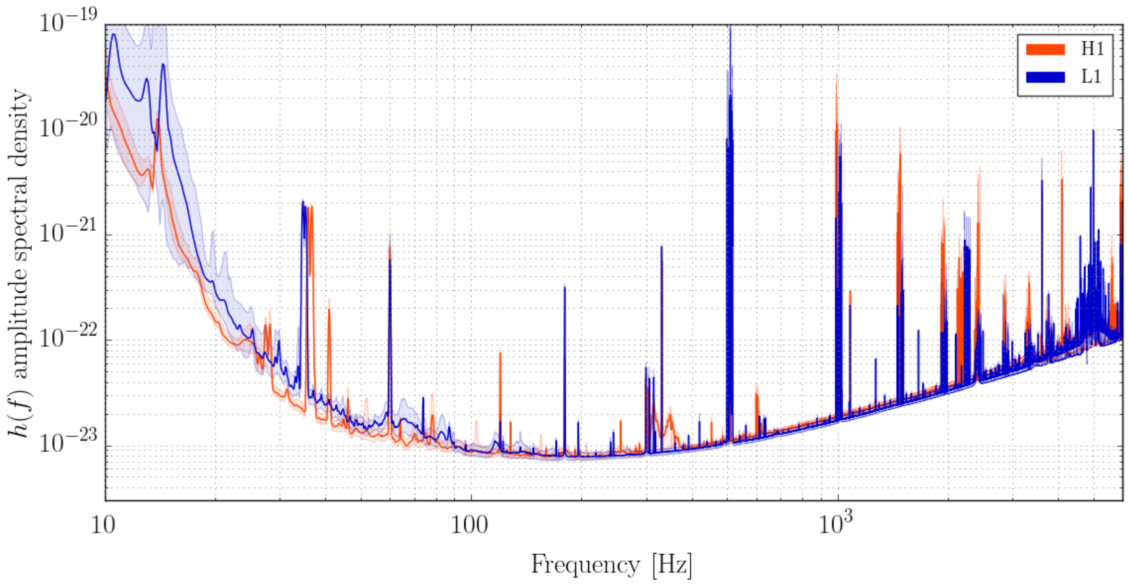

Figure 3: The average noise amplitude spectral density for the two Advanced LIGO detectors during the period of time used in the analysis of the significance of GW150914; H1 and L1 denote the detectors in Hanford and Livingston, respectively. The shaded regions show the 5th and 95th percentile variation with the median values shown in solid lines. The various sharp features are due to known mechanical resonances, harmonics from the power mains, and signals injected for calibration. This figure is obtained from the LOSC [2] and appears in [4]. It is used by permission.

- Mechanical noise at low frequencies is reduced by a series of vibration isolators, essentially oscillators comprising heavy masses and soft suspensions that cut down vibrations at few tens of Hertz at the cost of wider oscillations at even lower frequencies. Additionally, radiation pressure (also at low frequencies) is damped by using heavy ($\sim$ 40 kg) mirrors.

Gravitational wave sources

Compact objects—white dwarfs, neutron stars and black holes—are frequently invoked ingredients in the production of gravitational waves, since they are small enough relative to their mass to be able to withstand the large accelerations necessary to generate appreciable amounts of gravitational radiation. Except for the supermassive black holes found in the centres of galaxies, which may have been formed by some other method, these are the end products of stellar evolution for stars of about the Sun's mass or heavier (i.e. the remnant left after a star has exhausted all the material it has available to fuse together to resist gravitational collapse).

- Stars of about the mass of our Sun to a few times it will end up as white dwarfs, supported by the degeneracy pressure (i.e. the Pauli exclusion principle) of the high density of electrons—while a star expels some of its mass during its evolution to a white dwarf, these objects can have a mass of up to ~ 1.4 times the mass of the Sun, with a radius of about that of the Earth.

- Stars with larger initial masses will not lose enough mass to leave a white dwarf remnant. If the remnant is not too massive, it will be a neutron star, supported by repulsive nuclear forces. Here the matter is even more closely packed; the interior of the star is no longer atomic but nuclear matter, a soup of neutrons, protons, electrons and muons (and possibly even more exotic particles) without individual nuclei. These stars can have masses of up to 2 to 3 times the mass of the Sun, with radii of around 10 to 15 km. (The maximum mass of a neutron star and its radius for a given mass both depend on poorly understood nuclear physics at densities above those of nuclei on Earth, but 3 solar masses is quite a firm upper bound for the maximum mass, given well-understood nuclear physics at lower densities.)
- Even more massive stars will leave remnants more massive than the maximum mass of a neutron star. These will be black holes, objects of pure spacetime curvature with no material surface, with the matter that formed them collapsed (in classical general relativity) to a singularity. This singularity is cloaked by an event horizon from which nothing, including light, can escape.

Binary black holes are a prominent source of gravitational waves: During the final stages of their coalescence, as emission of gravitational radiation causes the two black holes to approach each other and merge into a single black hole, they are the most luminous gravitational wave sources in the universe. Additionally, since black holes can have large masses (tens of solar masses in the stellar-mass regime, and roughly 10^5 to 10^{10} solar masses in the supermassive regime), they generate strong gravitational waves (the amplitude is proportional to the mass of the system) and can be seen to large distances (billions of light years for ground-based detectors like LIGO, which are sensitive to gravitational waves from binaries of stellar-mass black holes). One can also obtain appreciable gravitational radiation from the coalescence of binaries containing a neutron star, with either another neutron star or a black hole as its companion. In all these cases we only expect to detect signals from sources in other galaxy clusters.

Binaries containing objects that are less compact, even white dwarfs, will have their constituents torn apart by tidal forces (or merge directly at relatively low velocities) before they can generate appreciable gravitational radiation in the audio band accessible to ground-based detectors. However, white dwarf binaries in our galaxy that are not close to merger, with periods on the order of minutes to hours, are a prominent source for proposed space-based detectors, which will be sensitive to gravitational waves in the millihertz band. Such detectors will also be sensitive to gravitational waves from coalescing binaries of supermassive black holes throughout most of the visible universe, as well as binaries of a supermassive black hole orbited by a stellar-mass companion, which will allow for exquisitely precise tests of general relativity, as they will complete millions of orbits in the detector's band, mapping out the spacetime of the large black hole. Heavy supermassive black hole binaries (10^8 to 10^{10} solar masses) far from merger generate gravitational waves in the nanohertz regime (corresponding to orbital periods on the order of years), which can be probed by timing an array of pulsars.

Compact binaries are not the only prospective gravitational-wave sources. For ground-based detectors, supernova explosions and magnetar outbursts can produce detectable gravitational wave bursts if they

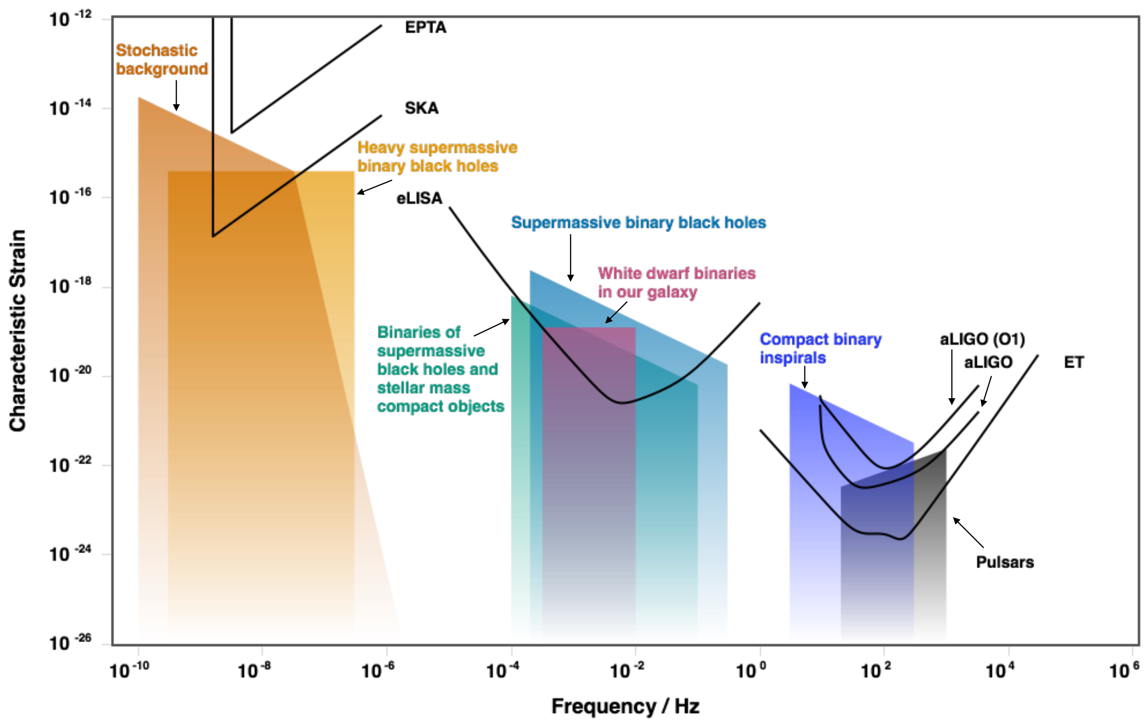

Figure 4: A schematic representation of the spectrum of gravitational wave sources, showing the noise curves of various detectors [5]. Here EPTA and SKA denote the current European pulsar timing array and the sensitivity expected for pulsar timing with the future Square Kilometer Array radio telescope. The stochastic background shown at low frequencies is that from unresolved heavy supermassive binary black holes. Similarly, aLIGO (O1) denotes Advanced LIGO's sensitivity during its first observing run, while aLIGO denotes its design sensitivity. eLISA is a proposed space-based detector and ET is the Einstein Telescope, a proposed successor to Advanced LIGO. Note that the amplitudes of the signals in the pulsar timing band and from pulsars in the ground-based detector band are particularly schematic.

occur in our own galaxy (or possibly in some of its close neighbours).

Another potential source in the Milky Way is a rotating neutron star with a nonaxisymmetric deformation. Such a star would produce a long-lasting periodic signal, but it is unclear if the deformations of any neutron stars are large enough for them to be observable with current or proposed detectors. Additionally, cosmologists are very excited about the prospects for observations of stochastic backgrounds of gravitational waves that could give us information about the very early universe, back to $\sim 10^{-30}$ seconds after the Big Bang.

However, there are also stochastic backgrounds formed by e.g. all the compact binaries in the universe, and these may obscure any cosmological backgrounds (but nevertheless carry interesting information themselves). See Fig. 4 for an overview of the noncosmological gravitational wave spectrum and the position of various detectors on it.

Source modelling

In order to detect gravitational waves signals that are buried in noise, and to infer the parameters of the system that emitted the waveform, one needs to be able to quickly generate highly accurate template waveforms for all possible astrophysical sources. Fortunately, for coalescences of binary black holes, the waveforms are relatively simple, and can be computed to high accuracy using only Einstein's equations of general relativity. Of course, this is much easier said than done, and computing these waveforms has been the subject of a number of researchers' entire careers.

