The 2018 Nobel Prize in Physics: A gripping and extremely exciting tale of light

The 2018 Nobel Prize in Physics honours three pioneers who used and shaped light in fascinating ways. As is typical of major breakthroughs, their research has not only re-energized an entire field of science and technology (S&T), but spawned several new areas which have pushed the frontiers much farther.

The Nobel Foundation awarded one half of the Prize to Arthur Ashkin 'for the optical tweezers and their application to biological systems' and the other half jointly to Gérard Mourou and Donna Strickland 'for their method of generating high-intensity, ultra-short optical pulses'.

It is being widely acknowledged that this Prize is a recognition of the laser as a tool for S&T. There is, however, an interesting contrast between the two halves of the Prize. The first half uses well-established, easily accessible technology to manipulate material particles, including live cells and viruses. Also, continuous-wave lasers with modest power are used. The second half goes to the other extreme – it uses ultrashort light pulses, manipulates them to increase their energy and creates ultrahigh powers in a compact geometry on a table top. By doing so, it creates monstrous light intensities in a small footprint which unleash applications in S&T that were not even dreamt of earlier.

Before I proceed further, let me point out that there is a great deal of lucid, well-illustrated material on the internet that can be readily accessed for learning about the work of these three Nobel laureates and its significance. I therefore choose to provide a personal perspective on the science/technology and its impact, with some sidelights thrown in.

A gripping tale

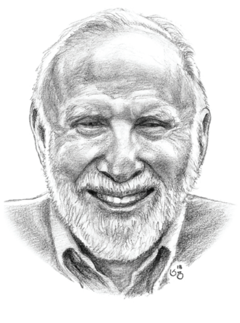
Arthur Ashkin, working at the Bell Laboratories, USA, did path-breaking experiments where he showed that the radiation pressure of light could actually push, hold and steer atoms and macroscopic particles[1]. The story of such manipulation of course began much earlier. It is now a part of undergraduate physics that light can exert 'radiation pressure' and move matter. From the time Maxwell proposed his theory of electromagnetic waves and their momentum in the 19th century, several experiments have been performed to observe these effects[2,3], a famous one being that by Beth[4] which measured angular momentum of light. It is now common knowledge that comet tails are pushed away from the sun by the radiation pressure of sunlight. Even electrostatic fields can squeeze matter via the gradient force, i.e. where the field has spatial variation – this is known as the Landau–Lifshitz force[5]. In the late fifties and during the sixties, Soviet physicists Gaponov and Miller[6], and Askaryan[7] considered the effect of the gradient force on particles in gases and plasmas.

The idea[1,8,9] is quite simple (Figure 1). Take a particle made of a material that is transparent to light of a certain colour and which has a refractive index larger than that of the medium in which it is placed (say air or a liquid). Place it in a light field that has intensity variation across the region occupied by the particle. All materials are polarizable and the light induces fluctuating dipoles in the material. These dipoles interact with the light field gradient resulting in a force that guides the particle towards the brighter region of light – if the light has a maximum intensity at the centre of the particle, the particle would be pulled to the centre. The opposite would happen if the particle has a refractive index less than that of the medium, i.e. it would move towards the darker region of the light field.

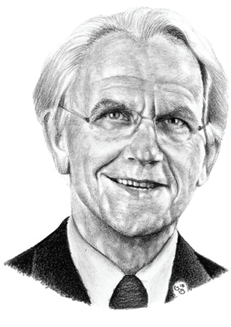
The crucial experiment that Ashkin[1] reported in 1970 was trapping a micron-sized dielectric sphere in two counter-propagating continuous laser beams from a low-power laser. He showed that the laser field gradient could create a potential well to trap the particle. With tight focusing to generate 100,000,000 W/cm^2 of irradiance, the lasers could exert an acceleration as large as 100,000 times the gravity of the earth on a sphere of 1 μm diameter with a light reflectivity of 10% (ref. 10). In the next decade or so, Ashkin extended this concept to steering, cooling and trapping atoms – all these ideas were encapsulated in the 1970 paper. That paper, of which he is the sole author, is therefore remarkable for the conceptual sweep and the insights it provides. A beginning student would marvel at the simple explanations provided there.

