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20 October 2015

**Einstein’s Annus Mirabilis, 1905**

Professor Raymond Flood

Thank you for coming to my lecture today. This is my first lecture of this academic year and it is about one of the most iconic persons in science or indeed in world history.

**Slide: Herblock Cartoon**

Einstein’s image is instantly recognised and he has had global impact as shown here in this cartoon by an American cartoonist called Herblock which depicts earth viewed from space and Earth carries a plaque saying *Albert Einstein lived here.* In this lecture I want to concentrate on just one year in Einstein’s life but what a year. In 1905, his *annus mirabilis,* or year of wonders he published four papers of exceptional importance. I will discuss each of them, concentrating on the last two where he developed special relativity and some of its consequences.

Gresham College will be offering later in the year a lecture to celebrate the centenary of Einstein’s announcement of general relativity in 1915 and I will give details of that later.

But I will concentrate on 1905 and start by giving a brief biography of Einstein picking out some features of his life and attitude that I, and I hope you, will find interesting. Then I will look at the 1905 papers and show their importance and, in particular, how the special relativity papers build on very simple assumptions to obtain very surprising conclusions.

**Slide: Hermann Einstein and Pauline Einstein (née Koch) and Einstein plaque**

Albert Einstein was born in Ulm in Southern Germany on 14th March 1879. His parents were Hermann and Pauline Einstein (née Koch). Within a year his father’s business had failed and they moved to Munich where Einstein spent the next 14 years. He seems to have been shy and his school years did not demonstrate any outstanding ability.

In later life he describes, in his autobiographical notes, an experience which had a great impression on him. It was when at a young age his father showed him a magnetic compass.

**Slide: Magnetic compass and quote**

He was very impressed that no matter how the compass was turned the needle kept pointing north. The compass needle although completely enclosed was influenced by an invisible untouchable force, his first experience of a force field. He said:

*A wonder of this kind I experienced as a child of four or five years when my father showed me a compass. That this needle behaved in such a determined way did not at all fit into the kind of occurrences that could find a place in the unconscious world of concepts (efficacy produced by direct 'touch'). I can still remember – or at least believe I can remember – that this experience made a deep and lasting impression upon me.*

At age ten he went to secondary school which he does not seem to have enjoyed. But while there when he was twelve he had another thrilling experience when he met Euclidean geometry where it is possible obtain concrete results from pure reasoning. He later wrote:

**Slide: Euclidean Geometry**

*At the age of twelve I experienced a second wonder of a totally different nature: in a little book dealing with Euclidean geometry, which came into my hands at the beginning of the school year. Here were assertions, as for example, the intersections of the three altitudes of a triangle in one point, which though by no means evident could nevertheless be proved with such certainty that any doubt appeared to be out of the question. This lucidity and certainty made an indescribable impression upon me. That the axiom had to be accepted unproved did not disturb me.*

He continued:

*In any case it was quite sufficient for me if I could peg proofs upon propositions the validity of which did not seem to me to be dubious.*

*For example, I remember that an uncle told me the Pythagorean theorem before the holy geometry booklet had come into my hands.*

*After much effort I succeeded in ‘proving’ the theorem on the basis of the similarity of triangles.*

Much later in his life he solved another school problem in Euclidean geometry. This problem was reportedly posed by a fifteen year old schoolgirl and the problem asks how to construct a common tangent to two circles of different radii.

**Slide: Finding a common tangent to two circles of different radii**

Here is Einstein’s sketch and solution for the problem which is like so much of his work: clever and concise.

In 1894 his father’s business again failed and his parents and sister moved to Milan. Einstein remained at school but re-joined the family after six months. His next year was one of enjoyable travel and then at age 16 he applied to the prestigious ETH – the Swiss federal Polytechnic School – in Zurich failing at his first attempt. He succeeded at his second attempt and in 1896 he began a four year course for teaching science and mathematics. Here is his matriculation certificate giving his results at the end of secondary school.

**Slide: Matriculation Certificate and Einstein at 17.**

On the matriculation certificate it is important to note that six is the highest grade and one the lowest.