One can compute analytically, by expanding Einstein's equations in a slow-motion and weak field approximation (known as the post-Newtonian approximation). However, while these analytic approximations generate waveforms quickly and also provide considerable intuition about general relativity's predictions for the motion of compact binaries, they cannot describe the very dynamical merger phase of the binary. Fortunately, it is also possible to solve Einstein's equations on a supercomputer with no approximations, besides the discretization necessary to make the equations amenable to numerical solution, whose associated error can (in principle) be made arbitrarily small. While such solutions are now relatively routine, the breakthrough that made them possible only occurred in 2005 after significant technical and conceptual developments.

However, numerical solutions to Einstein's equations are quite computationally intensive, often taking weeks or longer of supercomputer time to compute just the last 5 or 10 orbits of a given binary. Researchers have thus developed fast-to-evaluate models for the waveforms that include the results from analytical approximations, which can accurately describe the early stages of the inspiral, and are calibrated with the numerical solutions in the final stages of the evolution near merger.

Search for the signal and estimation of parameters

The signal is buried in noise, often with amplitude larger than that of the signal itself. However, unlike the random, incoherent noise, the signal is a coherent pattern that can be accurately modelled. This modelled signal can be searched for in the data—one can scan through the data looking for signals expected from various model parameters—in case a signal is present in the data, it shows up as a peak in the cross correlation around the values of the signal parameters. This technique is known as “matched filtering”. Since one uses template waveforms for this search, it is crucial to model the waveforms accurately, as discussed above.

Following a fast “search” that gives a crude idea of the waveform parameters, one needs to perform rigorous parameter estimation. The parameters to estimate include the intrinsic parameters of the system—the masses and spins, along with additional deformation parameters for neutron stars—and the extrinsic parameters—the distance to the system, its location and orientation in the sky. With a large number of parameters to estimate, one resorts to a stochastic sampling of the probability distribution on the space of parameters.

Estimation of parameters is crucial for various reasons. A quick estimation of the location in the sky is required to alert observational astronomers to perform follow-up searches. The more rigorous estimation of parameters eventually obtained can tell us about consistency of the waveform with predictions from general relativity, the physics of matter within neutron stars, the viability of astrophysical models and predicted rates of mergers, and even cosmological parameters.

GW150914 Results and Implications

On September 14, 2015 at 09:51 UTC (3:21pm IST), the LIGO detectors at Livingston and Hanford detected a strong gravitational wave signal with a signal-to-noise ratio of 24. The strength of this signal allowed us to independently detect it in multiple search pipelines which depend on very different algorithms, both generic unmodeled waveform searches and optimal searches using matched filtering. The former searches do not make any assumption about the validity of general relativity or the nature of the source, while the latter utilise very accurate source modelling in general relativity. The matched-filter analysis indicated that the signal was consistent with a merger of a binary of two black holes of masses of about 30 times the mass of the Sun. The probability that noise alone could mimic such a signal is less than one in 7 million. A careful analysis showed that the observed gravitational wave is from the last 0.2 seconds of the merger of black holes of component masses of about 36 and 29 times the mass of the Sun, at a distance of about 410 megaparsecs (1.3 billion light years). The event is localized to a patch on the sky of area 600 square degrees, mainly over the Southern Hemisphere. See Fig. 5 for an illustration of the detected waveform and a theoretical template consistent with it.

Although the spins of the initial component black holes are not very well estimated (only can only say the heavier black hole did not have more than 0.7 times the maximal allowed spin), the spin of the final remnant black hole is quite well-estimated to 0.67 the maximal spin allowed for rotating black holes. This is one of the *most accurate estimations of the spin angular momentum of a black hole*. The mass of the final remnant black hole is 62 solar masses. Thus, a total energy of about 3 solar masses was radiated as gravitational waves, mostly in a fraction of second around the merger—the peak luminosity of the radiation is estimated to 3.6×10^{51} erg/s, which is roughly 100 times brighter than the luminosity one would infer for the most luminous gamma-ray burst if it emitted its energy isotropically, instead of being strongly beamed, as it is expected to be.

The observed signal is found to be consistent with a binary black hole merger as predicted by general relativity. When the best-fit general relativity waveform is subtracted out from the signal, the residual data is completely consistent with noise at other times when no signal is present. The mass and the spin angular momentum of the final remnant black hole, estimated independently from the early "inspiral" and the late "merger-ringdown" stages are found to be consistent with each other, given the expectations from general relativity. There are no observed departures from the analytical waveform models obtained from general relativity, and much stronger constraints than previous ones are laid on the departures from general relativistic values of the post-Newtonian coefficients that parametrize the waveform models. The graviton field, expected to be massless, is demonstrated to have a mass consistent with zero, and stronger bounds than before are placed on this mass from the observation that there is no dispersion during the propagation of gravitational waves (i.e. gravitational waves of different frequencies all travel at the same speed).

Just after the merger, the newly-formed black hole is in an excited state and will radiate away the energy and angular momentum in the perturbations with some char-

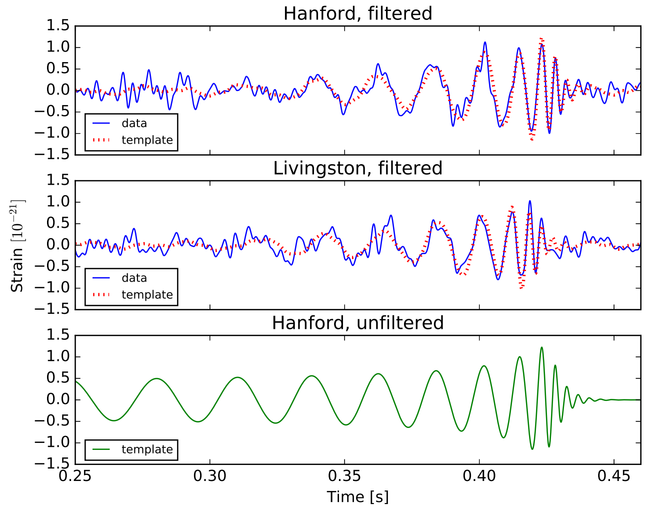

Figure 5: The data in the two interferometers and a theoretical template (from a large-scale binary black hole supercomputer simulation) that is consistent with the observed waveform, all obtained from the LOSC [2]; compare Fig. 1 in [1]. The upper two panels show the data and template after filtering by a 30–350 Hz bandpass filter, to concentrate on the detector's most sensitive region, and further filtering to remove the various instrumental lines seen in Fig. 3. Such filtering is done solely for the purposes of this figure to make the signal stand out from the instrumental noise—it is not used in our analysis. One can see the ~ 7 millisecond time shift between the signals arrival at the Livingston and Hanford detectors. The difference in amplitude between the two detectors is due to their differing orientation with respect to the source. All times are shown relative to September 14th, 2015, 09:50:45 UTC. The bottom panel shows the template waveform as it would appear in the Hanford detector with no filtering.

acteristic frequencies as it settles down into its final stationary state. This behaviour is much like a bell that has been struck, emitting a set of decaying but pure notes. The measured frequency and damping time of this least damped "quasinormal" mode is found to be consistent with the theoretical expectation for a black hole with the final mass and spin we infer from the data. All these tests are some of the *first tests of general relativity in the strong-field regime*, where the velocities of the objects being considered are almost half that of the speed of light.

This event reveals that binary stellar-mass black holes form in nature and merge within the age of the universe. This observation also reveals the existence of stellar-mass black holes more massive than the 25 solar masses previously inferred from electromagnetic observations. Formation of such massive black holes from stellar collapse implies that the stars were formed in an environment without many of the heavier elements and had a weak stellar wind (see e.g. [6] for discussion of a potential formation channel).

From this observation, LIGO has been able to estimate the rate of stellar-mass binary black hole mergers in the local universe to be 2–400 per cubic gigaparsec per year in the comoving frame (1 gigaparsec is about 3 billion light years) [7]. This is consistent with earlier predictions, though towards the higher end. Detection of a few tens of binary black hole mergers will allow us to understand the stellar evolution of massive binary stars in galactic fields and possibly also probe stellar interactions in dense regions such as globular clusters.

This observation implies that the stochastic gravitational-wave background from binary black holes, created by the incoherent superposition of all the merging binaries in the Universe, could be higher than previously expected. This background is potentially measurable by the Advanced LIGO/Virgo detectors operating at their projected sensitivity.

LIGO-India

Current plans call for a world-wide network of ground-based gravitational wave detectors that will become fully functional starting in the early 2020s. The addition of more detectors will improve our sensitivity to gravitational waves and also reduce the impact of downtime in any one detector. However, the most important improvement will be in our ability to locate the source on the sky: For gravitational wave detectors, such localization largely relies on timing—the difference in signal arrival time between the detectors lets one measure the direction from which the signal is coming—longer distances are thus a big help here. The upgraded Advanced Virgo detector in Italy is expected to become operational in 2016. The KAGRA detector in Japan is in the process of construction and is expected to become functional at baseline sensitivity around 2018.

The LIGO-India project, which recently received in-principle approval from the Indian cabinet, is a proposal in which a third LIGO detector will be built and operated in India, in collaboration with LIGO-USA and its international partners. India is in an excellent position for a detector geographically, with almost the maximum possible distance from the detectors in the US. LIGO-India will thus be a critical element in allowing the network of detectors to do astronomy, particularly in engaging with traditional electromagnetic astronomy to follow up sources.

The LIGO-India project will be led by teams at the three lead institutions, the Institute for Plasma Research, the Raja Ramanna Centre for Advanced Technology and the Inter-University Centre for Astronomy and Astrophysics, partnered with the LIGO Laboratories in the US. Initial site selection has already started—the detector will likely be located somewhere on the seismically stable Deccan Plateau.

What next?

LIGO is currently undergoing another upgrade to further improve its sensitivity. It will start its next observing run in mid-to-late 2016, for which it will be joined by the recently upgraded Advanced Virgo detector [8]. This run is expected to last for about six months, and we can expect to detect at least a few more binary black hole coalescences during that time, based on the rates of binary black hole coalescences we infer from our observation of GW150914 [7]. We can also hope to observe a compact binary coalescence containing a neutron star or gravitational waves from an isolated neutron star—possibly even something completely unexpected. Any of these would be another major first for LIGO and Virgo.

In subsequent years, the LIGO detectors and Virgo will undergo further upgrades to higher sensitivities, with Advanced LIGO predicted to reach its design sensitivity around 2019. They will also be joined for joint observing runs by the Japanese detector KAGRA, and eventually by LIGO-India. Additionally, pulsar timing observations will continue and increase in sensitivity. They have already placed constraints that rule out several models for the evolution of supermassive black hole binaries [9], and can potentially make a detection of a heavy supermassive black hole binary or the background due to a population of them in the future.

Looking further into the future, there are plans for even more sensitive ground-based detectors, notably the Einstein Telescope, which would be able to detect binary neutron stars 100 times further than Advanced LIGO at its design sensitivity [10]. Additionally, there are plans to build a detector in space, eLISA, which will be sensitive to millihertz gravitational waves [11]. The LISA Pathfinder experiment that was launched in 2015 has now started testing the technology crucial for eLISA to detect gravitational waves.

We thus look forward to learning much about the universe via gravitational waves, both from expected sources, as well as potentially things we never even thought of. While it might seem appropriate to say that the future of gravitational wave astronomy is bright, that is a very electromagnetic way of putting things. Thus, we will end by saying that the future of gravitational waves is (relatively) loud/strong!