Apart from its conceptual simplicity, the idea opened up fantastic possibilities for levitating and studying particles in vacuum (free from frictional forces) and isolating them from the effects of contaminating environments, if one wants to study the optical properties of a molecular sample by itself or by coating it on the microsphere. In fact, by the early 1980s scientists had begun to use this widely and it had become part of textbook material[10]! As a Ph D student I was astonished to hear a talk on the Raman spectroscopy of a particle levitated in free space[11] at a laser conference at IIT Kanpur in the mid-eighties. Ashkin's path-breaking work was the main inspiration for all laser-cooling experiments that were to follow and which won two Nobel Prizes in 1997 and 2001 (refs 12, 13). Ashkin however had to face discouragement in this pursuit[14].

Ashkin kept 'pushing and steering' the field throughout the seventies and the next decade, and provided a remarkable step forward when he used laser beams to trap viruses (Figure 2) and single



Arthur Ashkin



Gérard Mourou

Donna Strickland

molecules in the late eighties[15]. This would revolutionize the study of these systems in biology and chemistry, and these areas exploded with activity. The exciting possibilities that opened are captured in several books and today, there are thousands of labs with simple, low-cost tweezers which are used to push, pull and steer single cells and particles and study the mechanics, thermodynamics and optics of those systems. Roop Malik and his colleagues[16] (TIFR, Mumbai) demonstrated the action of molecular motors in intracellular dynamics using an optical tweezer (Figure 3).

It was widely expected that Ashkin would be honoured with the Nobel Prize for these efforts long ago, but that was not to be. In fact, the Nobel lectures of Steve Chu[12] and Bill Phillips[13] in 1997 begin by paying elaborate tributes to Ashkin's work, and how it motivated them to cool and trap atoms in the eighties. Ashkin showed the world how to trap particles, but could not get an early grip on the Prize for himself.

Extreme light

Soon after the laser was invented by Maiman[17] in the summer of 1960, rapid strides were made to produce short pulses of light with high 'peak' power. This can be understood in the following manner: If light energy of 1 J is emitted in 1 sec, it gives us a power of 1 W. If the same energy is delivered in a nanosecond (a billionth of a second), the peak power (energy/duration of emission) of such a pulse would be a gigawatt (billion watt). One can increase the energy by putting more and more amplifiers. From the mid-sixties to the mid-eighties, the pulses shrank in duration to picosecond and femtosecond but the peak power (in most short pulse laser systems) remained at the gigawatt levels. The reason for this is simple. As the pulse energy is amplified and the peak power increases, the materials in the light amplifier and the optical components used cannot survive the high intensity due to nonlinear effects and get damaged. In fact, in the eighties the highest peak powers (terawatt scale) were obtained only in the nanosecond pulse regime and to get to those peak powers on that timescale, the energy had to be very large (kilojoules) and the lasers gigantic in size and needed huge input power.

In this period, however, a great deal of the optics of femtosecond and picosecond pulses – the phase and frequency changes they undergo on propagation – was being understood and scientists became more and more capable of manipulating these pulses in terms of the spectrum they possessed and the smallest duration that could be produced[18]. In fact, in the mid-eighties, pulses as short as 6 fs were produced in a dye laser[19]. Simultaneously, the fact that material properties (refractive index, for example) changed dramatically as light peak power increased was observed, modelled and understood.

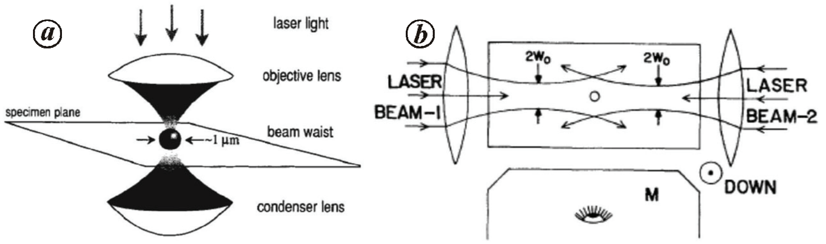


Figure 1. (***a***) The concept and schematic of optical tweezers. (***b***) The experiment by Ashkin[1]. For simple summaries on tweezers, see refs 8, 9. Reprinted (Figure 1 ***b***) with permission from Ashkin, A., *Phys. Rev. Lett.*, 1970, **24**, 156–159. © 1970 by the American Physical Society.

