Nobel Prize science in use across the country in Dodd-Walls Centre labs

The Dodd-Walls Centre is pleased to acknowledge the 2018 Nobel Prize winners in physics. The tools and techniques that they developed are used by Dodd-Walls Centre researchers in New Zealand on a daily basis. The prize winning tools are used in our labs across the country and contribute to new product development and services that we are working on to grow the New Zealand economy.

Chirped Pulse Amplification

The Nobel Prize committee awarded one half of this year's Nobel Prize to Gerard Mourou and Donna Strickland for their invention of the chirped pulse amplifier. This invention allows unprecedented powers to be obtained from lasers and this is now used in applications ranging from laser surgery to laser fusion. It has become the standard tool of laser physicists around the globe and clearly meets the standards of an invention of great benefit to mankind.

The problem that Mourou and Strickland set out to solve is simple — distortion. As anyone who has ever turned up their amplifier to 11 knows sound becomes distorted at high volumes. The same is true for light — it is relatively easy to create precise pulses of light at low powers and indeed physicists have been doing this almost since the invention of the laser, but creating high power pulses of light is hard and it was almost impossible before the invention of the chirped pulse amplifier.

To understand why this was a challenge, it is necessary to understand what causes the distortion. The distortion of light signal at high intensities is due to what is known as 'nonlinearities'. When a high intensity light beam passes through a material it responds differently than when a low intensity light beam passes through. This was first observed a couple of years after the invention of the laser when researchers observed the formation of second harmonics which is when the frequency of the light is doubled. This is a non-linear effect. These can be beneficial — green laser pointers all rely on frequency doubling to work, while more recently using a nonlinearly generated supercontinuum allowed Ted Hansch to win the 2005 Nobel Prize for optical frequency metrology. More often however such non-linear effects are a nuisance and can even cause catastrophic damage especially in laser crystals and this limits the peak powers that can be produced from a laser system.

One simple way to avoid the issues of nonlinearities is to increase the area of the laser beam. Intensity is the power per unit area and so increasing the area will decrease the intensity. This can easily be done using a lens, however in many cases it is not a practical solution. Increasing the beam size means that you need to increase everything else as well — the lens and the laser crystals mirrors and this becomes very expensive. In addition, larger laser crystals are difficult to make and also rapidly become almost impossible to cool during experiments. So researchers are forced to trade-off optical nonlinearities for thermal distortions which does not provide a significant increase in power.

Rather than stretching the pulse out in space, the Nobel Prize winners Mourou and Strickland came up with the brilliant solution of stretching the pulse in time. This is like changing a short tall rectangle to a long skinny one with the same area. The advantage of this is that you can now use the same optical systems as before but get much more energy out of the system before nonlinearities begin to distort the pulse. Furthermore it can be trivially extended to longer and longer pulses unlike spatially expanding the beam. To make this a reality however they needed to find a reversible way to stretch the pulse so that they could compress it at the end of the laser system. The scheme they used is familiar to anyone who has seen a rainbow — they used the fact that in most materials different frequencies travel at different speeds. Thus a pulse of light propagating in an optical fibre for example, will spread out and become longer and longer. In their original experiments Mourou and Strickland used a 1.4 km long fibre to stretch the pulse to a length of 300 ps (picoseconds) before amplifying it and then compressing it down to a pulse with of 1.5 ps.

In their seminal 1985 paper, Mourou and Strickland clearly recognised the importance of this technique. They state that "*it is important to note that this technique can be used to amplify any short pulse*". They similarly realized that "*this technique could be used to generate subpicosecond pulses, with energies at the Joule level*". And indeed these days researchers routinely use their technique on all types of short pulses producing exceedingly high power lasers capable of everything from studying fundamental physics to laser surgery and even exploring nuclear fusion.

Optical Tweezers

The other half of this year's Nobel Prize goes to Arthur Ashkin, for the invention of "Optical tweezers". Ashkin realised that light can be used to manipulate small objects. In particular, small objects that are mostly transparent to light, such as living cells, can be held on to by just using light. This allows researchers to manipulate biological systems without touch. It is also possible to chemically attach a part of a cell, say a DNA molecule, to a small plastic object for collection and further research. A small cell 'held' in this way can be manipulated with optical tweezers allowing scientists direct access to properties of a DNA molecule.

The way this works is using a property of light that until the time of Ashkin's discovery in the early seventies was considered relatively unimportant, the momentum of light. Imagine a lens, like one of your spectacles or a part of your binoculars. If you look through the centre of the lens, you will see an image of whatever is directly behind the lens. But if you move the lens, the image moves in a peculiar way, just because the lens is bending the light coming from the object. In that same way, this small object acts like a lens. If it sits in the centre of a laser beam, the light is not deflected, but if the lens moves to the side, the object will then bend the light. This bending of light changes its momentum and that gives a force back to the centre of the beam. This force is very small and can only act on very small objects, yet the force is big enough to capture single cells and objects of a similar small size.

Ashkin realised a short time later that the same principle can be used to trap atoms and molecules.

In the Dodd-Walls Centre (DWC) in New Zealand, researchers use this effect every day to trap neutral atoms at temperatures very close to absolute zero. One group of DWC researchers, at the University of Otago, uses atoms that are 'held on to' by optical tweezers to study atom-level collision processes and chemical reactions. In another group, single atoms are trapped to study the very basics of chemistry on an atom-by-atom basis. DWC researchers at the University of Auckland study atoms 'held' by tweezers of a particularly designed shape to study the quantum effects in atom motions.

Around the world, many other applications of this Nobel Prize winning technique are in use. For instance, atoms trapped by optical tweezers are used to build the best possible clocks, thereby improving the accuracy of GPS systems.

Arthur Ashkin's invention is about very small forces but his work has had a big impact on scientific research on biological systems as well as on physics.

Putting the Nobel Prize inventions to use for New Zealand

Both the chirped pulse amplification (CPA) and optical tweezer inventions are used on a daily basis by investigators and students in the Dodd-Walls Centre in New Zealand, and around the world, both to explore questions in fundamental science and to make practical advances that benefit everyone.

For example DWC investigators Cather Simpson and Neil Broderick use the CPA technique for laser micro-machining allowing laser light to cut almost everything. One example is their work using lasers for bone surgery — if this research is successful it will allow for smaller incisions resulting in major advances in key-hole surgery that will dramatically reduce hospital times for patients and costs to healthcare providers and insurers.

Other examples include the precision cutting of semiconductors, reducing material waste as compared to the current methods, which also reduces the overall cost of fabrication. Optical tweezers also play a major role for a new start-up company called Engender Technologies Ltd. The company and Cather Simpson will use the optical tweezers to sort bull sperm which will increase the efficiency of insemination and underpin increased competitiveness in an industry worth billions of dollars to New Zealand. Other DWC researchers use optical trapping to manipulate single atoms with applications for quantum computers and precision measurements.

For more information

https://www.nobelprize.org/prizes/physics/2018/summary/

https://www.nobelprize.org/prizes/physics/2005/hansch/facts/

https://www.sciencedirect.com/science/article/pii/0030401885901518

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