Einstein and the Atomic Theory

Albert Einstein : another 1905 paper facilitated a test for atomic theory

In the third of a series of articles celebrating Einstein's Miraculous Year, Cormac O'Raifeartaigh describes Einstein's ground-breaking contribution to atomic theory.

In the year 1905, a young Albert Einstein published a number of scientific papers that changed physics forever. The best known of these, the Special Theory of Relativity, quickly established the young Einstein as a scientist of note (see J.IEI vol. 59:6) and led to Einstein's General Theory of Relativity, one of the pillars of modern physics. In a second paper, Einstein published a controversial proposal concerning the nature of light that later formed a cornerstone of quantum theory, the revolutionary theory that underpins much of modern science and technology (see J.IEI vol. 59:7). Incredibly, the young Einstein made a third ground-breaking advance in 1905.

He published an analysis that pointed the way towards a crucial test of the reality of atoms, and of the validity of the laws of thermodynamics. The outcome of that test now underpins much of modern science, from our view of the atomic nature of matter to our understanding of meteorology and other complex systems.

Atoms and chemistry

The idea that all matter is made up of minute, indivisible entities called 'atoms' was first put forward by the philosophers of ancient Greece. The concept gained much credibility in the 19th century when scientists such as John Dalton used it to establish laws of chemistry that successfully described how the chemical elements combine to form molecules.

A listing of the known elements in order of increasing atomic weight led to the development of The Periodic Table by Mendeleyev, a development that revolutionized the study of chemistry. It was widely assumed that the properties of a given element was determined by the properties of its constituent atoms - however, there was no direct evidence of the existence of atoms, and some eminent scientists did not believe in the 'atomic hypothesis'.

Enter Einstein

Greatly interested in the atomic view of matter, the young Einstein devised a mathematical method of calculating the size of atoms and molecules in early 1905. From an analysis of sugar molecules dissolved in water, he calculated both the diameter of the sugar molecule and Avogadro's number (the number of molecules per unit volume under standard conditions) from the known viscosity of the liquid and the diffusion rate of sugar.

His calculations were in good agreement with previous theoretical estimates and were well-received. However, the very existence of atoms and molecules had still to be demonstrated in convincing fashion, and the 26-year-old Einstein applied himself to this task.

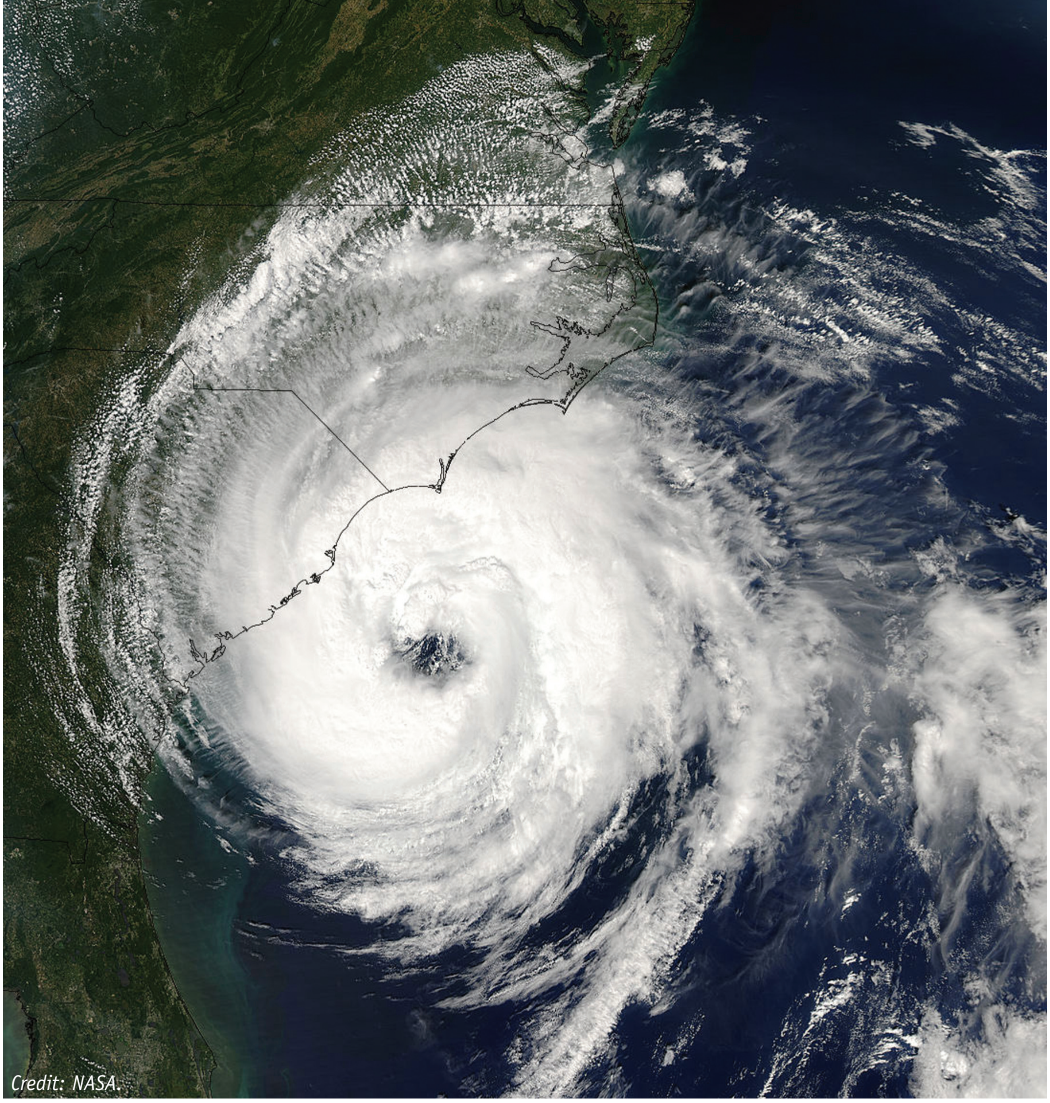
> Today, Einstein's notion of statistical fluctuations has found application throughout the sciences.