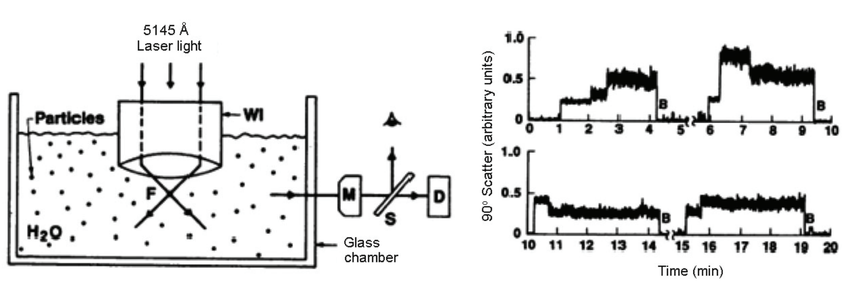


Figure 2. Optical trapping of virus and bacteria, which show increase in scattered light as they enter the optical trap[15]. (Reproduced from Ashkin, A. and Dziedzic, J. M., *Science*, 1987, **235**, 1517–1519, with permission from AAAS).

To understand the contribution of Mourou and Strickland, let us delve a little more to the high peak power (high intensity) regime. The peak power is boosted by successive amplification of laser pulses in a set of light amplifiers. As peak power increases, the larger electric fields give rise to nonlinear processes. One of the nonlinear processes discovered soon after the laser was born is self-focusing. This occurs because the refractive index of a medium gets modified by the light and a focusing nonlinear lens can be formed by the Gaussian transverse spatial profile of the propagating laser beam inside the amplifiers, leading to such large intensity that the amplifying medium or other optical components break down[10]. Peak power is energy/pulse duration and the shorter the pulse, higher is its peak power. Ultrashort pulses, therefore, can barely be amplified before they reach the power that can be damaging. So it is really difficult to amplify femtosecond pulses beyond a certain peak power.

A look at the history of science tells us that many a time, 'insurmountable' problems were solved by doing the 'opposite' of the usual practice. A similar ('inverse') approach was used here. The recipe appears simple in hindsight – take an ultrashort pulse, spoil (increase) its time duration by a large amount (i.e. reduce its peak power). This pulse with lower peak power is then amplified (given more energy) and finally it is compressed back to its original ultrashort duration. This final pulse can now have orders of magnitude larger energy (depending on the amplification factor) than at its initial (starting) duration, and hence its peak power is boosted by the same order of magnitude.

This idea (stretching and compression) was originally used in radar communication after World War II and was insightfully adopted by Strickland and co-workers[20,21] to cause a second revolution in light generation, 25 years after the laser was invented (Figures 4–6). The technique of stretching in time, amplification and compression is called chirped pulse amplification (CPA) – temporal stretching causes the pulse to 'chirp', i.e. its frequency evolves as a function of time within the pulse itself[18].

To quote the introduction from the classic 1985 paper by Strickland and Mourou[20] 'The onset of self-focusing of intense light pulses limits the amplification of ultra-short laser pulses. A similar problem arises in radar because of the need for short, yet energetic pulses, without having circuits capable of handling the required peak powers. The solution for radar transmission is to stretch the pulse by passing it through a positively dispersive delay line before amplifying and transmitting the pulse. The echo is compressed to its original pulse shape by a negatively dispersive delay line [1]. We wish to report here a system which transposes the technique employed in radar to the optical regime, and that in principle should be capable of producing short (<1 ps) pulses with energies at the Joule level' (ref. 1 in this quotation is ref. 22 in the present article).

CPA unleashes a revolution in laser physics and applications

The boost in laser intensities obtained by focusing high peak power pulses (terawatt and petawatt) resulted in intensities ranging up to 10^{22} W/cm^2. This is six orders of magnitude larger than the intensity corresponding to the electric field experienced by the electron in the $1S$ state of the hydrogen atom, i.e. the electron can be driven by light field three orders of magnitude larger than the Coulomb field. Obviously, this is intense excitation and the physics it has spawned deserves a much longer discussion. Suffice it to say that this triggered an explosion of activity in high energy density science (solid density matter elevated to extremely high temperatures on an ultrashort timescale), laboratory astrophysics, shock studies, warm dense matter, particle (both electron and ion) acceleration, coherent soft and hard X-ray pulse generation on a table top, etc.[23] Each of these deserves a long exposition of its own and I had an opportunity to describe some of these in an article published a decade ago[24]. In addition, there are several exciting applications of CPA lasers in laser machining, laser surgery, cancer therapies, etc. Figure 7 shows an example.