Einstein obtained the highest grade six in history, algebra, geometry, descriptive geometry and physics. He got grade five in German, Italian, Chemistry and Natural History. Geography and Drawing came in at grade four while his poorest result was a grade three in French language and literature.

While at university he read widely including original work of Kirchoff, Hertz, Maxwell and particularly Ernst Mach whose book on *The Science of Mechanics* probed the underlying ideas and assumptions of physics.

He graduated in 1900. After graduation he supported himself by part-time teaching until he obtained in 1902 a probationary position in the Swiss Patent Office in Bern.

**Slide: Wedding photograph of Einstein and Mileva Marić, January 6, 1903.**

Among his fellow students at ETH was Mileva Marić whom Einstein married in 1903. In 1904 his appointment at the Patent Office was confirmed.

**Slide: The title page of Annalen der Physik, Volume 17, 1905**

In 1905, his ‘year of wonders’, Albert Einstein published in *Annalen der Physik* four papers of ground-breaking importance.

**Slide: Photoelectric effect**

First he published the work that introduced quanta of energy — that light can be absorbed or emitted only in discrete amounts, a core idea of quantum theory and used it to explain the photoelectric effect.

**Slide: Brownian motion**

Next was a paper on Brownian motion, explaining the movement of small particles suspended in a stationary liquid.

**Slide: On the electrodynamics of moving bodies**

His third paper, on the electrodynamics of moving bodies, introduced a new theory linking time, distance, mass and energy. It was consistent with electromagnetism, but omitted the force of gravity. This became known as the special theory of relativity and assumed that c, the speed of light, is constant, irrespective of where you are or how you move.

**Slide: E = mc2**

Towards the end of 1905 he published *Does the Inertia of a Body Depend Upon Its Energy Content?* This contains one of the most famous equations of all, E = mc2, asserting the equivalence of mass and energy.

We will come back to look at these in more detail shortly.

These papers established his reputation but it was only in 1909 that he obtained his first academic post - a Professorship at the University in Zurich. But his stay in Zurich was brief moving to Prague then back to Zurich and then for a long stay in Berlin before emigrating to America in 1933 and from then on he was based at the Institute for Advanced Study in Princeton.

He announced his general theory of relativity in 1915 and this year marks the 100th anniversary of Albert Einstein's presentation of the Theory of General Relativity to the Prussian Academy.

**Slide: General relativity presentation**

This was done at a session of the Prussian Academy of Sciences in November 2015. This work led to a scientific revolution that has forever changed our understanding of the Universe.

**Slide: Nils Andersson lecture**

As you see on this slide Professor Andersson will discuss this story of brilliant physical intuition which has led to deep insights about the universe in which we live. His lecture is here at the Museum of London at 6.00pm on November 24th.

Einstein was awarded the 1921 Nobel Prize for his research on the theory of the photoelectric effect, one of the earliest applications of quantum theory. By the early 1920s his best scientific work was done although he was still very influential and was internationally renowned. As a reaction to the Nazi threat and the potential of atomic power he was involved with a letter to President Roosevelt warning about the possibility of atomic weapons although Einstein played no part in their development.

Scientifically he became increasingly dissatisfied with quantum theory and how to interpret it. His other major area of scientific concern was trying to obtain a unified field theory that would bring together gravity and electromagnetism. His work on a unified field theory is thought to be ingenious but of little lasting value.

He died in April 1955 from an abdominal aortic aneurism at the age of seventy six.

Let me finish this brief biography of Einstein with a quote from a speech he made to the German League of Human Rights, Berlin in 1932.

**Slide: My Credo political views**

On his political views he wrote:

*I am an adherent of the ideal of democracy, although I well know the weaknesses of the democratic form of government. Social equality and economic protection of the individual appeared to me always as the important communal aims of the state.*

**Slide: My Credo scientific views**

And on science he wrote:

*The most beautiful and deepest experience a man can have is the sense of the mysterious. It is the underlying principle of religion as well as all serious endeavour in art and science. He who never had this experience seems to me, if not dead, then at least blind.*

[A recording of Einstein reading *My Credo* is available at:

<http://www.einstein-website.de/z_biography/e_sound_credo_1932.html>]

Let us now return to 1905, Einstein’s year of wonders, to experience for ourselves this sense of the mysterious!

