Great Experiments in Physics

- The Evolution and Teaching of Experimental Physics

- and - in particular - **the Oil Drop Experiment.**

Much of our scientific knowledge goes back to historic experiments. Some produced discoveries; others proved - or sometimes disproved hypotheses; and others provided new or refined measurements of important physical quantities.

The first part of this talk will be about the history of great experiments in physics - not covering the experiments in chemistry, biology and life-sciences etc. Many of these were conducted by gentleman-scientists in the period between about 1650 and 1850. After this, the era of modern physics began, and one milestone was the inauguration of the Cavendish laboratory and professorship at Cambridge in 1871.

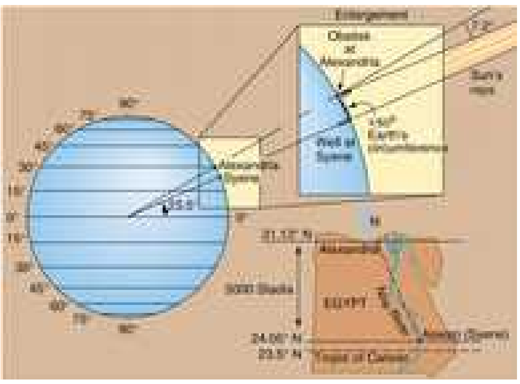
Then I shall go into more detail on one particular experiment, the 'oil drop experiment'. You may not have heard of it, but this fantastic experiment is on just about every informed top-ten list of historically important experiments, and it has been repeated over and over again by many generations of University Physics students, including me. You'll see why later.

You'll probably remember from school that classical physics was about five basic subjects which related directly to familiar life from early times.

Heat, leading to Thermodynamics
Light, or Optics
Sound
Mechanics, motion and gravity.
Properties of Matter

The early experiments related to these subjects.

Of course physics gradually expanded into new subjects within modern physics - electricity and electronics, electromagnetic waves and radio, relativity, atomic physics, low-temperature physics. This expansion has largely taken place over the last 150 years.



Let's first go back to the Greek, Eratosthenes who lived around 200 BC. Mathematicians remember him for the Sieve of Eratosthenes, concerning prime numbers. I mention him here because of his experimental determination of the circumference of the earth. It isn't strictly physics, but it was an early scientific approach to the indirect measurement of a physical quantity.

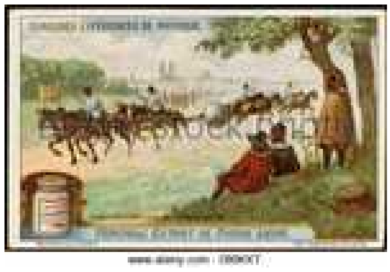
It was known that at Syene (Aswan) the sun was directly overhead at the mid-day equinox, shining straight down a well. This was not the case at Alexandria. Eratosthenes used the shadow of an obelisk to determine the angle of the sun's rays, and deduced the circumference of the earth quite accurately.

During the next 1800 years, the ancient Chinese, Arabs and Indians made their contributions to science. In particular Ibn al-Haytham produced his "Book of Optics" in 1021 AD, and backed up his propositions with experimental evidence.

But it was Aristotle's assertions which shaped Mediaeval scholarship, and that particularly applied to the Laws of Motion.

The real story of discoveries in Physics began in about 1600 AD, and several important experiments were carried out in the next 200 years.

We start with Galileo, responsible for the first great experiment on every list. There's a myth about him. Popular opinion has it that he dropped objects off the leaning tower of Pisa. Maybe he did that anyway, but there was far more to it. His work, ***Discourses and Mathematical Demonstrations Relating to Two New Sciences,*** published in 1638 , was his scientific testament. Following Copernicus and Kepler, he promoted the heliocentric view and made himself pretty unpopular with the Pope. But he also challenged Aristotle's assertions that heavy objects fall faster than light ones. He rolled balls down slopes, timing them with a form of water clock.

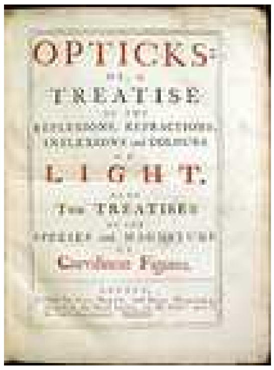


Another interesting event occurred in 1654, when the power of atmospheric pressure was demonstrated by the Magdeburg hemispheres.