Acknowledgments

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LED as Present Day Lighting Device

Madhusudan Jana*

THE YEAR 2015 was declared as the International Year of Light (IYL 2015) by the United Nations. The International Year of Light and Light-based Technologies, 2015 (IYL 2015) was a United Nations observance that aimed to create awareness of the achievements of optics, its applications, and its importance to humankind. We know that Isamu Akasaki, Hiroshi Amano and Shuji Nakamura were awarded the Nobel prize in physics for their work in 1994 for inventing an energy efficient and environment friendly light source—the blue LED! By this invention it is now easy to produce white LED light. White LED lamps can be produced in two different ways. One way is to use blue light to excite a phosphor so that it radiates in red and green. When all the colours are emitted together, white light is produced. The other way is to construct the lamp out of three LEDs, red, green and blue, simultaneously and the three colours combines together to turn into white. With the advent of white LED lamps we now have more long-lasting and more efficient alternatives to older light sources.

1. Man's tryst with lighting systems

Man's first attempts to devise lighting systems dates back to 70,000 years ago. Light then was a lamp made of a shell, hollowed-out rock, or other similar non-flammable object which was filled with a combustible material (probably dried grass or wood), sprinkled with animal fat and ignited. The Greek civilization started to develop terra cotta lamps to replace handheld torches around the 7th century BC. In fact, the word lamp is coined from the Greek word lampas meaning torch. Before that, buildings were constructed in Roman atrium style to bring in light from the top and sides of the buildings. The sun has been the primary source of light for humans. Lamps with oil/wax wicks served as a major source of light almost up to the 18th century. In the 18th century, the central burner was invented and that was a major improvement in lamp design. The fuel source was then firmly enclosed in metal. The intensity of light was regulated by a metal tube in the burner. Around the same time, another modification became popular with small glass chimneys which were added to lamps to both protect the flame and control the flow of air to the flame. Olive oil, bees wax, fish oil, whale oil, sesame oil, nut oil, and similar substances were used as lighting fuels in early days. The lamp design became complex and popular like the kerosene lamp (first introduced in Germany in 1853), coal and natural gas lamps etc. Street lights were mostly natural gas lamps up to the mid 20th century. Meanwhile low pressure sodium and high pressure mercury gas lamps gained acceptance.

Next generation house-hold or common lighting came from electricity. It was in 1801, when Sir Humphrey Davy, an

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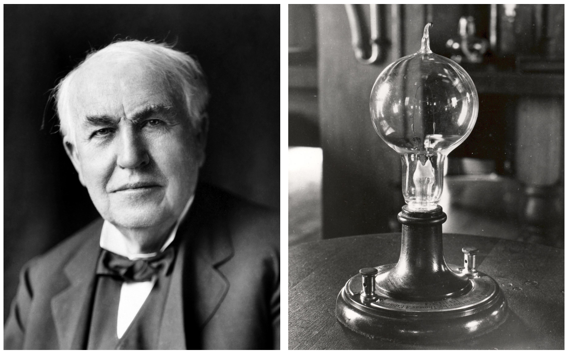

Figure 1: Thomas Edison and the incandescent lamp.

English chemist demonstrated carbon-arc lamp and that was thought to be the first electric lamp. All arc lamps are generally based on the current running through different kinds of gas plasma. A.E. Becquerel of France developed the theory about the fluorescent lamp in 1857. However, electric lamps became popular in the form of the incandescent lamp patented by Thomas Edison in 1880. In this type of lamp, the electricity flows through the filament kept inside the bulb. The filament has resistivity to the flow of electricity. This resistance makes the filament hot to a high temperature and the heated filament then radiates light. It is said that Thomas Alva Edison did not actually invent the first light bulb, but he improved upon a 50-year-old idea. Rather, two inventors, Henry Woodward and Matthew Evan patented incandescent light bulb before Thomas Edison did.

Such bulbs were inefficient due to the short life of the filament. Edison tried to develop a long lasting bulb. Edison is still considered the inventor of the light bulb because he made incandescent bulbs usable, efficient and durable. In 1915, American, Irving Langmuir developed an electric gas-filled tungsten lamp replacing carbon filament by tungsten filament. Earlier lamps with carbon filaments were both inefficient and fragile, so tungsten became a standard and popular metal filament instead of carbon filament.

In the 19th century, two Germans—glassblower Heinrich Geissler and physician Julius Plcker were able to produce light by removing almost all of the air from a long glass tube and passing an electrical current through it. This invention became popular as the Geissler tube. This is basically a type of discharge lamp and is the basis of many lighting technologies, including neon lights, low-pressure sodium lamps (used as streetlamps) and fluorescent lights. Peter Cooper Hewitt created a blue-green light by passing an electric current through mercury vapour and incorporating ballast (a device connected to the light bulb that regulates the flow of current through the tube).

Around 1927, mercury vapour lamp was replaced by fluorescent lamps. These fluorescent bulbs are coated on the inside to increase efficiency. At an early stage, beryllium was used as a coating material, however, because of its high level of toxicity, beryllium was replaced with safer florescent chemicals. In 1976, Edward Hammer

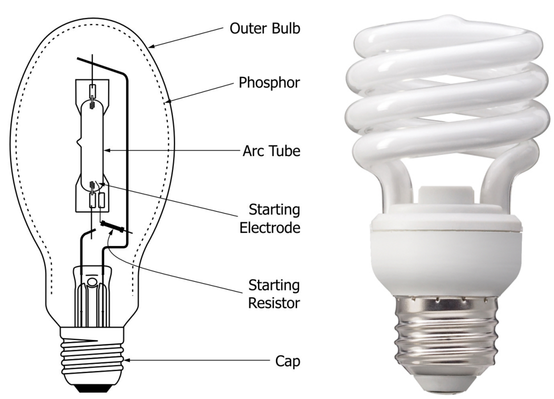

Figure 2: The structures of mercury vapour lamp and compact fluorescent lamp

demonstrated how to bend the fluorescent tube into a spiral shape and thereby developed the first compact fluorescent light (CFL). Now CFLs are commonly used in indoor and outdoor lighting as well as in decorations because of it low power consumption and high brightness. Presently these are available in market in various shapes in different wattage. In spite of several advantages, this technology suffers from low life time of the CFLs. Research and development towards better longevity is being carried out.

2. Light Emitting Diode (LED)

Light Emitting Diodes (LED) are the latest type of artificial light. This light is based on the electronic property of certain materials. Basically, it is a tiny electronic device that emits light. The major difference between common sources and LED is that most light sources emit light in all directions, whereas, LED's are quite different in this respect as the light is radiated in about a 90-degree pattern. That is why it is called directional light. This property makes LED's more efficient in aiming towards general lighting; street lighting and other types of lighting that require light to be directional. However, with the use of some optical and other devices, an LED fixture can give out light at 360 degrees also.

2.1 LED Structure

LEDs are p-n junction devices designed mainly from semiconducting materials like gallium arsenide (GaAs), gallium arsenide phosphide (GaAsP), or gallium phosphide (GaP). However, the most popular semiconductors silicon and germanium are not suitable because those junctions produce heat but not appreciable amount of IR or visible light. The junction in an LED is forward biased and when electrons cross the junction from the n- to the p-type

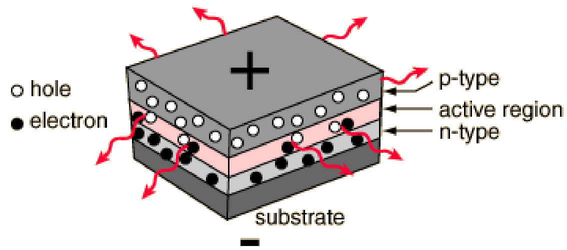

Figure 3: Schematic diagram of LED structure.

material, the electron-hole recombination produces some photons in the IR or visible range in a process called electroluminescence. Actually when an electron meets a hole, it falls into a lower energy level, and releases energy in the form of a photon. An exposed semiconductor surface can then emit light. The LED lighting is making great steps in power and efficiency. It is expected that LEDs will play a more major role in general lighting. It is a long lasting semiconductor device, some types last 100,000 hours, compared to about 1000 hours for an incandescent bulb. Now that blue LEDs have become a reality, white light LEDs can be produced by combining the red, green and blue chips in a single device. The possibilities of LED light cover a wide spectrum, from the infrared LED in our television's remote control to ultraviolet LED light used in the medical field for sterilizing.

Sometimes, between p-type and n-type semiconductor layers, an active region is deposited. This active region emits light when an electron and hole recombine. Considering the p-n combination to be a diode, when the diode is forward biased, holes from the p-type material and electrons from the n-type material are both driven into the active region and radiative recombination occurs. In this particular design, the layers of the LED emit light all the way around

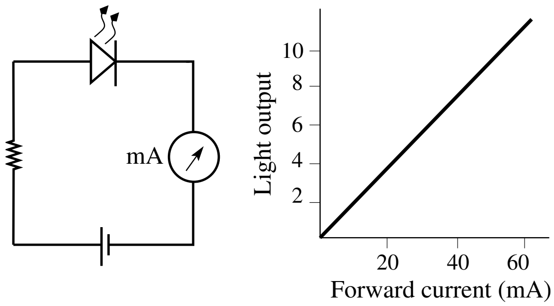

Figure 4: Circuit diagram and characteristics of ideal LED

Table 1: The luminance of different sources

Sources	Illuminance in Lux
Sunny Day	100,000
Overcast Day	10,000
Very Dark Day	1,000
Twilight	10
Deep Twilight	1
Full Moon	0.1
Quarter Moon	0.01
Starlight	0.001

the layered structure. To get emitted light in a desired direction, the LED structure is placed in a tiny reflective cup so that the light from the active layer will be reflected toward the desired exit direction.

2.2 LED Characteristics

When an LED is forward biased to the threshold of conduction, its current increases rapidly and must be controlled to prevent destruction of the device. It is observed that the light output is quite linearly proportional to the current within its active region. The output light characteristics and the circuit diagram are shown in Fig. 4.

3. The quantity of light

To get idea about which lighting system is more advantageous, we must have knowledge about quantity of light and its distribution over the whole area generating the overall intensity pattern. In general light output is defined as the quantity of light that comes out of a lamp. This is measured in lumens. Most of us think of measuring light as how much light comes out of a traditional incandescent bulb. But now that more efficient lighting sources are developed, the general public will have to start considering how to measure light in lumens. For example, a 100 watt incandescent bulb is about 1700 lumens. An equivalent CFL (Compact Fluorescent Light) would be a 28 watt bulb at 1600 lumens; whereas a 15 watt LED can generate output as much as 1620 lumens. Illuminance is the amount of light measured on the work surface, such as a desk in the lighted space. This is measured in lux (in metric system) or footcandles (British system). A lux is one lumen per square meter. A footcandle is one lumen per square foot. One footcandle equals approximately 10 lux. Table 1 shows the illuminance we can expect to see outdoors in different conditions.

When we want to determine acceptable light levels, it is usually more important to think of Lux or Footcandles rather than lumens. Lux or Footcandles more accurately measures the amount of light that is actually utilized by the human eye to visualize something. A good number of surveys on several types of lighting space or working space revealed that most space had lux levels of less than 10% or more of the recommended levels. With the help of a lighting expert and a simple light meter called Lux-meter, we may be assured about the lighting level which is very important for our health and safety-security. The recommended light levels are given in Table 2.

