Nobel Prize in Physics – 2018

Debabrata Goswami

On Tuesday, 02 October 2018, Arthur Ashkin of the United States, who pioneered a way of using light to manipulate physical objects, shared the first half of the 2018 Nobel Prize in Physics. The second half was divided equally between Gérard Mourou of France and Donna Strickland of Canada for their method of generating high-intensity, ultra-short optical pulses. With this announcement, Donna Strickland, who was awarded the Nobel for her work as a PhD student with Gérard Mourou, became the third woman to have ever won the Physics Nobel Prize, and the 96-year-old Arthur Ashkin who was awarded for his work on optical tweezers and their application to biological systems, became the oldest Nobel Prize winner. According to Nobel.org, the practical applications leading to the Prize in 2018 are tools made of light that have revolutionised laser physics – a discipline which in turn is represented by generations of advancements and not just a single example of brilliant work.

Debabrata Goswami is a Senior Professor at Indian Institute of Technology Kanpur, and holds the endowed Prof. S Sampath Chair Professorship of Chemistry. His research work spans across frontiers of interdisciplinary research with femtosecond lasers that have been recognised globally, the latest being the 2018 Galileo Galilei Award of the International Commission of Optics. As a part of his doctoral thesis at Princeton, Prof. Goswami developed the first acousto-optic modulated ultrafast pulse shaper, wherein the 2018 Physics Nobel Laureate, Prof. Strickland, also participated as a postdoctoral fellow in the same laboratory.

It is easy to take lasers for granted; more so in 2018, as they are a near-ubiquitous symbol of technological acumen. Light may be a wave, but producing coherent (in-phase), monochromatic (of a single wavelength), and high intensity (high power) light is still non-trivial. These are just some of the factors that make lasers and their study so unique. Lasers are used at a lab scale for machining, spectroscopy, and various detection tools. They are also amongst the most sensitive instrumental probes possible for large scientific equipment to measure disturbances. For example, Laser Interferometer Gravitational-Wave Observatory (LIGO) measures tiny changes in spatial distances when a gravitational wave passes.

Keywords
Nobel, lasers, optical tweezer, pulses, chirped pulse amplification.

However, lasers are also used for atmospheric remote sensing, optical communications, for measuring the distance to the Moon, quantum optics, and for creating artificial 'guide stars'

Figure 1. Physics Nobel Laureates for the year 2018: Arthur Ashkin (left most), Gérard Mourou (middle) and Donna Strickland (right most). (Photo courtesy and copyright of Nobelprize.org.)

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in astronomy. Nevertheless, lasers go well beyond mere engineering and industrial applications. They are the fundamental probes for expanding human perception to the extremities of measurement and nature itself. They are used in laser cooling that achieves the coldest temperatures ever reached and in confining atoms into Bose–Einstein condensates. Pulsed lasers are the essential components in attempting to develop nuclear fusion on Earth through inertial confinement fusion. There are several applications of lasers in various sectors including medicine (like eye surgery and cancer treatment), military (like laser sights and laser targeting), and industries (laser etching, welding, and drilling). The barcode readers at the supermarkets are also laser-based.

Despite their widespread use, it is important to realise that the laser was invented only in 1958, and as such is still relatively novel. Laser is a bit of a misnomer as well since, Light Amplification by Stimulated Emission of Radiation (LASER), has in reality, nothing to do with amplification. Lasers, in their basic generation scheme, work by the emission of photons due to the controlled electron oscillations between allowed states (ground and excited). Since their invention, scientists have devised several ways for improving the properties of lasers, e.g., by finding different materials for making electronic transitions at different energies, one can create tunable lasers with a large variety of constituent wavelengths. Similarly, by optimising the collimation (parallel) design of lasing systems, the density of laser light generated can be increased tremendously at long distances to result in many more photons-per-unit-volume than might be otherwise attainable. One can also create a more energetic and powerful laser using a better amplifier. However, what is often more important than power is control. If we could control the properties of the laser, we would be able to explore an entirely new range of possibilities involving the probing and manipulation of matter and other physical phenomena. That is where the 2018 Nobel Prize in Physics comes in.