Newton went to Cambridge to study about 15 years later. The Aristotelean views were still being taught, but he learnt of Galileo and Kepler, and of course that formed the base of much of Newton's most famous work in formulating the equations of motion and stating the law of gravitation.

But Newton was also very interested in Optics. His famous experiments included the use of prisms to split white light into a spectrum of colours.

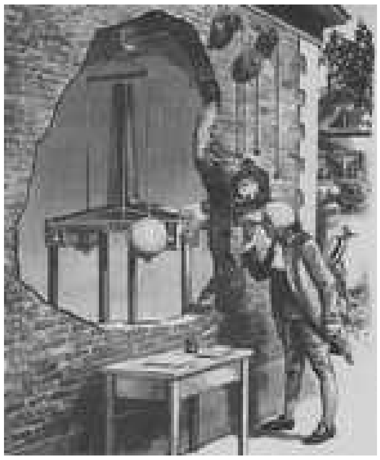
He published his work Opticks. He supported the Particle theory of light, and asserted that the splitting of the spectrum occurred because red light particles were heavier than blue ones.


OPTICKS:
TREATISE
LIGHT.

Newton was the Lucasian Professor at Cambridge, the post which Stephen Hawking more recently held. Cambridge will re-enter the story with a bang in the 19th century.

But many of the discoveries in the next period were the work of gentleman scientists - aristocrats with money to spend on an interesting hobby. Starting from about 1667 their work was described in transactions of the Royal Society, and FRS remains the recognition of scientific acievement.

There was Robert Boyle, son of the Earl of Cork. His famous experiment showed that a bell in an evacuated jar could not be heard.



Another was Henry Cavendish, grandson of the Duke of Kent, and one of the wealthiest men in Britain.   His famous experiment related to gravity and the density of the earth.

But then we move on to the 19th century and science accelerates.

There was Robert Young, not only an innovative scientific experimenter, but also a physician, linguist, and egyptologist. His great experiment was the double-slit which finally disproved Newton's particle theory of light.

Improved understanding of heat emerged from Joule's experiment in 1845.

Further ingenious experiments related to light, and especially the speed of light, followed. First Fizeau in 1851. He reflected light from a mirror 8km away,, with a rotating toothed wheel intervening in the outward and return path. Gradually increasing the wheel speed eventually led to extinction of the light

And there was Foucault's pendulum, which showed the effect of rotation of the earth.

So by the middle of the 19th century the phenomena of heat, light and sound were pretty well understood. The ideas of atomic physics were beginning to emerge. providing the subjects for more great experiments.

And the University of Cambridge became increasingly influential, first through Lucasian Professors. Newton was a Lucasian professor, and also Babbage. In 1819 George Stokes became Lucasian professor, and held the post for 54 years. George Stokes is important to this story. Newton's laws for falling bodies applied in a vacuum. Stokes' Law, published in 1854, dealt with the slowing-up effect of air, or viscous fluid.

But at Cambridge and elsewhere there was no such thing as experimental physics in teaching. Professors passed on the perceived wisdom, with strong emphasis on theory. Their own experiments were performed in their own college accommodation. It was time for change. A Senate committee was formed at Cambridge and established that the creation of a dedicated Laboratory and Professorship would cost the frightening sum of £6,300 (which of course was nearly a million in todays money).

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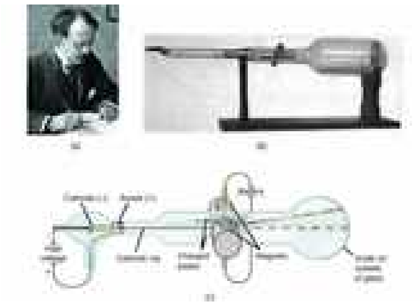
The funds were not immediately found. However the University Chancellor was the Duke of Devonshire, William Cavendish. He provided the funds from his own pocket and did not demur when the final cost was some £8000. The Cavendish name was attached to the result - to remember both the benefactor William Cavendish and the earlier George Cavendish.

James Clerk Maxwell was appointed to the new professorship and planned the new laboratory which opened in 1874.

Elsewhere there was another great experiment. The concept of the lumeniferous aether which carried light waves in some magical way still survived until the Michelson Morley experiment. the aim was actually to verify the existence of the aether - and it failed!

