Extra Dimensions in Physics

A common theme in theoretical physics is the idea of extra dimensions which has been highly popularized by string theory. This article aims to explain how and why extra dimensions play a role in physics.

It was the great mathematician Riemann with his development of differential geometry in the nineteenth century who gave the tools necessary to study higher dimensional descriptions of the world. Riemann held the belief that three-dimensional space was not enough to provide an adequate description of nature. Improvements in physics led to Maxwell's unified theory of electricity and magnetism and Einstein had formulated both GR and had unified space and time with Special Relativity (SR). Inspired by these unifications physicists of the early twentieth century wanted to unify gravity and electromagnetism.

The first to attempt this was Nordstrom in 1914 and later Weyl and Kaluza followed two separate paths. Weyl's attempt involved trying to alter the geometry of space-time in four dimensions. His early attempts had physical consequences which did not match experimental data, however his work was extended by Einstein and Schrodinger independently who arrived at the Einstein-Schrdinger non-symmetric field theory which is widely regarded as the most advanced unified field theory based on classical physics.

It was Theodore Kaluza who was the first to introduce an additional dimension into Einstein's equations. With this simple addition Kaluza was able to build a theory which included both gravity and the electromagnetic field. Kaluza contacted Einstein in 1919 about his idea, but the introduction of an extra dimension was considered so radical at the time that he was unsure and it wasn't until 1921 that Einstein encouraged him to publish. As well as unifying electromagnetism and gravity one additional field physicists call a 'scalar' field was predicted. This was an embarrassment to Kaluza at the time as no scalar field had ever been observed in nature. That problem coupled with the fact that we clearly live in three spatial dimensions caused the theory to draw heavy criticism from the physics community.

In 1926 Oskar Klein suggested that the fifth dimension compactifies so as to have the geometry of a circle of extremely small radius. One way to envisage this space-time is to imagine a hosepipe. From a long distance it looks like a one dimensional line but a closer inspection reveals that every point on the line is in fact a circle. Because the space had a circular topology, the higher dimensional periodicity allowed for mathematical solutions which included charge quantization, something that was becoming important in the developing theory of quantum mechanics.

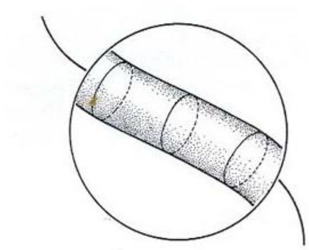

Figure 1: *An extra dimension remains hidden to us due to its size.*

Theories of extra dimensions lay dormant for over forty years however in 1968 the physicist Gabriele Venziano who at the time was a research fellow at CERN suggested that certain properties of the strong nuclear force could be mathematically modeled by a one dimensional string. Prior to this all elementary particles were considered to be point like particles (effectively zero dimensional). Many research papers followed this exciting observation and bosonic string theory was born. Within a few years it was discovered that certain vibrations of the string had the characteristics that matched the graviton, the gravitational forces messenger particle. This was an extremely exciting discovery at the time because physicists believed they may be on the correct track to formulate a quantum theory of gravity, the holy grail of theoretical physics. The theory had two problems however. One was that it contained a particle with imaginary mass called a Tachyon, and the other was that the theory was only mathematically consistent in

26 dimensions, although bosonic string theories answer was similar to Klein's idea which was to wrap them up into a very small 'compact' space.

As string theory developed it branched into a number of seemingly separate theories named Type I, Type IIA, Type IIB, Heterotic and $E_8 \times E_8$. Each theory had a different predictive power, for example type IIA string theory describes massless fermions. These five theories required not 26 but only 10 space-time dimensions. Although string theory showed much promise it was a problem that there were five theories. In the mid-nineties by a stroke of genius the physicist Ed Witten was able to show that these five seemingly separate theories could in fact be unified into a single theory he called M-theory which requires 11 space-time dimensions. M-theory is still an active field of research and although it is not without its critics, it is still the most promising theory we have to date which promises to unify all the forces of nature.

The common thread in this discussion is the theme of unification of the forces of nature. Kaluza-Klein theory attempted to unify gravity and electromagnetism, and now M-theory are efforts to provide a complete description of nature at the subatomic level which includes gravity, electromagnetism and the strong and weak nuclear forces. Although string and M-theory are the most well known of theories which involve extra dimensions there are in fact a number of popular theories in existence which utilize the rich and tantalizing possibilities offered to physics by extra dimensions which will be discussed in future articles.