The Lighting Research Centre notes that in the early part of the twentieth century, when electric street lighting was beginning to be installed in many countries, moonlight levels at full moon were commonly used as a standard or reference point for outdoor lighting. When we consider the need of an outdoor lighting installation, it is still helpful to think in terms of moonlight levels. In rural areas, moonlight, with a luminance of approximately 0.1 lux on the floor, often provides adequate lighting for people's basic requirements such as walking or finding a house or a car.

4. What happens if we use low intensity light

Proper Lighting at working place or in home is very important to the health and safety of everyone. Poor lighting leads to symptoms like eyestrain, migraine and headaches, Sick Building Syndrome in new and renovated buildings (which includes headaches, lethargy, irritability and poor concentration.)

Proper balancing of natural and artificial lightning at work place and at home is essential, because too much light or flickering light may damage our eyes. Human eye cannot properly perceive the shape, proximity and the depth of spaces and objects without proper lighting. Bad lighting can cause accidents both at home and at work. Aged people are particularly in danger in dark places.

4.1 Adequate lighting for home

Lighting is all about aesthetics, tasks, ambience and creating a better atmosphere in your house. Direct lighting is best suited to be used in your workplace or on the reading-table, indirect lighting can be used to provide better ambiance and total lighting of a room. Multiple light sources for the different rooms may be used to create a soothing ambiance. The lighting for ceiling is installed on a metallic platform

Table 2: The recommended levels of illumination

Space or purpose	**Illuminance**
Ambient Light	(in Lux)
(Home, Office, Classrooms)	150-300
Office Work, Reading	500
Supermarkets, Stores	750
Detailed Task Lighting	1000
Very Detailed Task Lighting	1500-2000

and offer additional subtlety and directional capabilities. It can easily be connected to the dimmer switches to provide a full range of light ranging from precisely dim to total brightness to enlighten an entire space. A table lamp or a dim wall sconce can serve as the perfect night lighting for nurseries and kid's rooms.

5. Advantages of LED Light

i) Long life of LEDs: LED is a solid-state light device. It has very long lifetime and is generally very stable. In general, incandescent bulbs have an expected lifetime of about 1000 hours while LEDs have an expected life of up to 100,000 hours i.e., more than 11 years. However, this figure is extremely confusing because like all other light sources, the performance of LEDs degrades over time, and this degradation is strongly affected by factors such as operating current and temperature. Although no clear-cut definition of lifetime is given as such, conventionally, it is defined as the time taken for the LED's output to fall to some percentage (such as 70% or 50%) of its original value.

ii) High Efficiency: LEDs are emerging as high-efficiency light sources. White LEDs with efficacies of more than 25 lumen/Watt are commercially available. Also, the directional nature of light produced by LEDs allows the design of luminaries with higher overall efficiency.

iii) Low maintenance: Due to long life of LEDs, it will not be required to replace failed/inactive lamps often, and this can lead to significant savings in terms of money and maintenance effort. This also makes LED fixtures useful for installation in relatively inaccessible locations.

iv) Low power consumption: The power consumption of LEDs is very low. This leads to significant energy savings that encourage people for the installation of LED-based systems, for example at traffic signals. Several countries have taken national programs to develop effective solid-state lighting industries as a part of the potential energy savings associated with using LEDs.

v) Low heat production: LEDs don't produce heat in the form of infrared radiation. Such infrared radiation makes surface of the incandescent bulbs hot. The absence of IR radiation allows LED fixtures to be positioned in locations where heating from conventional sources would cause problems e.g., illuminating food or textiles. Actually, LEDs do produce heat at the semiconductor junction within the device. Thermal management and heat sinking arrangement prevent rise of the junction temperature of the LED. Rise of temperature may lead to the LED characteristics to change. Sometimes permanent damage may occur.

vi) Availability in different colours: LEDs are available in modules containing different-coloured LEDs (typically red, green and blue), and can be modulated to a huge range of colours, and easily dimmed. This is a particular advantage in applications such as backlighting liquid-crystal displays (LCDs).

vii) Environment Friendly: LEDs do not contain mercury or any other harmful elements and in many cases steps are being taken to replace lead-containing soldering material with lead-free material to fix on a board. The energy-efficient nature of LEDs also makes them environmentally friendly. LEDs are low-voltage light sources, generally require a constant DC voltage or current to operate optimally. So in respect to electrical hazards it is also very friendly.

viii) Compensating cost: At present, LEDs are expensive compared with other light sources. LED manufacturers are trying to carry out research and development towards reducing their production costs while at the same time increasing the light output of their devices. However, high initial cost of LED-based systems is counterbalanced by lower energy consumption, lower maintenance costs and other factors.

ix) Small in size: LEDs are available in the form of very small high-brightness chips. The availability of small, high-brightness devices have enabled significant market advancement. In mobile phone handsets, where blue, green and white LEDs are now used in most models to backlight keypads and liquid-crystal display (LCD) screens.

x) Instantaneous switch-on: LEDs switch on instantaneously, even when it is cold, and this is a particular advantage for certain applications such as lights in vehicle brake.

xi) Advantageous dimming effect: LEDs are ideal for use in applications that have to operate in frequent on-off cycling. Fluorescent lamps burn out more quickly when cycled frequently. LEDs mostly fail by dimming over time, rather than with abrupt burn-out like incandescent bulbs. This fact provides additional safety for any space illuminated by LEDs. Even if the LEDs dim over time, they never fail completely like incandescent sources. LEDs need to be replaced only after their 30% lumen depreciation.

xii) Not affected by cold temperatures: The environment of cold temperatures does not hamper the life-span and the amount of light output of LED. This makes LEDs suitable for use in refrigerators and freezers. Other sources like CFLs are extremely dim at cold temperatures and can take significant time to warm up to full brightness. LEDs have no warm-up time and turn on at full brightness regardless of how cold environment it is. This makes them suitable for use outdoors in colder climates.

6. Disadvantages of using LEDs

i) Comparatively expensive: LEDs are currently more expensive, when measured in price per lumen, than conventional lighting technologies. However, the additional expense is partially compensated by the low cost of the driver circuitry and power supplies needed. Long life time is also another encouraging fact to compensate the initial high cost.

ii) Performance deterioration in high ambient temperature: LED performance largely depends on the ambient temperature of the operating environment. Getting proper performance of LED is difficult in high ambient temperatures as it may result in overheating of the LED package. High level of heating may eventually lead to device failure. Ample heat-sinking is essential to maintain long life. This is very important when considering automotive, outdoor, medical, and military applications where the device must operate over a wide range of temperatures, and is mandatory to have a low failure rate.

iii) Comparatively low brightness: Although LEDs have high efficiency and consume a small amount of power; the devices produce a small output in terms of lumens. For example, a 40 W incandescent bulb with an efficiency of 20 lm/W produces 800 lumens, whereas one-watt LED with an efficiency of 32 lm/W produces only 32 lumens i.e. 25 such LEDs are required to produce the same amount of light output as the incandescent bulb.

iv) Problems in RGB LEDs and colour mixing: It is a fact that LED characteristics change with time, temperature and current, and from device to device. For RGB (producing light of red, green and blue colour) LEDs, the performance of different-coloured devices changes at different rates. So, this can result in variation of lamp colour and intensity, and poor reproducibility.

v) Problem in semiconductor processing: Production of LEDs is a complex high-consuming process involving the growth of crystalline layers across the surface of a semiconductor wafer. The properties of the LED depend on the quality of these layers. Reproducibility is a big problem till date. Some LEDs processed from a wafer will yield high quality devices, while others from the same wafer may have much lower quality.

vi) Knowledge gap: In general, there is a gap in understanding between the LED manufacturers and the lighting community. The commercial manufacturers do not provide information that is directly comparable to the information available for competing light sources. So common people are not familiar with crucial issues such as thermal management, or why white LED performance is not highly consistent.

7. Conclusions

For most intents and purposes, LEDs are already great replacements for incandescent bulbs as well as CFLs in several applications. Night lights can be replaced with low cost, low power consuming LED bulbs that will last for years. Progress has been made in the use of low-wattage LED bulbs in reading, closet appliances (like refrigerators), and table lamps as good alternatives for using higher wattage LED bulbs. For LEDs to truly gain the market peak, the disadvantages have to be greatly reduced, but with the impending phase out of the incandescent bulb, manufacturers will be investing heavily into research and development of better LED bulbs. Researchers are predicting that future LED bulbs will generate even less heat and more light for the amount of energy they consume, leading to brighter bulbs that consume even less energy. In their opinion, LEDs are expected to be a good substitute for incandescent bulbs for all our basic needs. Nothing can be a complete replacement, but LEDs may become suitable in terms of energy consumption as well as longevity and maintenance. The 2014 Nobel Prize given for the development of blue LED, on account of advances towards production of white light through LED route, is a great boost for LED research. With 20% of the world's electricity used for lighting, it is estimated that optimal use of LED lighting could reduce this to nearly 5%. With the advent of LED lamps we can expect to have more long-lasting and more efficient alternatives to older light sources in the near future.

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A Brief History of Science
Part 12: The Rise and Fall of Positivism

Soumitro Banerjee*

The Advent of Positivism

We have seen earlier that post-Renaissance development of science relied, to a large extent, on empirical evidence in order to dispel common misconceptions held since antiquity. Francis Bacon advised scientists to gather empirical data on a large scale. In order to build a more complex body of knowledge from these direct observations, he recommended the use of inductive reasoning (making generalizations based on individual instances). This approach saw quite a bit of success in the following century. Thus, the mood of the time was to rely on empirical evidence in judging truth.

This line of thinking was formalized by John Locke and David Hume in England, by theorizing that all knowledge derives from sense experience. This point of view, called empiricism, says that all concepts are about or applicable to things that can be experienced. All rationally acceptable beliefs or propositions are justifiable or knowable only through experience, also called *a posteriori* knowledge.

But what is amenable to sense experience? In Germany, Immanuel Kant (1724-1804) considered this question. His opinion was that corporeally existing things, by themselves, are not amenable to sense experience; only parts or aspects of it are. For example, we can experience the taste, smell, colour, and other aspects of an apple. But the apple is not a sum-total of these sense experiences about it. It is something else. This, he said, is the 'thing-in-itself', and the aspects that we have access to through our sense experience constitute, in his language, the 'thing-for-us'. He proposed this as a general concept: in everything that are subjects of scientific investigation, there are 'things-in-themselves' and 'things-for-us', the former being unknowable while we try to make sense of the world through the latter.

We have seen that in the early part of the 19th century there was great advancement in different branches of science. With that, scientists faced the question of epistemology: how do we come to know? What is the correct way of knowing, or of investigating phenomena? At that time a viewpoint developed in continuation of the empiricist tradition that was to exert enormous influence on the scientific community in the latter part of the 19th century. It was called positivism.

The initial proponent of positivism was the French philosopher and social scientist Auguste Comte (1798-1857) who described his ideas in his books 'The Course in Positive Philosophy' and 'A General View of Positivism'. The term 'positivism', coined by Comte, derives from the emphasis on the positive sciences—that is, on tested and systematized experience rather than on undisciplined metaphysical speculation.