Needless to add, the biggest stimulus for the spread of all the above has been the compactification and simplification of laser technology needed for high intensity pulse generation. No more the big buildings for locating the laser and no more the huge funding of tens of millions of dollars for each such installation. The space and costs have shrunk by factors of hundred or more, and the research area has been 'democratized' with the participation of several smaller laboratories around the world. This should also count as one of the big boons of the CPA technique.

Currently there are many petawatt lasers around the world and the community is moving towards 100 petawatt power. India has been using CPA-based 100 TW (TIFR, Mumbai) and 150 TW (RRCAT, Indore) lasers since 2010. Presently, a petawatt laser is being installed at RRCAT, Indore and another one is planned at the Hyderabad campus of TIFR.

Before concluding, I wish to make some general and personal remarks on aspects that strike me as unusual in the awards this year. Ashkin is the oldest Nobel laureate at 96 years and many who hold his accomplishments in high esteem are relieved that Ashkin has finally got the recognition he richly deserved – but one tends to think that such late recognition may not be the best way to acknowledge path-breaking contributions.

It is also interesting to note that the basic idea of CPA originated in microwave research, just like the radiation amplification idea also came up with the maser. However, translating them to the optical region seemed to have produced huge dividends – first the laser and now the CPA. And good, 'blue sky' research always pays dividends over a long period. Just like the laser, CPA has opened up a multibillion dollar industry in ultrashort pulse and related technologies, and the growth seems relentless.

Strickland got her Nobel Prize for the very first paper she wrote. There are very few parallels to this feat. Also, this is a happy situation where a Ph D advisor and his student shared the Prize. Some other students have not been so fortunate. Unlike Ashkin's pioneering papers

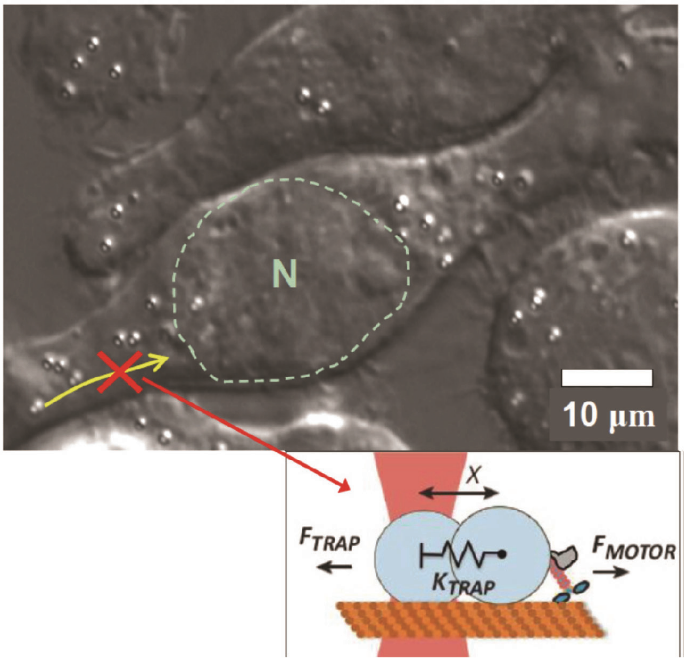


Figure 3. Optical trapping measures force from molecular motors inside a living cell. Plastic beads of 1 μm diameter are ingested inside a cell grown on a coverslip. The nucleus (*N*) of the cell is outlined. These beads acquire molecular motors via cellular processes and move around vigorously inside the cell (yellow arrow). An optical trap (red cross) is focused on a moving bead. The schematic shows the bead being pulled out of the trap by force from a single motor (F_{MOTOR}). This motion is resisted by opposing force from the trap (F_{TRAP}) that behaves like a Hookean spring. A force balance is reached for a certain value of the displacement (X). This displacement can be measured precisely to obtain the force from motor proteins. The calibration of the optical trap inside living cells is non-trivial and described in ref. 16. (Photograph and text: Courtesy Roop Malik, Department of Biological Sciences, TIFR, Mumbai.)