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The Nobel Committee in 2018, recognised the work of three scientists (*Figure* 1) as instrumental to the task of harnessing laser light for miniaturised tools. Arthur Ashkin invented 'optical tweezers' which utilize light 'pressure' from highly focused laser beams to manipulate microscopic objects, including living organisms like viruses and bacteria. This revolutionary discovery allowed Ashkin to realize a long-cherished dream of humanity, much anticipated in science fiction, i.e. the ability to use the light radiation pressure to move physical objects. He demonstrated how the potential well of a laser could push small particles towards the beam's centre, and hold them there [1]. By altering the configuration of the experimental setup, the same principle of light allowed myriads of physical objects to be pushed around. Motion through photon flux is not about high levels of power; it is more of a precision optimization as precise control is paramount. Soon after the invention of the optical tweezers, Ashkin began studying biological systems. However, the ramifications of his theory and instrumentation were still not resolved, and experimentalists were at a loss on how to amplify high-energy laser pulses without damaging the amplifiers.

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It is imperative to note that light is always an electromagnetic wave irrespective of how it is produced and as such, it creates oscillating electric and magnetic fields as it travels through space. Both electric and magnetic fields are in-phase and perpendicular to one another, and their strength can increase, decrease, reverse direction, or continue to propagate in that oscillating pattern. If we could control these electromagnetic fields arising from light, by controlling their direction and magnitude in a particular region of space, the interaction of light and matter at any location could be manipulated.

The ability of lasers to manipulate matter has been long anticipated in science fiction and exemplified by the fictional technology of 'tractor beams' used to pull large objects through space with great precision.

Such an ability to manipulate matter has been long anticipated in science fiction and exemplified by the fictional technology of 'tractor beams' used to pull large objects through space with great precision. Half of the 2018 Nobel Prize in Physics has gone to the development of optical tweezers, which are the real-life analogue of such technology. However, crucially, one might not want to (or be able to) control the electric and magnetic fields directly, but instead may vary the power and pulse frequency of the laser. Typically, one thinks of laser light as being emitted continuously, but that is not necessarily true. Another option instead would be to produce all the energy associated with a continuous wave (CW) laser in a single, short burst after storing the laser light emitted. This laser 'pulse' may be achieved entirely in one go or could be repeated periodically, with the potential for the repetition at frequencies that can be relatively high. The biggest danger in building up a short, ultra-powerful laser pulse is that it would destroy the material that is used to amplify the light. Thus, one of the Rosetta stones for the manipulation of matter with light has been the ability to emit a short-period, high-energy pulse. Unleashing that power would lead to a suite of new applications for laser physics. Gérard Mourou and Donna Strickland solved that exact problem. In their revolutionary paper [2], they detailed how exactly they created an ultra-short, high-intensity laser pulse repetitively, while the amplifying material remained unharmed. The basic setup involved four simple steps:

(1) First, they produced relatively standard laser pulses.

(2) Then, they stretched the pulses in time to reduce their peak power and in turn, render them less destructive to the material.

(3) Next, they amplified the time-stretched, reduced-power pulses, without worrying prohibitively about the amplifying material getting damaged.

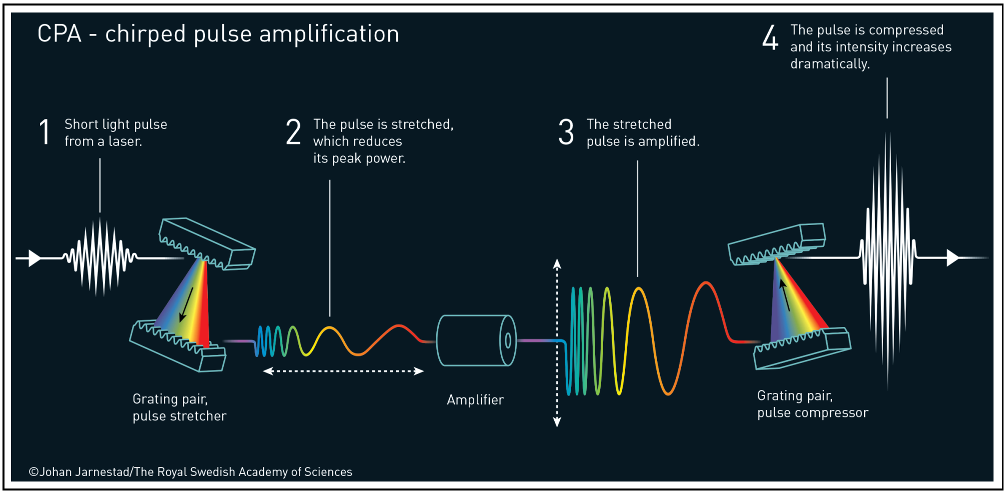

Figure 2. Schematics of CPA. (Photo courtesy: Nobelprize.org, Attribution: Johan Jarnestad/The Royal Swedish Academy of Sciences.)