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August Comte (1798-1857)

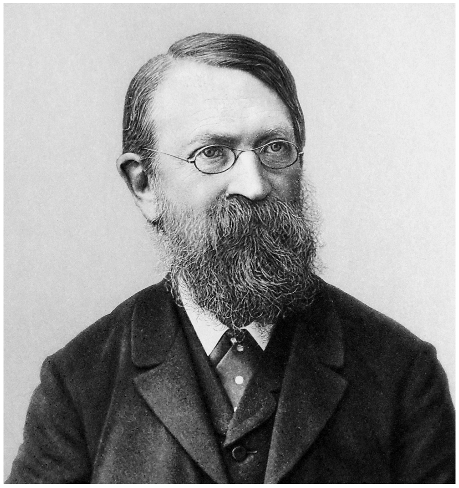
According to him, techniques for investigating phenomena should be based on gathering observable, empirical, and measurable evidence, subject to specific principles of reasoning. In the study of social sciences, he stressed the adoption of a 'value-free' or objective approach to the study of humanity that shares much in common with methods employed in the natural sciences, as contrasted with speculation of how things should or ought to be.

In the later part of the 19th century, the doctrine of positivism was further developed by Richard Avenarius (1843-1896) in Switzerland, and especially by the famous scientist Ernst Mach (1838-1916) in Austria. Their viewpoint is also known as empirio-criticism. For them, the answer to the question "How do we know?" was: we know with the help of our sense perceptions. Our knowledge about anything is nothing but a combination of sensations received from that thing. The nerves carry these sensations to the brain, and the brain forms perception about that object using these signals. That is why, they said, sense experience is the only reliable source material for forming knowledge.

They insisted on a strict adherence to empirical data. According to them, the goal of knowledge is to describe the phenomena that we experience. The purpose of science is simply to stick to what we can observe and measure. Knowledge of anything beyond that, a positivist would hold, is impossible. Kant had divided the physical world into things-in-themselves and things-for-us, but believed in existence of the things-in-themselves. Mach went a step further and renounced even formal recognition of real material objects. According to Mach, taking any step beyond what is given by sensory data would tantamount to metaphysical speculation. "The materialists, we are told, recognise something unthinkable and unknowable—'things-in-themselves'—matter 'outside of experience' and outside of our knowledge. They lapse into genuine mysticism by admitting the existence of something beyond, something transcending the bounds of experience and knowledge."

The essence of positivism is to say that our knowledge of the world, which starts from our sensations and sense-impressions, can never extend to anything beyond those sense-impressions, and that the job of science is simply to correlate observational data. The famous physicist Arthur Eddington said that the data of physics consisted in "pointer-readings and similar indications"; the physicist could never say what lay behind those observations; all he could do, or needed to do, was to state their correlations. The real world could never be known to science. The positivists opined that science should concern itself only with the 'observables,' for, in their opinion, what cannot be observed is not real.

As a result, positivists could not accept the idea of causality. According to positivists, causality is nothing but a useful word to use when correlating observations. But since all we can observe are the repeated occurrence of events in a definite sequence (for example, cloud and rain),



Ernst Mach (1838-1916)

science can only document the sequential occurrence of events and cannot infer the existence of any real, objective causal connection.

On the face of it, the strict adherence to empirical data obtained from sense perceptions (enhanced with the aid of instruments) seems to be a correct scientific standpoint. After all, this can be used to dispel many unscientific beliefs. To the question "do ghosts exist?", a scientist would say "no, because we do not perceive a ghost through our sense perception." That is why, most scientists in the later part of the 19th century were swayed by the positivist argument, and this approach became the de-facto 'scientific method'.

Even though this line of thinking sounds materialistic, in actuality it stands in sharp contrast to materialism. Materialists hold that the universe is composed of matter, the material world exists independently of our consciousness, and there is nothing supra-matter in this material world. The multitude of phenomena which science investigates is nothing but different forms of matter in motion. That is why they hold that all truths are to be found in the properties of matter and the interactions between its different forms. The sharp line of difference between the positivists and materialists was that the first group refused to treat anything as real unless it is observable, while the second group argued that since matter exists independently of our consciousness, the reality of any concept does not depend on our ability to observe it. The way to reach the underlying reality of phenomena is through theory-building, and by testing the theories objectively.

The Development of Science, 1870-1900

What was the intellectual climate in the later part of the 19th century? Idealism was still very strongly entrenched in common peoples' minds. Materialism had overcome the shortcomings of mechanical materialism and metaphysics, and was spreading among the rationally minded people and among the scientists. But at the same time the positivist philosophy emerged, received wide publicity, and was gaining prominence as the guiding principle of science.

The materialists' emphasis on objectivity helped dispel many unfounded beliefs. The positivist approach gave impetus to experimental research and data collection. This resulted in many important discoveries and technological inventions in the period from 1870 to 1900. Here we list some of the important advancements that occurred in this period.

There was a speculative idea prevalent at that time, that the development of an individual embryo repeated the same evolutionary stages of its ancestors. Wilhelm His (1831-1904) rejected this idea and sought to discover the physical and chemical causes for embryonic development. His new experimental approach gained many followers, who studied the internal responses of an egg to an altered physical environment. Thus, over the period 1875-1900, embryology became an experimental science.

It was a prevalent belief at that time that epidemic diseases were caused by something called *miasma*, a noxious form of 'bad air' emanating from rotting organic matter. Louis Pasteur (1822-1895) experimentally showed that this belief was false, and that most infectious diseases are carried by micro-organisms or germs. He showed that germs do not grow spontaneously; these can originate only from other germs. Thereby he established the germ theory of diseases and revolutionized medical science. Following his lead, Robert Koch (1843-1910) studied the bacteria that cause diseases like tuberculosis, cholera and anthrax, and established the experimental techniques of bacteriology. By 1880, the miasma theory was abandoned. Viruses were discovered in the 1890s.

The cathode ray was first observed in 1869 by German physicist Johann Hittorf, and was named in 1876 by Eugen Goldstein. The study of cathode rays revealed many new aspects including the eventual discovery of the electron in 1897 by Joseph John Thomson (1856-1940). Thomson's novel experiments on the properties of cathode rays passing through gases led him to conclude that these were minute particles carrying negative charges. Photoelectric effect was first observed in 1887 by Heinrich Hertz (1857-1894). The German physicist Philip Lenard conducted detailed experiments on the photoelectric effect. But the results remained unexplained for a long time.

At that time it was believed that there was a substance called 'ether' that pervades all of space, and light and other electromagnetic waves are waves in this ether medium. If that be so, the velocity of light as seen from bodies moving with different velocities, i.e., the relative velocities, should be different. In 1887 the American scientists Albert Michelson and Edward Morley tried to detect the relative velocity of light using the motion of the Earth in its orbit employing a very precise spectrometer. They found that the velocity of light through vacuum is the same irrespective of the motion of the observer. This result also remained a mystery for a long time.

In 1896 Henri Becquerel of France was using naturally fluorescent minerals to study the properties of x-rays, which had been discovered in 1895 by Wilhelm Roentgen. He exposed a uranium compound—potassium uranyl sulfate—to sunlight and then placed it on photographic plates wrapped in black paper, believing that the uranium absorbed the sun's energy and then emitted it as x-rays. He found that even when the compound was not exposed to sunlight, it darkened the photographic plates. Thus he serendipitously discovered radioactivity. Subsequently he carefully analyzed the nature of the radiation and showed that it contains charged particles; hence could not be x-rays. Ernst Rutherford conducted further experiments on these rays, and named them alpha, beta, and gamma rays.

Quite a few technological inventions were made in this period that dramatically changed the life-style of people. The electrical generator was invented by Werner von Siemens in 1866. In 1878 Thomas Edison improved the design of the incandescent lamp and made it commercially usable. In 1882, Edison introduced the 110V direct current electrical power supply system in the United States. The Serbian engineer Nicola Tesla immigrated to the United States in 1884. He invented the transformer and the AC induction motor, and using these, the Westinghouse Electric Company introduced the alternating current power supply system in 1888. From the 1890s, electrical power was introduced in most of the industrialized countries. The telephone was invented in the 1870s by Alexander Graham Bell and Elisha Gray. Motor vehicles using internal combustion engines were invented by Gottlieb Daimler in 1885-86. The German engineer Carl von Linde invented a continuous process of liquefying gases in large quantities, which formed a basis for the modern technology of refrigeration. He developed refrigerators employing methyl ether (1874) and ammonia (1876) as refrigerant.

The Impact of Positivism on the Development of Science

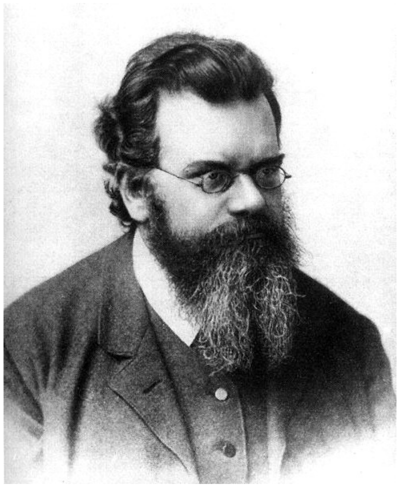
In spite of these advancements in experimental science and technology, it is noticeable that not much theoretical development occurred in the last three decades of the 19th century. The last major theoretical development in biology was Darwin's theory of evolution (1859), that in physics was Maxwell's theory of electromagnetism (1862), and that in chemistry was Mendeleev's periodic table (1869). What was blocking the development of theoretical sciences?

To probe this issue, let us take the case of statistical mechanics in general and kinetic theory of gases in particular. We know that the English scientist John Dalton proposed the atomic theory—which was a major theoretical breakthrough in the first decade of the 19th century. Dalton said that if we continue breaking up any piece of matter into smaller and smaller pieces, in the end we will get tiny particles called atoms, and there are only a few "species" of atoms. All atoms of a given element are identical in mass and properties. Compounds are formed by a combination of two or more different kinds of atoms, and a chemical reaction is nothing but a rearrangement of atoms. This theory helped chemists understand chemical reactions. That is why the chemists started using the theory out of practical necessity.

But most physicists did not recognize the existence of atoms and molecules. From the positivist viewpoint they asked: Have you ever seen a molecule or an atom? Has anybody ever experienced it through sense perceptions? If not, there is no reason to believe that atoms and molecules actually exist. True, that concept helps chemists in their calculation of proportions. But it should not be taken as anything more than a convenient tool of imagination.

Still, a few physicists started using these ideas to develop the kinetic theory of gases. They assumed that gases were made of innumerable small molecules moving randomly at high speed, and then argued that the behaviour of the gas in terms of the relationships between pressure, temperature and volume could be explained on the basis of the average motion of molecules. In 1856 August Kronig (1822-1879) of Germany created a simple model, by considering the translational motion of the particles. The next year, Rudolf Clausius developed a more sophisticated version of the theory by including rotational and vibrational molecular motions as well. In 1859, after reading a paper by Clausius, James Clerk Maxwell formulated the famous Maxwell distribution of molecular velocities, which gave the proportion of molecules having a certain velocity in a specific range. This was the first-ever statistical law in physics. In 1871, Ludwig Boltzmann generalized Maxwell's achievement and formulated the Maxwell-Boltzmann distribution. He also formulated the concept of entropy in mathematical terms, based on probability theory.