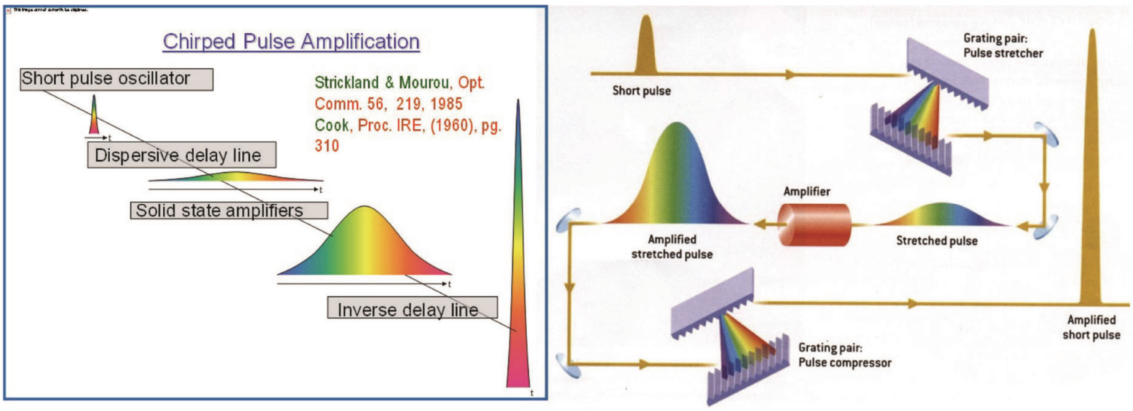


Figure 4. (Top left) The principle of chirped pulse amplification (CPA). (Top right) The stretching and compressing is done by adjusting dispersion of light in a set of prisms or gratings. (Image taken from ref. 25.)

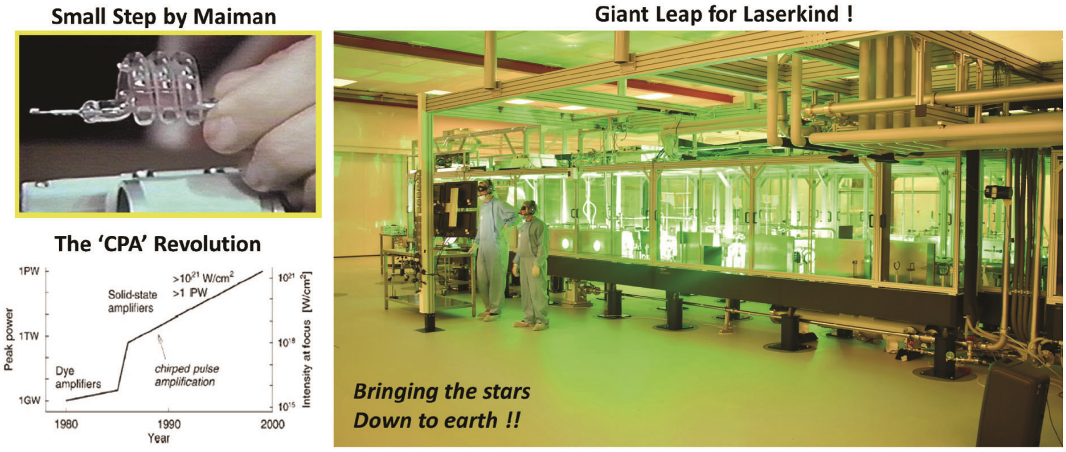


Figure 5. (Top left) A picture of the first ever laser unveiled on 16 May 1960 by Theodore H. Maiman at the Hughes Laboratories, USA. (Bottom left) Peak powers which were stranded till the 1980s at the gigawatt level in most labs around the world, got boosted by a factor of 100–1000 (1000 GW = 1 TW) almost immediately after CPA was invented. Today, the highest power available is at the petawatt (=1000 TW) level and these lasers use CPA. (Right) A portion of one of the biggest laser facilities in the world, at ELI Beamlines, Prague, Czech Republic.