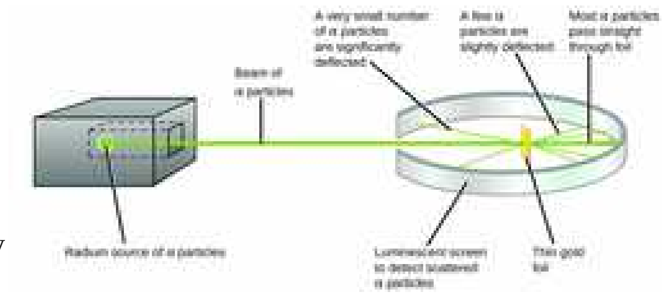
Back at Cambridge, J J Thomson became the professor. He was then only 28, and held the post for 35 years.

That brings us on to the next great experiment. Cathode rays had recently been discovered but were not yet correctly understood. Thomson soon postulated that the rays consisted of tiny particles - much smaller than atoms. He called them corpuscles, but they were soon called electrons. Thomson soon conducted a famous experiment. He subjected cathode rays to electric and magnetic fields which deflected them, and thereby deduced the charge-to-mass ratio for electrons.



Thomson also attempted to determine electronic charge itself by studying charged water droplets in a cloud-chamber. This was never accurate, but provided the stimulation for Millikan. I'll soon come back to that, but I'll first continue the Cavendish Laboratory story.

The next great experiment was associated with Rutherford and was the first step in understanding the structure of the atom, with a central nucleus.



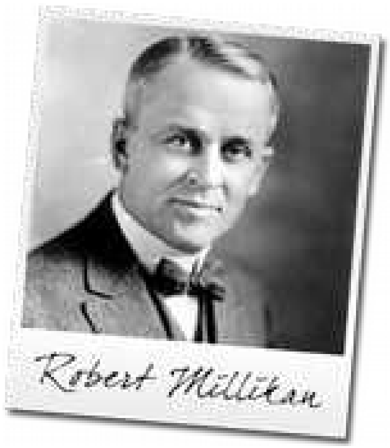
He was at Manchester then, but subsequently became the Cavendish Professor ay Cambridge, succeeding J.J.Thomson. Under Rutherford, the Cavendish Laboratory became the leading centre for atomic and nuclear physics.
In it's teaching role, experimental physics played a large part. A lecturer called George Searle played a large role. He was the son of a Cambridgeshire vicar, joined the Cavendish in JJ Thomson's time, and remained until the 1940s. He developed countless experiments, always skilfully weaving theory and practice.

Here he is, in the teaching laboratory at the Cavendish. It is probably the same laboratory which I attended in 1950/52. Some of the experiments then were still Searle's experiments.

Now back to Millikan. Most of the earlier great experiments had concerned things that were tangible. Millikan and other physicists wanted to know more about the electron. Did it have a specific electrical charge - and if so what was the value. How on earth do you set about getting hold of an electron, and then measure the infinitesimally small electric charge precisely.

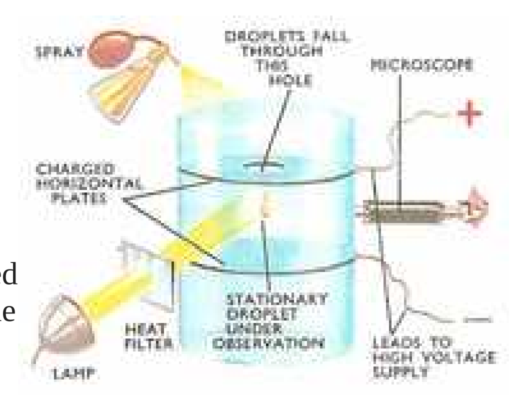
J.J. Thomson's attempts to determine the charge on the electron had been based on a cloud of many charged water droplets. Millikan decided to study single droplets individually.

Millikan was the professor at Chicago and Harvey Fletcher was a young graduate researcher. Their method was based on the observation of individual charged droplets; and they used a very stable oil rather than water. Their result was very close to today's accepted value for the electronic charge. Millikan took the sole credit and got a Nobel Prize. Harvey Fletcher had made significant conributions but received little credit.



Millikan and Fletcher first performed the oil drop experiment in 1908 and Millikan eventually published his most famous paper on the oil-drop experiment in 1913. When he started, the existence of the electron as a sub-atomic particle was generally recognised, but it was still not universally accepted that it carried a fixed electrical charge.