These were works of path-breaking importance, as shown by the later developments in physics. But Maxwell and Boltz-



Ludwig Boltzmann (1844-1906)

mann were severely criticized by positivists. The physicist Mach and the chemist Ostwald were particularly unsparing in their criticism of Boltzmann. In 1895 Wilhelm Ostwald gave a talk under the title "The Overcoming of Scientific Materialism" in the city of Lubeck (and later published a book with that title) in which he identified the belief in atoms and molecules with the philosophy of scientific materialism, and attacked both. During Boltzmann's lifetime the physics community did not accept his theory. Why? Because molecules were treated only as figments of imagination. Maxwell and Boltzmann had committed the 'error' of basing their theory on something that were not observable. Boltzmann appealed to the famous scientist Max Planck for support, but did not get it, because at that time Planck was also influenced by the positivist philosophy. Boltzmann was so heartbroken at this rejection of the work of his lifetime that he committed suicide. Such was the influence of the positivist doctrine on physicists.

The Nobel Prize winning scientist Steven Weinberg commented on this episode in his book 'Dreams of a Final Theory' : "Positivism was at the heart of the opposition to the atomic theory at the turn of the twentieth century. The nineteenth century had seen a wonderful refinement of the old ideas of Democritus and Leucippus that all matter is composed of atoms, and the atomic theory had been used by John Dalton and Amadeo Avogadro and their successors to make sense of the rules of chemistry, the properties of gases and the nature of heat. Atomic theory had become part of the ordinary language of physics and chemistry. Yet the positivist followers of Mach regarded this as a departure from the proper procedure of science because these atoms could not be observed with any technique that was then imaginable. The positivists decreed that scientists should concern themselves with reporting the result of observation, as for instance that it takes 2 volumes of hydrogen to combine with 1 volume of oxygen to make water vapour, but they should not concern themselves with speculations about metaphysical ideas that this is because the water molecule consists of two atoms of hydrogen and one atom of oxygen, because they could not observe these atoms or molecules. Mach himself never made peace with the existence of atoms."

The discovery of the electron reveals an even stranger impact of positivism. The year Thomson performed his famous experiment that resulted in the discovery of the electron, the same year a German physicist named Walter Kaufmann (1871-1947) performed practically the same experiment in Berlin. Yet we know the name of Thomson as the discoverer of electron and not of Kaufmann. Why? That was because Kaufmann, who adhered to the positivist doctrine, reported his observation (from which we know that he had obtained a better charge-to-mass ratio of the electron), but believed that it is not his business to say anything beyond the pointer readings of instruments. So he did not realize that he had discovered a new kind of particle!

These are well documented cases. But there may have been many other instances where scientific advancements were nipped in the bud or where scientists were led astray by the belief in positivism before the work reached a stage of maturity where the attempts would be publicly known.

Einstein stands against Positivism

In the formative phase of his life, Einstein was also influenced by the positivist argument. But during his post-college days, when he was actively seeking a correct philosophy to guide his scientific pursuits, he became disillusioned about positivism and embraced the materialist philosophy. All his scientific work carries the mark of his conviction about the existence of matter independent of human consciousness and sense-perception.

Very few know that his first scientific work was to prove the existence of molecules. He argued that if molecules and atoms really exist, their existence would not depend on our consciousness, and on our ability to observe them. But if they exist, and if our theory about them is correct, we should be able to deduce certain manifestations which can be tested. He wrote some half a dozen papers to prove the reality of molecules from different angles, out of which let us mention two important ones.

One is his Ph.D. thesis, entitled "A new determination of molecular dimensions," submitted to the University of Zurich on 20 July, 1905. He forwarded a new line of reasoning to prove the reality of molecules. He argued that if molecules exist, they must have some dimension—however small. The question is, can we measure the dimension? By assuming a molecular picture of a sugar solution, Einstein showed that the viscosity and coefficient of diffusion of the liquid will change due to the mixing of sugar, and the extent of change is dependent on the radius of the solute molecules. Since viscosity and the coefficient of diffusion are measurable, the radius of the sugar molecule can be obtained by measuring these quantities before and after mixing with sugar.

The second research paper proving the existence of molecules was published in the same year in the German journal 'Annalen der Physik', with the title "On the motion of small particles suspended in liquids at rest required by the molecular-kinetic theory of heat." It concerned Brownian motion: pollen particles placed in a drop of water can be seen as moving about in a random fashion in small straight line segments when observed with a microscope. The cause behind this peculiar type of motion was not known at that time. Einstein showed that this particular zigzag motion of the pollen was an important evidence of the existence of molecules. If the apparently stagnant drop of water was composed of millions of molecules, the kinetic theory of heat would require that the molecules should move about at high speeds due to thermal motion. If a pollen particle with size and mass much larger than those of water molecules was placed in the drop, it would be subjected to innumerable collisions with the water molecules. Since the water molecules would strike from all directions, the resultant effect would be a random motion of the pollen particle. It would traverse in a straight path as a result of one collision, and successive collisions would change the direction of motion. If molecules are real, this is what is naturally expected to happen. Since the motion of the pollen particle had been observed, Einstein argued that we had in effect observed molecules in motion.

But this is a qualitative argument. In order to establish a theory—a controversial one at that—it is necessary to talk in terms of quantities on the basis of which it can be objectively tested. So Einstein asked: If the motion of the pollen is completely random, is it possible to say what distance the particle will traverse from the starting position after, say, a thousand impacts? Einstein showed that even though the motion is random, it is possible to work out a probabilistic estimate of the distance traversed, and that it would be proportional to the square root of the time elapsed. This means that if one measured the distance traversed, then the average distance over a number of trials will be approximately equal to that obtained from Einstein's theory. This is something that can be objectively tested. People did the test, and found that the motion of the pollen did indeed follow Einstein's equation.

After such objective proof, it was impossible to question the existence of molecules.

Next, he took up another issue to fight the positivists' position from a materialist standpoint. The nature of heat radiation from a body had intrigued scientists for a long time. After Maxwell's discovery it was known that heat radiation is also electromagnetic wave, which means it is defined by frequency and wavelength, which are measurable quantities. It was found that the radiation emitted by a heated body does not have a single wavelength, rather, it is a mixture of waves of many wavelengths. The natural question was: Is there any law that tells us which frequency component will be emitted in what proportion?

Experimental results obtained from a close approximation to the ideal black body (something that can absorb all the radiation falling on it and whose thermal radiation

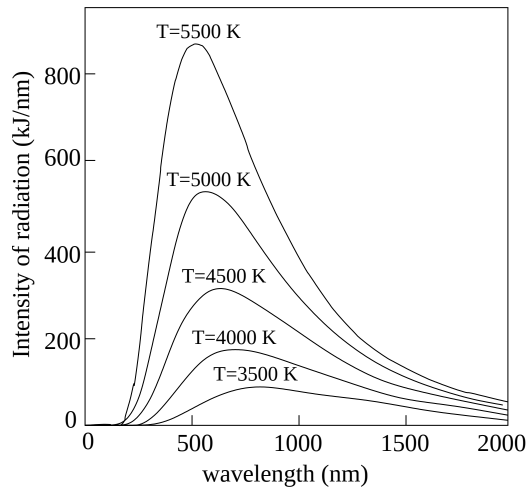


Figure 1: The experimentally observed nature of black-body radiation at different temperatures.

depends only on its temperature) showed a definite relationship between the intensity of radiation and the frequency. For any given temperature of the radiating body, the radiation has a maximum value at a specific frequency, which falls off following well defined curves for higher and lower frequencies (see Fig. 1).

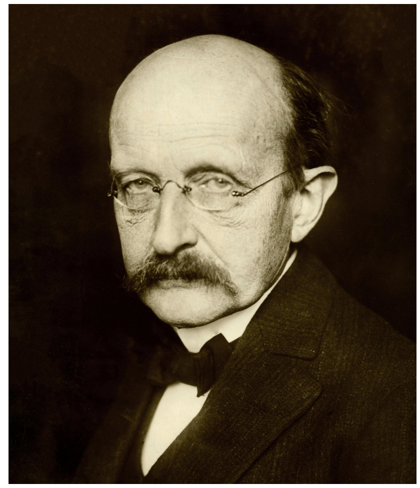
Then scientists faced the problem of explaining why black body radiation follows this specific curve. This is where the crucial problem occurred. Physicists found that if the existing theory is followed, that is, if one assumes that energy is emitted in continuous stream in a wavelike fashion, the predicted graph does not match that obtained from experiment.

When physicists were groping in dark for an answer to the problem, Max Planck showed that if we assume, ad hoc, that energy is not radiated continuously, rather it is emitted in distinct 'packets,' then one obtains exactly the same curve from theory as is obtained from experiment. People were not happy at all: What is this ad hoc assumption that has no basis? Has anybody observed the packets of energy? Has anybody measured? If one assumes for the time being that Planck is right, the quantity of energy in each packet is very small — so small that they would never be observable individually. According to positivist philosophy, what is not observable is not real. The opposition was so intense that Planck's calculation was not accepted by the main body of scientists. Planck also could not forcefully defend his own theory.

In this situation Einstein looked at the problem from a materialist standpoint. If the quanta of radiation exist, their reality would not depend on our consciousness, that is, on our ability to observe them individually. But the fact that Planck's calculation did tally with experimental observation was, to Einstein, an indirect evidence of their reality.

But more direct evidence is needed. He did not have to look very far. Many experimental observations had accumulated over the years that were yet unexplained. The phenomenon of fluorescence and Stoke's rule relating the incident and emitted radiations were not properly understood. It had been observed that gases ionise if radiated with ultraviolet light, and this also was not properly explained. Then there was the photoelectric effect. Einstein solved all these apparent mysteries in another paper published in the same year in 'Annalen der Physik', and showed that all these were evidences that quanta of radiation were not just convenient assumption; they were real.

The case of photoelectric effect has earned some fame, as the Nobel Committee cited this as *the* contribution for which the Nobel Prize was awarded to him (even though it was a small part, Section 8, of his original paper where his main contention was to prove that quanta are real). So let us explain it in some detail.



Max Planck (1858-1947)

It had been observed some years earlier that when light falls on plates made of some metals, electrons are emitted. At first nothing seemed unusual about it, because light has energy, and when light is absorbed by an electron, the energy goes into it. If the energy is sufficient to overcome the electrical attraction of the nucleus, it is natural that electrons will be ejected. Only, it should take some time to accumulate sufficient amount of energy to overcome the electrical attraction, and so it was expected that the electrons would be emitted after some delay. But the experiments showed that the electron flow starts from the moment light falls on the metal plate.

Scientists now looked at the situation carefully. If the incident light is monochromatic, it has a specific frequency (or colour), which can be varied. It can also have a specific intensity which can be varied. In the output side also there are two measurable quantities: the number of electrons emitted and the average kinetic energy of the electrons. It was found that no electrons are emitted below a certain frequency (not intensity). If we choose the frequency above this minimum value and vary the intensity, the number of emitted electrons varies but the energy of each electron remains fixed. If we keep the amplitude constant and vary the frequency, the number of emitted electrons remains fixed but the kinetic energy of the electrons varies.

Einstein showed that these characteristics of the photoelectric effect actually proved the reality of the quantum. If radiation is emitted in packets, it must also be absorbed in packets. Therefore if electrons absorb radiation, the increase in energy will be exactly the same as that contained in one packet. It is not possible to absorb radiation slowly, with continuous increase of energy. If the energy of the electron is to increase, it must happen in one jolt, and if that is sufficient to overcome the attraction, the electron will be emitted. That is why electrons start flowing the moment light falls on the metal plate.