(4) Finally, they compressed the amplified pulses in time. The generated intense laser pulses from the process last only a femtosecond, which is one-millionth of a billionth of a second.

As the pulses get shorter in time, their energy content and intensity increase massively. Thus, the method of 'Chirped Pulse Amplification' (CPA) was developed that lead to high-intensity, ultra-short laser pulses (*Figure* 2).

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An immediate slew of a wide range of real-world applications followed as a result of this innovative development – enabling manufacturers to drill tiny, precise holes, and leading to the development of Lasik eye surgery. It is understood that CPA may eventually be employed for accelerating subatomic particles, replacing giant contraptions like the Large Hadron Collider with tabletop experiments, etc. As stated by Robbert Dijkgraaf, Director of the Institute for Advanced Study, Princeton, New Jersey, "bigger is not necessarily better," in the physics of tomorrow.

However, the path to the recognition of these seminal contributions to science was not as straightforward as might be expected from the applications of this body of work.

Arthur Ashkin was born in New York City in 1922 and went on to receive his undergraduate degree from Columbia Univer-

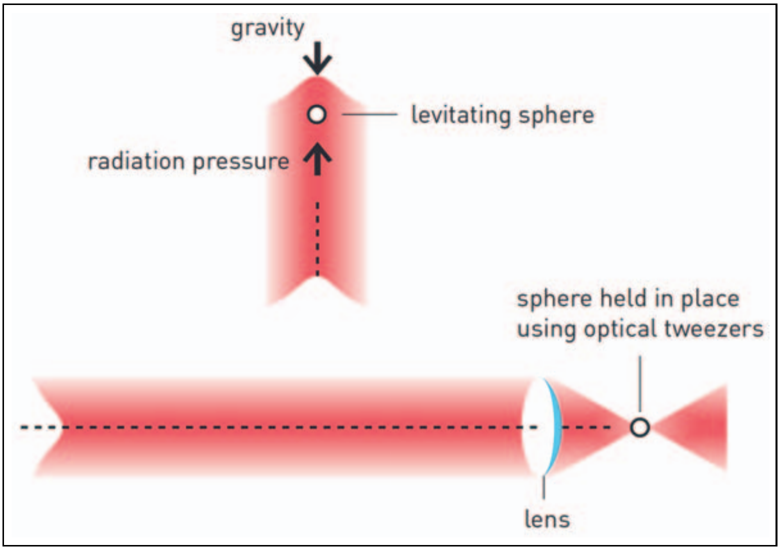

Figure 3. Schematic of 'optical trapping' of a bead by a laser beam.
(Photo Courtesy: Nobelprize.org, Attribution: Johan Jarnestad/The Royal Swedish Academy of Sciences.)

Ashkin reasoned and proved that the same light pressure that sweeps from a comet's tail could be used to push a micron-sized ball around in the lab. He demonstrated unequivocally that the forces at play within the laser beam drew a bead into the centre of the laser beam and trapped it there.

sity in physics in 1947. In 1952, he received a PhD in nuclear physics from Cornell and joined Bell Labs, Murray Hill, New Jersey, wherein he worked until 1991. In the 1960s, he began experimenting with lasers almost immediately after their conception. Ashkin reasoned and proved that the same light pressure that sweeps from a comet's tail could be used to push a micron-sized ball around in the lab. He demonstrated unequivocally that the forces at play within the laser beam drew a bead into the centre of the laser beam and trapped it there – the first step towards optical tweezers (*Figure* 3). David G Grier, a physicist at the New York University and a former colleague of Ashkin at Bell Labs, said, "Optical tweezers were not an invention, they were a surprise." For Grier, that was a new frontier of science, a field unlocked by the fact that light can pull.

In 1987, Ashkin was able to show that optical tweezers could be used non-destructively for the capture of live bacteria, without harming them or modifying their physiology. Since that watershed advancement, optical tweezers have been used for studying biological systems and for investigating at the scale of individual cells or smaller, the machinery of life. As envisioned by Ashkin, optical tweezers have thus been especially important in biological research on viruses and other microbes.