Here's the setup. Droplets created by a scent-spray fell through a hole into the observation chamber and the calibrated microscope could see indivdual drops. Friction in the scent spray had transferred a few electrons, so that many drops were electrically charged. Because the drops were of varying sizes, their velocities varied and were linked to their size by Stokes' Law. When a voltage was applied between the top and bottom plates, droplets which were charged were slowed up or reversed. Indeed a selected droplet could be held stationary by adjusting the voltage so that the gravitational force downward just balanced the electrical force upwards.



It turns out if you do the maths, that the electric charge on a droplet can be determined by making two measurements on that droplet, one with the voltage switched off and droplet falling, and the other when switched on and droplet rising. Now that charge is not the charge on one electron, but the charge on an unknown number of electrons. Fortunately that number is small.

This is the basic equation in its simplest form. It involves the viscosity of the air , density of the air and the oil, applied voltage and separation of the plates. But the need for precision adds further complications. Stokes' Law requires a correction for increasing droplet size. And viscosity varies with temperature. So the full equation ends up like this (taken from my own 1952 practical notebook)

$$q = \frac{9\pi d(v_1 + v_2)}{V}\sqrt{\frac{2\eta^3 v_1}{g(\rho_{oil} - \rho_{air})}}$$

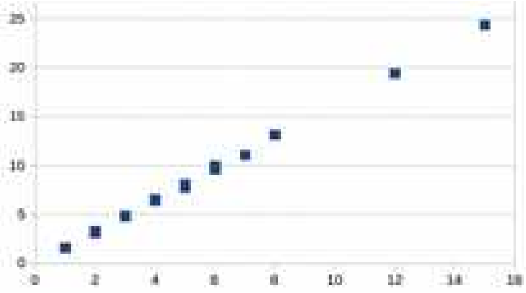
So Millikan and Fletcher made observations on many droplets, did the sums for each one, and discovered the charge on each droplet. The results were all numerically related, with a highest common factor, showing the quantisation of electric charge. Each calculated charge was a multiple of e, the charge on one single electron.

During the next 15 years or so, the experiment was repeated and refined by other researchers.

And academics realised that it was a splendid experiment for final year undergraduates, involving both laboratory skills and computational skills.

I carried out the oil drop experiment as an undergraduate in 1952, when it was conducted in the traditional way - particularly in relation to computation. For today's students the computational part is easy, using a computer spread-sheet. They would hardly give a thought to the computational challenge faced by Millikan and Fletcher. But in 1952 there were still no computers, or even scientific calculators. The answer lay in the skilfully organised use of mathematical tables. They are not only log tables and the wording in the 1946 preface is interesting - written without any comprehension of the revolution in computation to come in only a few years.

I made measurements on 25 oil drops and filled many pages of my notebook with the calculations. Here are tables of calculations for just seven of the droplets. The logical arrangement strongly resembles a computer spreadsheet, but the cells are filled, one-by-one, by painstakingly looking up values in tables. The tables essentially provide the instruction set for a procedure which strongly resembles a stored program computer - where the sheet of paper is the store. We can see my time measurements in the first two columns, a progression of intermediate results leading to a column where the perceived number of electrons on the drops is inserted, and then more intermediate results. A further table (not shown here) leads on to the final value. Just like an excel spreadsheet.



My own results are summarised here, clearly showing the quantisation of charge. My final value, averaged over all the drops, was 1.61 X 10 -19 Coulombs, pretty close to the accepted value of 1.602. Millikan's original result was 1.592, but at the time of his experiment the value of the viscosity of air was in error. Just consider what small amounts of charge are represented. A Coulomb of charge is transferred by a current of 1 ampere flowing for 1 second. And the oil drop experiment captures the tiny charge, and achieves a precise value.

A century on, Millikan's oil drop experiment is still important. Many scientific equipment firms produce their version of the apparatus, and many undergraduates still perform the experiment, though with the aid of computers for the computation. They have less appreciation of the computational work carried out by Millikan - and by me and my fellow students.

One can use plastic spheres, which are far more uniform, instead of oil drops.

And the experiment is still done for serious science.

Quite recently, the US National Accelerator Laboratory measured 100 million drops in an automated system in an abortive search for fractionally charged particles.

So that's the story of a remarkable experiment, which merits it's place in lists of famous and significant experiments.