Moreover, as per Planck's assumption, the energy in the packet is proportional to the frequency. Therefore if the frequency is increased keeping the intensity fixed, the number of packets remains fixed but the energy in each packet goes up. On the other hand, if the frequency is kept fixed and the intensity is increased, the energy in each packet remains fixed and the number of emitted electrons goes up. It is clear that if one assumes the quantum nature of light, the whole picture fits in like a jig-saw puzzle. Einstein presented this natural explanation of the photoelectric effect, and thus proved that light quanta are not just figments of imagination. The concept actually reflects the underlying reality, irrespective of our ability to observe individual quanta.

In his special theory of relativity also, he reflected a staunch anti-positivist position. He showed that space and time are relative, in the sense that distances and time-durations between two events would be different as seen by different observers moving at different velocities. When he proposed this, did he have any indication coming from sense perceptions? No. It was based on pure logic. But then, he demanded experimental physicists to check if the predictions of his theory were indeed correct. The predictions of the theory of relativity were found to be true in all experiments conducted so far. It is interesting to note that the same Walter Kaufmann conducted the key experiment that confirmed Einstein's prediction of the change in an electron's mass moving at high velocity.

Similarly, in his General Theory of Relativity proposed in 1916, he showed that space-time itself becomes curved in the neighbourhood of a heavy mass, and other bodies (including light) moves in the shortest path available in that curved space-time. Did he have any inkling of that coming from sense perceptions? No. He just noticed that Newton's theory of gravity was not compatible with the Special Theory of Relativity, and he developed the GTR to resolve the conflict. Thus, it was a product of pure logic. At the same time, he demanded scientists to check the predictions of the theory objectively. The prediction that light would bend when it goes past a heavy body was observationally confirmed during a total solar eclipse in 1919. The prediction on gravitational waves has been observationally confirmed only in 2016, a century after Einstein made the prediction. If we adhered to the prescriptions of positivism, such development of human understanding of nature would not have been possible.

Thus, we see that the cornerstone of Einstein's thought process was the belief in existence of objective reality independent of observer. He believed that sensory experiences provide information about reality, but empirical data do not automatically lead to conceptualization. He underscored the necessity of scientific speculation constrained by empirical facts, and insisted that the emerging picture of reality has to be tested through targeted experiments.

Positivism loses its hold

One of the staunchest proponents of positivism, the Nobel Laureate chemist Wilhelm Ostwald accepted the existence of atoms and molecules in 1908, following Einstein's argument on Brownian motion. Max Planck, who adhered to the doctrine of positivism up to his forties, became its bitter critic. He nominated Boltzmann to the Nobel Prize, but before any decision was made, Boltzmann committed suicide in 1906. Planck later regretted not having defended Boltzmann when he needed it the most.

In the book "Where is science going?" written in 1933, Planck forwarded powerful arguments against positivism. According to him, if positivist ideas are followed, all conclusions of science will turn into 'as-if' statements. For example, if a stick is dipped into a glass of water, it looks bent. That is the observation, and the positivist would state that and only that. He cannot say whether the stick is really straight or bent, because his source of knowledge is his sense-perception. He can at most say that the stick looks as if it were bent.

Einstein, as we have seen, was all along rooted in materialist philosophy. In 1931, on the occasion of the hundredth birth anniversary of Maxwell, he wrote "The belief in an external world independent of the perceiving subject is the basis of all natural science. Since, however, sense perception only gives information of this external world or of "physical reality" indirectly, one can only grasp the latter by speculative means." That is, the scientist has to imagine beyond the immediate sense perceptions, has to formulate hypotheses and postulates, and has to test these against objective reality—in order to unravel the working of nature. "If you want to find out anything from the theoretical physicists about the methods they use, I advise you to closely stick to one principle: Don't listen to their words, fix your attention on their deeds." (Herbert Spencer lecture, Oxford, June 10, 1933).

Werner Heisenberg, one of the originators of quantum theory, was a staunch positivist. Along with Niels Bohr, he was responsible for formulating the positivist interpretaion of quantum mechanics, known as the Copenhagen interpretation. Yet, he, too, was disillusioned towards the end of his life. In an essay titled 'Positivism, Metaphysics and Religion' (1969), He wrote: "The positivists have a simple solution: the world must be divided into that which we can say clearly and the rest, which we had better pass over in silence. But can any one conceive of a more pointless philosophy, seeing that what we can say clearly amounts to next to nothing? If we omitted all that is unclear we would probably be left with completely uninteresting and trivial tautologies."

What was really the problem with Positivism?

What needed to be done was to show, in philosophical terms, why the positivist prescription is not the right way of reaching truth about nature. This was done by the Marxist philosopher and the leader of the Russian revolution, V I Lenin. In 1908 he wrote a book titled 'Materialism and Empirio-Criticism', in which he clearly pointed out the differences of viewpoints of scientific materialism and positivism, and showed that positivism, in effect, comes very close to the idealist position—which is directly opposed to science.

The positivists viewed matter as metaphysical abstraction. Mach wrote, "To us investigators, the concept 'soul' is irrelevant and a matter for laughter. But matter is an abstraction of the same kind, just as good or as bad as it is. We know as much about the soul as we do of matter."

Lenin clarified that the concept of matter is concrete as it comes from abstraction and generalization from the objects existing in the external world. The words "fruit" or "mammal" are also products of generalization. There is no palpably existing thing called fruit. There are mangoes, cherries, bananas, and we get the concept of "fruit" through a process of abstraction and generalization. Similarly, there are tigers, monkeys, deer, etc., from which we form the idea of mammals through a process of abstraction and generalization. That is why the words like "fruit" or "mammals" convey concrete ideas; these are not metaphysical abstractions. The concept of matter is also a product of abstraction and generalization in the same way. "Matter is a philosophical category denoting the objective reality which is given to man by his sensations, and which is copied, photographed, and reflected by our sensations, while existing independently of them."

Next, he asked, are the sense perceptions really the *source* of knowledge, or are they the *means* of knowledge? What is the source of our sensations? What exactly causes excitement at the nerve-ends, which are conveyed to the brain by the nerves, thus giving rise to the sensations? He pointed out that matter, existing independently of our consciousness, act on our sense-organs. Through the sense organs we perceive matter. Thus, matter is the source of sensations, and thence of perceptions. The positivists erred by considering sensations as the source of knowledge, thus eliminating matter from the purview of scientific discussions. The correct approach should be to view matter as the source of knowledge, and sensations and sense-perceptions as the means of knowledge.

Third, he pointed out that knowledge and experience are not the same thing. Experience is personal, and the ideas born out of individual experience are subjective. But knowledge is born out of collective experience; that is why its nature is impersonal. Moreover, knowledge is not the result of 'pure' experience; it is the result of a mixture of experience and logic. Only the application of logical reasoning can filter out unnecessary and irrelevant things from human experience, and can give birth to impersonal knowledge. We see the sun rising from the East, setting in the West, and appearing to go round the Earth. That is our experience. It is only by the application of logic we realize that the sense perception was deceptive, that in reality the Earth is going round the sun while spinning around its own axis. "Knowledge is the reflection of nature by man. But this is not simple, not an immediate, not a complete reflection, but the process of a series of abstractions, the formation and development of concepts, laws, etc., and these concepts, laws, etc., embrace conditionally, approximately, the universal, law-governed character of eternally moving and developing nature."

Then he points out that, in order to obtain correct knowledge about nature, any theory should be tested. And the test of correctness of any idea comes from practice, not from mere sense perceptions. One has to apply that idea to formulate deliberate experiments. One has to try to use that idea to make something that works. Only through practice we can test the correctness of a theory.

And finally, quoting the idealist Bishop Berkeley, Lenin showed that the positivist position is not close to materialism. In fact it is veiled idealism which is directly opposed to science. While materialism says that matter exists independently of our consciousness, idealism holds that matter exists only in our consciousness. By demanding to build science only on the basis of sense perceptions, the positivists effectively said the same thing as idealists did, because sense perceptions are part of our consciousness.

The hangover of Positivism

As the limitations of positivism became clearer, it came to be recognized that science should try to understand the character of the real world existing independent of our consciousness, and for that it should make theoretical constructs about the nature of physical reality—things that are observable as well as the ones that are not observable at a given time. This view came to be known as scientific realism, which says that we can reasonably construe scientific theories as providing knowledge about unobservable entities, forces, and processes, and that understanding the progress of science requires that we do so. It recognizes the objective existence of reality, empirical observations and on their basis theoretical constructs which reflects the truth or approximate truth about reality.

Even though most leading scientists came out of the influence of positivism in the first half of the 20th century, its hangover remained in different fields. Then came a time when exposure to different lines of philosophy was dropped from the education of a scientist. Scientists became indifferent to and unconscious about their own philosophical positions. Most scientists today do not have any exposure to the lines of philosophical thoughts that have accelerated or retarded the march of science in the past, and unconsciously subscribe to idealistic and positivist trends of thought. This is an aspect that is blocking the unrestricted growth of science, because, in the language of Planck, "You cannot be a scientist if you did not know that the external world existed in reality."

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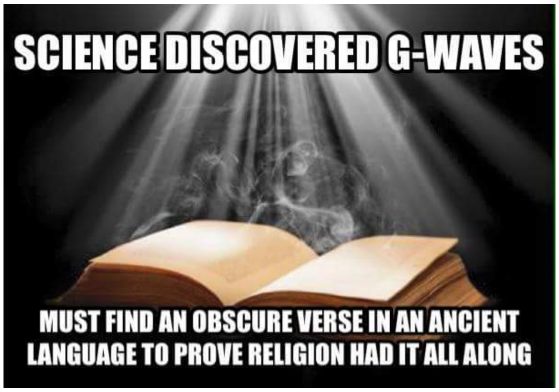
On a lighter note



Organizational News

Observance of Scientific Temper Week

The *Breakthrough Science Society* observed the week from 21 February to 28th February, 2016, as the "Cultivation of Scientific Temper" week. During this week, programmes were organized by all the units of BSS to cultivate scientific temper, to oppose the propagation of pseudo-sciences, unscientific beliefs, and false picture of India's history. The week-long programme culminated on 28th February, the National Science Day, which was observed as "Day of Pledge to Defend Scientific Temper." The following is a brief outline of the programmes organized (a detailed report can be found in our website www.breakthrough-india.org).

Barcelona, Spain

A one-day Science Workshop was organised on 28 February 2016 at Barcelona, Spain. Nine Indian students, mostly PhD and Masters students in various branches of science and technology actively participated and presented the research works they are involved in. The workshop ended with an interactive discussion on 'Science and scientific outlook' and its urgent need in the Indian scenario. The interactive session was led by Dr. Manabendra Nath Bera, member of the Executive Committee of BSS.

Karnataka

Breakthrough Science Society, Karnataka chapter observed the National Science Day on 28 Feb, 2016 by taking out a 'Science March' from Indian Institute of Science to Raman research Institute (RRI), Bangalore. Students from three districts took part in the march raising science slogans and holding placards bearing quotations by great scientists. The program was followed by a seminar at RRI.

Prof Shiv Sethi, Dept of Astrophysics and Astronomy, Raman Research Institute addressed the gathering. He spoke about C V Raman on his life history starting from childhood, education; history of Raman Research Institute and a detailed explanation on Raman Effect. Prof Sethi also commented on Raman's interest in community science activities. Ms Rajani KS (All India Treasurer, BSS), highlighted the importance of National Science day and cultivation of scientific temper. At the end of the seminar, the students were taken to the museum where CV Raman's personal collections are kept. A documentary on great scientists was also shown.