Although Brownian motion is the second of the four 1905 papers that I will look at, I will consider it first as the other three have a common connection involving light.

Brownian motion is named after a nineteenth century Scottish botanist Robert Brown. In 1827, while examining under a microscope grains of pollen suspended in water, Brown observed minute particles executing a continuous jittery, very irregular and erratic motion. He then observed the same motion in particles of inorganic matter, enabling him to rule out the hypothesis that the effect was caused by the pollen particles being alive.

**Slide: Simulation of Brownian motion**

The reason for this jittery, very irregular, erratic and wiggly motion was the large number of impacts on the particles by a large number of molecules of water. If a particle was being continuously bombarded by molecules and the bombardment is slightly stronger at any one instant from one direction then the particle will move appropriately. Then once the particle has moved a little way from its starting point it is just as likely to get kicked further away as to get kicked back.

Here we see a simulation of Brownian motion. The yellow blob represents the particle and the rapidly moving many grey ones the molecules.

It was Einstein who was able to quantify mathematically the jittery erratic motion. It is also worth saying that the physical reality of atoms and molecules was not accepted by all physicists at the beginning of the twentieth century and it was Einstein’s work on Brownian motion (which built on earlier work on his thesis) that convinced physicists beyond reasonable doubt of the existence of atoms.

**Slide: Einstein Distance proportional to the square root of the time.**

Einstein found that the average distance travelled in the x direction was:

λx = where *D* is a constant called the coefficient of diffusion and *t* is the time.

So, if you ignore all the zigs and zags of the zigzag motion a particle will travel, and measure only the straight line distance between its start and finish, it will travel twice as far in four seconds as it does in in 1second. And it will travel three times as far in nine seconds as it does in I second. And so on.

Einstein key idea was that the particle was in thermodynamic equilibrium with the atoms in the liquid. Essentially he was thinking of the particle as an “atom” that you could see.

In the last section of the paper Einstein calculates the mean displacement of a particle one thousandth of a millimetre across suspended in water at 17°C.

**Slide: Last section**

Then the straight-line distance travelled from its starting point in one minute would be six thousandths of a millimetre or six times the width of the particle. The important point is that he is able to make quantitative predictions which he could use to work out estimates for the real size of atoms or molecules which explains the title of this last section:

*Formula for the mean displacement of suspended particles. A new method of determining the real size of the atom.*

This paper on its own would have established Einstein’s reputation and got him an academic job. But it was only the second of the great papers to appear in 1905.

The first was Einstein’s contribution to quantum theory and this was the work for which he was to be awarded the Nobel Prize sixteen years later in 1921.

He and Mileva divorced in 1919 and part of the divorce settlement was that Einstein promised her the proceeds of the Nobel Prize when he was awarded it.

To set the scene for Einstein’s paper on the photoelectric effect let me say a little about why quantum theory was needed.

**Slide: Why Quantum theory was needed.**

Towards the end of the nineteenth century there was an increasing belief that the basic goals of physics had been achieved. Newton’s laws of gravity and motion had been exceptionally successful. Maxwell had unified electricity, magnetism and light and the discovery of radio waves confirmed his predictions.

All that was essentially left was to account for the interaction between matter and radiation, such as light.

**Slide: Electric Light bulb**

However the newly invented electric light bulb caused problems because at a given temperature it obviously shone with a characteristic mix of different wavelengths of light giving it a particular colour. But classical physics was unable to explain why this should be so and by early 1900 experimental results differed from theoretical predictions. Essentially classical physics predicted the wrong amount of radiation at the different wavelengths or frequencies, in particular much too much at very high frequencies.

Classical physics was unable to explain the electric light!

It was Max Planck who realised about 1900 that the difficulty could be avoided if radiation could only be emitted in packets or quanta.