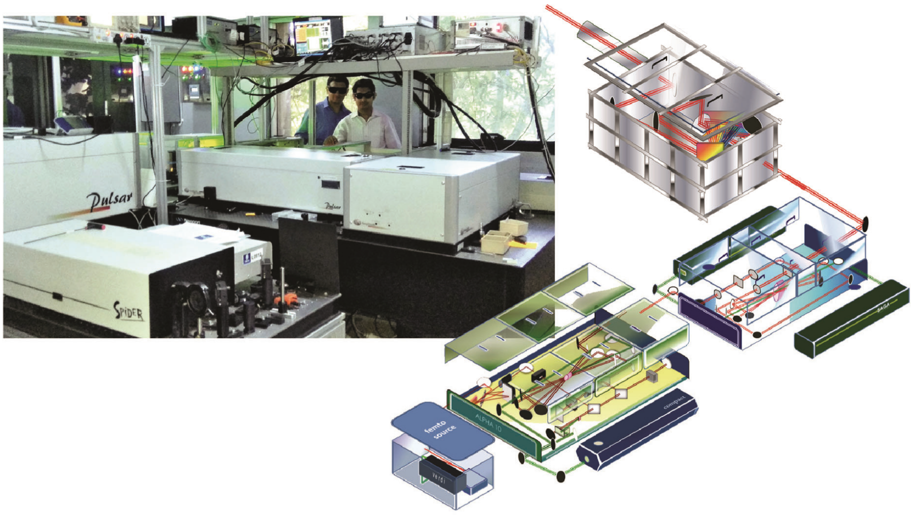


Figure 6. The 100 TW, 25 fs table-top CPA laser at TIFR, Mumbai. RRCAT Indore and BARC, Mumbai also have similar custom-built systems. For more details visit www.tifr.res.in/~uphill.

Coherent Inc. TRUMPF Inc. TRUMPF Inc.

Figure 7. Femtosecond laser enabled engraving of micro-chip (left), precision patterns on metal alloys (centre) and micro-hole drilling in circuit boards (right). (Image taken from ref. 26.) CPA-based femtosecond lasers make the cleanest cuts.

which appeared mostly in top-ranked, prestigious journals of 'broad scope' published by professional societies, the work of Mourou and Strickland appeared mainly in specialized journals that are not so 'famous'. Fortunately this was the pre 'impact factor' era and it is good to see that work gets recognized for what it is and the pedigree of the journal may not matter (though all around us, the present indications are that we may have left that era far behind).

Mourou has been recognized for CPA, but he has several other pioneering contributions to his credit, including subpicosecond electrical sampling, picosecond electron diffraction, femtosecond laser micromachining, femtosecond laser eye surgery, self-channelling of femtosecond pulses in the atmosphere, etc. All these were also leaps ahead of their time.

Since our group works in an area that was directly facilitated by the CPA revolution, we have had opportunities to interact with Mourou and observe how he thinks and works. He is a dreamer who sees much farther than anyone, extremely bold in his approach, unafraid that his contemporaries may think that the ideas are far-fetched and always restless for the next big leap. And he leaps many orders of magnitude with every idea, even if they cannot be realized in the present or near future. It was he, who in 2009 conceived the billion euro 'extreme light infrastructure' project in Europe with 4 PW pillars for the next-generation science and technologies. Mourou has led the community from the front and coalesced their efforts by founding and leading associations and networks like the International Committee of Ultrahigh Intensity Lasers, which holds biennial conferences on ultrahigh intensity light across the continents (the sixth one was held in Goa in 2014, which Mourou attended with great enthusiasm).

Some websites on intense laser field science

I provide here some websites where one can get more details of the kind of research being performed in intense laser physics and perhaps can even access some of the research papers published. These have been chosen just to give a flavour of the field.

Ultrashort Pulse High Intensity Laser Lab, TIFR, Mumbai: http://www.tifr.res.in/~uphill/

Rutherford Appleton Lab: https://stfc.ukri.org/about-us/where-we-work/rutherford-appleton-laboratory/

Forschungszentrum Dresden-Rossendorf, Dresden: http://www.fzd.de

Laboratoire d'Optique Appliquée LOA Palaiseau: http://loa.ensta.fr

Ecole Polytechnique – Applied Optics Laboratory, Paris: http://www.polytechnique.edu

Extreme Light Infrastructure, Europe: https://eli-laser.eu/

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