27 Feb, 2016: BSS Karnataka chapter organized 'Science March' on the eve of the National Science Day, at various localities of Bangalore such as Basaveshwaranagar, Malleshwaram and Basvanagudi. Similar programs were held in Dharwad, Gulbaraga and other districts of Karnataka. Students from schools, colleges along with teachers marched along streets raising science slogans and holding banners depicting quotations from great scientists on the need for fostering scientific temper. The students took pledge to defend scientific temper and to uphold the ethics and culture of sci-

The Science March in Bangalore on the occasion of the "Day of Pledge to Defend Scientific Temper" on 28th February, 2016.

ence. A miracle exposure programme was conducted by Mr Nandish at KLE College Rajajinagar.

In Kalaburagi, Gulbaraga, 'Science March' was conducted from Mini Vidhana Soudha to the Science Centre on 27 Feb, 2016. 300 students from 5 different schools participated in the march and took pledge to defend scientific temper.

Andhra Pradesh and Telengana

BSS Hyderabad chapter along with Yuva Sahithi Sravanthi organised a miracle exposure show and a drama at Lamakhan, a public meeting place in the city on 21 Feb, 2016. A miracle exposure show was also organised at Master Talent School, Khairathabad, Hyderabad on 27 Feb, 2016.

BSS Kurnool city committee organised its 2nd conference at Dr. K. V. Subbareddy College of Engineering for Women, Kurnool, on 22 Feb, 2016. Around 220 delegates from various Colleges actively participated in the conference. Ms Rajani K S, Treasurer, BSS All India Committee, was the Main speaker.

Bihar

The Einstein Science Club, Jamalpur, organized a discussion on the book 'Science in Ancient India – Reality vs Myth' on 14 Feb, 2016. Members of the club discussed the various topics in the book such as science in Indus valley Civilization, the Vedic period, the post-Vedic period, etc. The discussion was summarized by Mr Swapan Chatterjee.

Gujrat

The Universe Science Forum organised a photo exhibition on 'Charles Darwin and the Theory of evolution' at M. G. Science College, Ahmedabad on 15 Feb, 2016.

Jharkhand

A science exhibition and a seminar were held at Ghatshila College on 28 February, 2016. The chief guest was Dr R P P Singh, Vice Chancellor, Kolhan University. Nearly 500 students participated in the program. In Aditpur and Chandil, discussions and science experiment demo programs were organised and in Jamshedpur, a seminar was held.

BSS Bokaro unit organised a seminar on 'Development of Science in Ancient India' at Hindi Sahitya Parishad, Chandrapura on 27 Feb, 2016. Mr B N Saha, Chief Engineer and Project Head, was the chief guest. Mr Kanay Barik, Jharkhand state in-charge was the main speaker. Quotation exhibition and debate competition were conducted on 28 Feb, 2016.

Uttar Pradesh

On 28 February, a seminar was organised at Harcourt Butler Technological Institute (HBTI), Kanpur. Thye speakers were Prof Brajesh Singh Katiyar of HBTI and Mr Dinesh Mohanta, Member, National Executive, BSS.

On the occasion of National Science Day, a discussion was organised on 'Science in Ancient India' at George Town in Allahabad, UP on 29 February. Mr Dinesh Mohanta conducted the discussion.

A state level discussion was organised in Lucknow on 28 February. Dr Sarjeet Sensarma, Member of State Advisory Body of BSS and Professor in Geology, Lucknow University was the main speaker.

Tamilnadu

Madurai: BSS Madurai chapter organised a two-day Science Workshop on Feb 26-27, 2016 at Gandhi Museum, Madurai. Dr R Murali, former Principal, Madura College, inaugurated the workshop. A booklet in Tamil titled 'The Achievements of Science in Ancient India' was released on the occasion.

Theni: A science discussion was held at Theni on 28 Feb. Dr Dipankar Datta, Chief Medical Officer, Aravind Eye hospital and Dr R Venkatesan spoke.

Villupuram: A meeting was held at Kalvikendra Rural Community Training Centre, Vikravandi, Villupuram on 22 February. Mr A Anavaradhan was the main speaker.

Chennai: Quotation exhibitions were held in public parks in Perambur and K K Nagar, Chennai. On 26 Feb, a Science Day program was held in Corporation High School, Vysarpadi, Chennai. Mr Ilango Subramanian, Retd BSNL engineer and a science communicator spoke to students.

On 28 February, a public program was conducted at Sivan park, KK Nagar, Chennai. Dr Subbaiah Pandian, Principal, Govt Women's College, Pudukottai and a National award winner for science communication conducted a two hour long science demo program that thrilled the audience.

Kerala

Kozhikode: A workshop on 'Science in Ancient India – Reality and Myth' was organised on 20 Feb, 2016 at Kozhikode, attended by BSS members from northern districts of Kerala. Mr G S Padmakumar presided. Prof. K P Saji and Dr. P P Rajeevan made presentations in the workshop.

A public lecture on the life and contributions of Giordano Bruno, the first martyr of modern Science was held at Sports Council Hall, Kozhikode on Feb 20. Mr G S Padmakumar was the main speaker.

Palakkad: A public meeting was organized on 25 Feb, 2016 under the auspices of Madame Curie Science Club, affiliated to BSS at Anicode, Chittur, Palakkad. Ms. K M Beevi addressed the gathering.

Thiruvananthapuram: A workshop on 'Science in Ancient India' was organised on 27 Feb, 2016 in association with Kerala State Science and Technology Museum at Priyadarsini Planetarium, Thiruvananthapuram. Mr G S Padmakumar presided. Mr P S Gopakumar, Prof P N Thankachan and Dr P P Rajeevan made presentations.

Ernakulam: BSS Ernakulam district chapter organised a public programme on 28

Dr. Murali addressing the workshop in Madurai, Tamil Nadu, 26-27 February, observing the "Cultivation of Scientific Temper" week.

Feb, 2016 at Marine Drive, Kochi on the occasion of National Science Day. The book titled 'Science in Ancient India – Reality versus Myth' was released by Prof. M K Prasad by giving a copy to Mr N Venugopal, Chairman, GCDA. A sky watch program was arranged at the end of the meeting.

Alappuzha: A public meeting was organised on 28 Feb, 2016 at the Alappuzha beach. Dr. K Hariprasad and Dr. P S Babu spoke. A documentary film on the life and contributions of Albert Einstein was screened after the meeting.

Thuravur: A science day program was organised on 29 Feb, 2016 at S N G M Senior Secondary school, Thuravur. The book 'Science in Ancient India – Reality versus Myth' was released by Mr P R Ramachandran, Principal of the school.

Kottayam: Astronomy club, Kottayam affiliated to Breakthrough Science Society organised a meeting in association with Astronomy club of Karappuzha NSS High School on 27 Feb, 2016. Mr. Benny Joseph and Mr. K Thankappan spoke on the occasion.

Pulari Balavedi, Thiruvanhoor, Kottayam organised a meeting on 29 Feb, 2016 to observe National Science Day. Mr. P G Sasikumar, Mr. A N Sudeesh and Ms. Ashna spoke.

Vaikom: Breakthrough Science Forum, Vaikom affiliated to BSS, organised a meeting on 28 Feb, 2016. Prof. P N Thankachan and Mr. Babu, Lecturer, Govt. Polytechnic College, Kottayam were the speakers.

Vadakara: C V Raman Science Club, Vadakara, affiliated to Breakthrough Science Society, organised a meeting on 28 Feb, 2016. Prof. P N Thankachan was the main speaker.

Changanacherry: Netaji Balavedi, Pankipuram, Changanacherry organised a meeting on 28 Feb, 2016 to observe of National Science Day. Mr. P G Sasikumar, Ms. K S Sasikala and Mr. K N Rajan were the speakers.

West Bengal

Book stall and literature campaign were conducted at Jadavpur University, Presidency University, Moulana Azad College, Dumdum and Asutosh College during 22-27 February.

A science convention was organised by Progressive Science Association, Kolkata at Kailash Vidya Mandir on 28th February. Dr Nilesh Ranjan Maity was the main speaker.

11 Feb, 2016 – A Sky Watch programme was organized by Galileo Science Forum, Nimta, Belghoria.

17 Feb, 2016 – To observe the Science Martyrs Day, a Sky watch program was organised by the members of Madame Curie Science Society, Sarsuna, Kolkata.

Geordano Bruno Science Society of Purulia town organized a Book Stall on 21-23 Feb. Adra Science and Cultural Forum of Adra town organized a Book Stall on 27 February.

A discussion was organized on 28 Feb at Mohananda High School, Minapore town. Prof. Debashis Aich was the speaker.

A seminar was organized in Belda on 28 Feb. Topic of the seminar was 'Science and Ethics', Speakers – Prof. Bashudev Dhara and Dr. Soumen Bag.

Science Martyrs Day was observed at Rajabazar (Midnapur town), Jhargram, Sabang and Belda on 17th February.

A cycle rally was organized by the students and teachers at Fulia, Nadia on 28 Feb. After the programme students, teachers and science loving people gathered to form a Science club and named it 'Juktibadi Jagoron Mancha, Fulia, Nadia'.

On 28 Feb, an awareness program on food adulteration was held at Tulsighata (Joynagar). Prof. Debabrata Bera was the speaker.

17 Feb: Discussion on Giordano Bruno at Panskura Banamali College seminar hall. Dr. Radhakanta Konar conducted the discussion.

21 Feb: Discussion on Giordano Bruno at Deulia School organised by Satyen Bose Bigyan Sanstha. Speaker: Sri Sumanta Shee and Sri Swapan Jana. In the evening sky watch program through telescope was organized.

21 Feb: Discussion on Giordano Bruno was organized by Mahisadal Science Society. Speaker: Sri Sidhartha Roy. The science club committee was reorganised.

27 Feb: Discussion on Giordano Bruno at Palpara. Speaker: Sri Nimai Pradhan. A new science club has been formed.

27 Feb: Discussion on Giordano Bruno was organized by Bajkul Science Society. Speaker: Sri Gopal Mandal.

28 Feb: Tamluk Science Society organized a discussion on 'Giordano Bruno and How to Defend Scientific Temper'. Speaker: Dr. Madhusudan Jana.

28 Feb: Contai Science Society organized a discussion on 'Giordano Bruno and How to Defend Scientific Temper'. Speaker: Sri Abhijit Mondal.

28 Feb: A discussion was organized by Haldia Science Society. Speaker: Prof. Sanjib Kuila. The science club committee was reorganised.

Kolkata International Book Fair: BSS West Bengal Chapter participated at the 40th International Kolkata Book Fair held at Milan Mela Prangan from 27th Jan to 7th Feb 2016. Many book enthusiasts visited the BSS stall. The total sale of magazines and books was Rs. 24611.

Nature Study: 7 Feb, 2016 – The west Bengal state chapter of BSS organized a Nature Study program at the AJC Bose Indian Botanic Garden, Shibpur. More than a hundred enthusiastic nature lovers thronged the Garden from morning till evening. Dr Nilesh Maiti, Sri Subrata Gouri and Dr Safiq-Ul Alam guided the study program.