**Slide: Max Planck in 1878 at age 20**

Electromagnetic energy could be emitted only in quantized form, in other words, the energy could only be a multiple of an elementary unit, where is a constant and is the frequency of the light.

Then there would not be enough energy to make the high frequency packets or quanta and the colour of the radiation would be modified and would now agree with experiment.

Planck seemed to think that these packets of energy were the method by which the atoms were able to release energy. An analogy was the way a stretched string of a given length would admit a note of a certain frequency when it was plucked. It was Einstein who realised that the quanta were *not* a characteristic of atoms *but of light itself* and he used this insight to explain another phenomenon, the photoelectric effect.

**Slide: Paper on the photoelectric effect**

He did this in a paper which was received on March 18 and published June 9. Its titlewas**:**

*On a heuristic point of view about the Creation and Conversion of light*

So, let me describe the photoelectric effect and then give Einstein’s explanation of it.

**Slide: Photoelectric Effect**

Solar panels have shown us that sunlight falling on certain materials can eject electrons and cause a current to flow.

**Slide: Photoelectric Effect with puzzles**

There were two puzzles:

1. Increasing the frequency of the light increased the energy of the ejected electrons but not their number. Indeed if the frequency of the light dropped below a certain value no electrons were emitted.
2. Increasing the intensity of the light increased the number of ejected electrons but not their energy.

Einstein’s resolution of the puzzles was revolutionary. He broke with a century of experimental evidence that suggested that light consisted of waves. He said that if one thought of light as consisting of energy quanta or photons with energy proportional to their frequency then we could explain the two puzzles.

**Slide: Puzzle 1**

When the frequency was low no photon would have enough energy to eject an electron.

But as the frequency, and so the energy of the photons increased, each photon could then eject a single electron. If we increased the frequency of the light the energy of each photon would increase and so the ejected electrons would have more energy but the number of ejected electrons would not increase.

**Slide: Puzzle 2**

On the other hand increasing the intensity of the light increases the number of photons but does not change the energy of each individual one so more electrons are ejected with the same energy.

For many years many people thought that Einstein’s approach was just a mathematical device without physical reality.

But a series of experiments showed that we had to think of light as both waves and particles. This wave-particle duality lies at the core of the new quantum mechanics developed in the 1920s and which lies at the heart of our understanding of the atomic and subatomic world.

Not long after finishing his papers on the photoelectric effect and Brownian motion, Einstein submitted what was arguably his most important paper of 1905.

**Slide: On the Electrodynamics of Moving Bodies**

It was called *On the Electrodynamics of Moving Bodies* and introduced the Special Theory of Relativity. This paper changed our understanding of the nature of space and time and how we describe and interpret the physical world. It is an outstanding paper, some 30 pages long, and I’ll discuss what Einstein achieved by first introducing Galileo’s principle of relativity and then how it was modified by Einstein.

**Galileo’s Principle of Relativity**

Galileo’s Principle of Relativity states that:

*No mechanical experiment can distinguish between two uniformly moving frames of reference.*

And he gave a beautiful and compelling description of it in his *Dialogue Concerning the Two Chief World Systems – Ptolemaic and Copernican* of 1632.

**Slide: Frontispiece and title page of *Dialogue Concerning the Two Chief World Systems***

The *Dialogue* was Galileo’s powerful advocacy of a sun centred universe and to pursue his advocacy he had to consider the question of why we did not feel any effects from the rotation of the earth and its revolution around the sun.

The book is presented as a series of discussions and I want to show you the one that discusses what is now called Galileo’s Principle of Relativity introduced by the character Salviati who argues for the Copernican view of a sun centred universe.