Steven Chu, currently at Stanford University, had worked with Ashkin at Bell Labs and had received the 1997 Nobel Prize in Physics, for using optical tweezers to investigate the quantum mechanical properties of atoms. Though Ashkin was overlooked at that time, his focus on the biological applications of optical tweezers has yielded a prolific body of work. The Nobel Committee's recognition of his fundamental contribution is most apt.

The biological applications of optical tweezers has yielded a prolific body of work.

The remaining half of the 2018 Nobel Prize in Physics was awarded jointly to Gérard Mourou (74 years) of the Physics Department at the École Polytechnique in France, and Donna Strickland (59 years), an Associate Professor of Physics at the University of Waterloo, Canada "for their method of generating high-intensity, ultra-short optical pulses." Their work formed the foundation towards the shortest and most intense laser pulses ever created. Their article [2] was published in 1985 and was a cornerstone of Strickland's doctoral thesis.

Gérard Mourou was born in 1944 in Albertville, France, and earned a PhD from the University of Grenoble in physics in 1973. Presently, he is the Director of the International Center for Zetta-Exawatt Science and Technology that focuses on studying ultrafast laser pulses of high-intensity. Before returning to France, Mourou spent thirty years in the United States. He was initially at the University of Rochester and then at the University of Michigan, where he remains an Emeritus Professor. He took Donna Strickland as a graduate student at the University of Rochester. Mourou is a highly decorated laser physicist, credited not only with the CPA technique but also as a renowned administrator, who has led several large laser infrastructure projects to fruition across Europe.

Donna Strickland was born in 1959 in Guelph, Ontario. She heads a research group called the Ultrafast Laser Group at the University of Waterloo. One of her favourite activities in the laboratory is to generate white light, which is a full-colour spectrum from a narrow bandwidth of wavelengths. However, before her recognition by the Nobel Committee, her work did not get widespread attention.

As a part of her dissertation research, Donna developed the CPA technique that became the standard for generating high-intensity lasers. Its uses include the millions of corrective eye surgeries that are conducted every year using the sharpest of laser beams. Strickland expressed hope in a telephone news conference after the declaration of the Prize that CPA might one-day help cure cancer.

Donna Strickland joins the league of Marie Curie (1903) and Maria Goeppert Mayer (1963) as the third woman to win a share of the Nobel Prize in Physics.

The societal impact and connotations of the Award are also very bracing. Strickland was surprised to note that she is only the third female Nobel Laureate in physics. She said. "I don't know what to say," and continued, "I thought it might have been more than that". Donna Strickland said in an interview with NobelPrize.org (the official website of the Prize) that she suspected that it might be a prank when she first heard that she had been awarded the Nobel. About her work with short-pulse lasers, she said, "It was just a fun thing to do, and so I enjoyed putting many hours into it". Her upbeat attitude has always been a hallmark of her approach to scientific problems as I recall from my PhD days with Prof. Warren S Warren at Princeton, where she was a postdoctoral fellow [3]. Strickland joins the league of Marie Curie (1903) and Maria Goeppert Mayer (1963) as the third woman to win a share of the Nobel Prize in Physics. On learning about this rarity, Strickland noted that it is important to celebrate women physicists as that is indeed a fact and that she is honoured to be one of those women physicists. Arthur Ashkin stated that he is busy expanding the frontiers of science to advance solar energy, and is not willing to celebrate old achievements. Indeed, after the announcement on 02 October 2018, the Royal Swedish Academy of Sciences said that Ashkin was not available immediately for comment because he was busy with his next scientific paper. What could be more rewarding than celebrating life in such a glorious and fulfilling way – bagging the Nobel Prize and still being busy with the next scientific paper!

Suggested Reading

[1] **Arthur Ashkin, Acceleration and Trapping of Particles by Radiation Pressure, *Phys. Rev. Lett*., 24, 156, 1970.**

[2] **Donna Strickland and Gérard Mourou, Compression of Amplified Chirped Optical Pulses, *Opt. Commun*., 56, pp.219–221, 1985.**

[3] **Curt W Hillegas, Jerry X Tull, Debabrata Goswami, Donna Strickland, and Warren S Warren, Femtosecond Laser Pulse Shaping by Use of Microsecond Radio-frequency Pulses, *Opt. Lett*., 19, pp.737–739, 1994.**

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