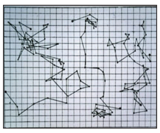
Einstein and statistics

According to the atomic view of matter, a liquid is made up of a huge number of molecules in random, ceaseless motion, the properties of the liquid arising from the average behaviour of its constituent molecules. Working from first principles, Einstein made a careful study of the statistics of such an assembly and, in May 1905, he made a key proposal concerning its behaviour.

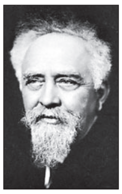
He proposed that any such system would experience statistical fluctuations, during which random elements depart from their average behaviour (just as a dice player can occasionally throw several sixes in a row).

Applying this concept of statistical fluctuation to the case of molecules in liquids, Einstein proposed that a small group of neighbouring





Brownian motion : the random motion of a particle suspended in a liquid was first studied by botanist Robert Brown (1773-1858).



Above: Jean Perrin was awarded the 1926 Nobel Prize for his experimental verification of Einstein's predictions.

Left: The notion of statistical fluctuations underpins our view of complex systems such as the weather.

molecules could momentarily move in the same direction – a fluctuation that would cause a body immersed in the liquid to experience a tiny push in that direction. Another group of molecules could cause the same body to experience a tiny push in a different direction moments later and the immersed body would therefore experience a zig-zag motion in the liquid – a motion that might be observable. Hence, while the molecules of a liquid were far too small to be observed directly by microscope, their motion might be detectable by its effect on a larger particle suspended in the liquid!

Brownian Motion

Excitingly, a zig-zag motion of particles suspended in a liquid had long been known to scientists (named 'Brownian Motion' after the English botanist who studied the effect in detail). The cause of this motion had been a great mystery – and accurate measurement of the 3-D random motion of an immersed particle had proved extremely difficult. Here, Einstein made a second vital contribution.

Starting with the assumption that the motion was indeed due to a buffeting of the immersed particle by the molecules of the liquid, he calculated the average horizontal distance an immersed particle would travel in a given time. Hence, from his own statistical analysis, Einstein delivered a well-defined, measurable estimate that could be easily tested.

The experiment

The French scientist Jean Perrin rose to Einstein's challenge with a series of experiments in 1908. Equipped with nothing but a microscope and a stopwatch, Perrin and his team measured the horizontal displacement of gum extract particles suspended in water as a function of time. The data were in exact accord with Einstein's predictions, giving the world the first unequivocal evidence of the reality of molecules. Einstein was delighted, as was Perrin – the Frenchman was later awarded the Nobel Prize for this work!

Young Einstein devised a mathematical method of calculating the size of atoms and molecules in early 1905.

Implications

Einstein's 'Brownian-motion' paper facilitated the first real glimpse of the atomic nature of matter, an advance that underpins almost all of modern science. Another consequence of the paper was that, since the properties of matter were now known to be determined by the behaviour of huge numbers of atoms, it was realized that the laws of thermodynamics were valid only in a statistical sense.

For the first time, the role of probability in the laws of physics was established, a defining moment in the philosophy of science.

Modern Applications

Today, Einstein's notion of statistical fluctuations has found application throughout the sciences. From the study of cell membranes to our view of evolution, from the analysis of weather systems to the study of the stock market, it underpins our understanding of all complex systems. Perhaps the 'Brownian–motion' paper did not have quite the dramatic impact of the Special Theory of Relativity, or indeed of Einstein's quantum view of light – but it resulted in a quiet revolution that has had an lasting influence on modern science.

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