**Slide: Salviati quote page 1**

SALVIATI *Shut yourself up with some friend in the main cabin below decks on some large ship and have with you there some flies, butterflies, and other small flying animals. Have a large bowl of water with some fish in it; hang up a bottle that empties drop by drop into a wide vessel beneath it. With the ship standing still, observe carefully how the little animals fly with equal speed to all sides of the cabin. The fish swim indifferently in all directions; the drops fall into the vessel beneath; and, in throwing something to your friend, you need throw it no more strongly is one direction than another, the distances being equal; jumping with your feet together, you pass equal spaces in every direction.*

**Slide: Salviati quote page 2**

*When you have observed all these things carefully (though there is no doubt that when the ship is standing still everything must happen in this way), have the ship proceed with any speed you like, so long as the motion is uniform and* ***not fluctuating this way and that***(my emphasis)

**Slide: Salviati quote page 3**

*You will discover not the least change in all the effects named, nor could you tell from any of them whether the ship was moving or standing still. In jumping, you will pass on the floor the same spaces as before, nor will you make larger jumps towards the stern than toward the prow even though the ship is moving quite rapidly, despite the fact that during the time that you are in the air the floor under you will be going in a direction opposite to your jump. In throwing something to your companion, you will need no more force to get it to him whether he is in the direction of the bow or the stern, with yourself situated opposite. The droplets wilt fall as before into the vessel beneath without dropping towards the stern, although while the drops are in the air the ship runs many spans.*

**Slide: Salviati quote page 4**

*The fish in their water will swim toward the front of their bowl with no more effort than toward the back, and will go with equal ease to bait placed anywhere around the edges of the bowl.*

*Finally the butterflies and flies will continue their flights indifferently toward every side, nor will it ever happen that they are concentrated toward the stern, as if tired out from keeping up with the course of the ship, from which they will have been separated during long intervals by keeping themselves in the air....*

**Slide: Principles of Relativity – Galileo’s**

Well, what did Einstein do? He extended Gallileo’s Principle of relativity to all our physical experience and not just the part of it dealing with mechanical effects.

This is Einstein’s Principle of relativity

**Slide: Principles of Relativity – Einstein’s**

No experiment can distinguish between two uniformly moving frames of reference.

In particular Einstein argued that Maxwell’s equations for light apply as they stand in any uniformly moving frames of reference, for example on the ship or on the shore, and so:

**Slide: Principles of Relativity – speed of light**

In particular, the speed of light in a vacuum has the same value in two uniformly moving frames of reference

Although Einstein postulated that the speed of light in a vacuum has the same value in all uniformly moving frames of reference for theoretical reasons connected with the work of Maxwell the constancy of the speed of light has been shown experimentally to great accuracy.

It is on these two simple postulates that Einstein builds his theory of special relativity. It is stunning, not mathematically difficult but totally counterintuitive.

For example, we are used to adding and subtracting speeds in what seems an obvious way. This doesn’t work with light. If you and I are standing and I shine a torch at you then you will measure the speed of light at a certain value, let us call it *c.* If I start walking towards you still shining the torch you will still measure the speed of the light reaching you as *c* – the speed of light is independent of the motion of its source.

If I stop and you walk towards me then you will still measure the speed of light as *c* - the speed of light is independent of the motion of its observer. If we both walk towards each other then you will still measure the speed of the light as *c.* This is very different from the results you would obtain if I were, instead of shining a torch at you were throwing snowballs, and you were measuring the speed of the snowballs when they arrived.

This fact that the speed of light is independent of the motion of the source *and* the observer means that our usual way of adding and subtracting speeds is wrong. But if our conception of speed has something wrong with it then because speed is just distance divided by time it implies there is something wrong with our concepts of distance, or time, or both.

Let me show you one consequence of the constancy of the speed of light.

**Slide: Time taken for space craft**

I am in a space craft moving uniformly along above the earth, you are on earth and we both have identical clocks. I am going to carry out a simple experiment. It is to fire a pulse of light from the floor to a target on the ceiling. The distance from the floor to the ceiling is 4 metres. The pulse travels directly upwards at right angles to the direction of motion of the space craft. The time it takes for the pulse of light to get from the floor to the target is 4/*c* because the speed of light is *c* and the distance travelled is 4 metres.

**Slide: Time taken for earth**

Now you are observing this from the earth. From your perspective as the craft passes overhead during the time taken for the pulse to move from the floor to the target the space craft has moved forward and you will see the path of the pulse as sloped not vertical and therefore longer than it is from my viewpoint on the spacecraft. Let us suppose that the space craft moves forward a distance of 3 metres while the pulse of light travels from the floor to the target on the ceiling.

Then Pythagoras’s theorem tells us that the distance the pulse travels according to you is 5 metres because

52 = 32 + 42

So how long do you say it takes the pulse to travel from floor to target? Well it is the distance 5 divided by the speed of light which is **also** *c* for you!

**Slide: Time taken for earth is 5/c**

So for you the time it takes for the pulse of light to get from the floor to the target is 5/*c.*

So we disagree on how long it took the pulse of light to complete the trip from floor to ceiling. According to you my clock is running slow as I say the time taken is 4/*c* whereas for you it is 5/*c.*

This is the famous time dilation effect: - I have my time in the spacecraft and you have your time on earth.

I have used the numbers 3, 4 and 5 so as not to let algebra get in the way of the explanation.

**Slide: Argument for velocity *v***

But the argument is the same if we take the speed of the craft as *v* relative to the earth.

According to the person on earth:

BC is the distance travelled by the spacecraft in the time it takes the light pulse to reach the target and

AC is the distance travelled by the light pulse

While according to the astronaut:

AB is distance travelled by the light pulse

Time for the pulse to get from floor to ceiling viewed from the space craft

= (Time for the pulse to get from floor to ceiling viewed from the earth)

The expression arises frequently in special relativity. If *v* is small in the expression it approximates very closely to 1 so this time dilation effect although there at all speeds has very little effect.

**where c = 299,792.458 kilometres per second**

Example: If *v* = *c* then and

Time for the pulse to get from floor to ceiling viewed from the space craft

= (Time for the pulse to get from floor to ceiling viewed from the earth)

This time dilation effect has been experimentally confirmed, for example using subatomic particles. The factor also occurs in another effect predicted by special relativity which is that you on earth and me on the spacecraft must measure distances differently.

**Slide: Length contraction**

Suppose my spacecraft is travelling from earth to the moon. We both *agree* on the relative speed between us but because of time dilation we will have different measurements of the time it takes to get to the moon so we must have different measurements of its distance away. How do our measurements of distance differ? It must be in the same ratio as our times differed namely

This is another phenomena predicted by special relativity. It is known as length contraction. The spacecraft measures the distance between the earth and the moon as times the distance that the person on earth measures it.

So we each measure the time between two events differently and measure the distance between two events differently. Is there anything we can agree on?

Yes there is and let me introduce it by way of an analogy.

If I hold a pencil up you will all see something different because you are looking at it from different positions in the room. Some of you looking at it nearly end on because of your position will see the pencil as very short while others looking at it broadside because of your position will see it as longer. We know the reason for this.

**Slide: Analogy of the length of a pencil**

This is because each of you is seeing a projection of the pencil into two dimensions at right angle to the line of sight of you to the pencil. Different people have different lines of sight and so different projections of the pencil. Of course, we can understand why we are all observing different lengths. It is because the pencil has extension in a third dimension along your line of sight and when we take account of this we will all arrive at the same length for the pencil – its length in three dimensions. For those of you looking at the pencil broadside there is very little or no extension in the third dimension whereas for you looking at the pencil end-on there is a lot of extension of the pencil in the third dimension.

Let me use this analogy to help with thinking about our different perceptions of time and space in special relativity.

**Slide: Minkowski**

This way of thinking about space and time is due to one of Einstein’s teachers Hermann Minkowski and he announced it in 1908. I think it is the most productive and least confusing way to think of relativity.

**Slide: Minkowski and quote**

Minkowski said:

*Henceforth space by itself, and time by itself, are doomed to fade away into mere shadows, and only a kind of union of the two will preserve an independent reality.*

In Minkowski’s view we should not think as space as separate from time Instead we should think of them in a kind of union that is now known as space-time. Space and time are now no longer separate, as Newton had thought, but are intermixed.

When looking at the pencil the length you saw depended on your position, your viewpoint. In space-time changing your viewpoint corresponds to a change in speed (not just position). Observers in relative motion have different viewpoints and so get different results or projections when they measure distances or times.

But just as the pencil I held up had a true length in three dimensions there is a way of calculating the separation between two events in space-time that we will all agree on regardless of our relative speeds. An event is just something that happens at a certain point in space and at a certain time. So an event is a point in space-time and needs four numbers to describe it – three space numbers and one of time.

So what is the separation between two events in space-time?

**Slide: Separation between events in space-time**

In two dimensions the distance, *l,* between pointsA and *B* can be written in terms of their projections, *x* and *y*, along two axes at right angles then

or

In three dimensions we introduce another axis at right angles to the first two. If the projection along this third axis is *z* then:

or

The separation, *s,* between two events in space-time incorporates a fourth term coming from the time and for it to be the same for all observers the space and time terms appear with different signs.

or

**Slide: Space-time diagram**

This geometrical approach can be represented using space-time diagrams. Here is a space-time diagram simplified because it has time along the vertical axis but only has one space dimension shown along the horizontal axis. The lines labelled light lines show the passage of two light pulses, one to the left and one to the right. The line labelled world line is me wandering about from left to right.

The distance of each point (*x, t*) to the origin is

Einstein initially thought little of Minkowski’s geometrical approach to space-time, but later found it invaluable, indeed essential, when he was trying to extend his theory to include gravity.

**Slide: Energy and mass**

The last Einstein paper in 1905 that I want to have a brief look at is the one where he establishes the equivalence of energy and mass. It is a short paper, entitled *Does the Inertia of a body depend on its Energy content?*

**Slide: All of the paper**

It is only three pages long and here it is in translation. We can think of the inertia of a body as its mass.

At the top of the third page Einstein concludes that:

**Slide: Top of page 3 of Inertia paper**

*If a body give off the energy L in the form of radiation, its mass diminishes by .*

So the factor connecting mass and energy is *c2* andthe result is usually now written as *E = mc2.*

His approach is to have a body which emits two pulses of light in opposite directions and he views this process from one frame of reference which is stationary with respect to the body and another frame of reference which is moving at a uniform velocity *v* relative to the body*.* Of course, the speed of light is the same in both frames.

**Slide: Isaac Newton and Woolsthorpe Manor and binomial**

So what is Newton doing here? It is because Einstein in the derivation of his result uses the factor and Einstein approximates it using the general binomial theorem discovered by Isaac Newton during *his* annus mirabilis when he returned to his home at Woolsthorpe Manor during 1665 to 1666 because an outbreak of the plague at Cambridge University.

**Slide: End of Einstein article**

After concluding that;

*If a body gives off the energy L in the form of radiation, its mass diminishes by.*

He continues:

*The mass of a body is a measure of its energy-content; if the energy changes by L, the mass changes in the same sense by the energy being measured in ergs, and the mass in grammes.*

*{The speed of light is about 3 x 1010 cms per second so its square is 9 x 1020}*

*It is not impossible that with bodies whose energy-content is variable to a high degree (e.g. with radium salts) the theory may be successfully put to the test.*

*If the theory corresponds to the facts, radiation conveys inertia between the emitting and absorbing bodies.*

This equivalence of energy and mass is the energy that fuels the sun and nuclear weapons. Einstein’s calculation of the energy equivalent of a mass of 1 gram is approximately enough energy to power the daily domestic use of a city of a million people.

This has been a quick tour through relativity and I have not had time to introduce many important features but I have tried to pick out some crucial ones which should help you if you want to discover more about it. I found the following two books very useful.

**Slide: Some references**

Albert Einstein *Relativity: The Special and General theory.* This image is of my copy of the fifteenth edition reprinted in 1962 by Methuen. But there are electronic versions of it available for less than a pound!

Russell Stannard *Relativity, A Very Short Introduction,* OUP, 2008.

This is an excellent book in Oxford’s Very Short Introduction series.

**Slide: Hamilton, Boole and their Algebras**

My next lecture is on November 17th on Hamilton, Boole and their Algebras when we will show how the work of these two mathematicians freed algebra from the constraints of arithmetic. Thank you!

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