Entangled Holograms

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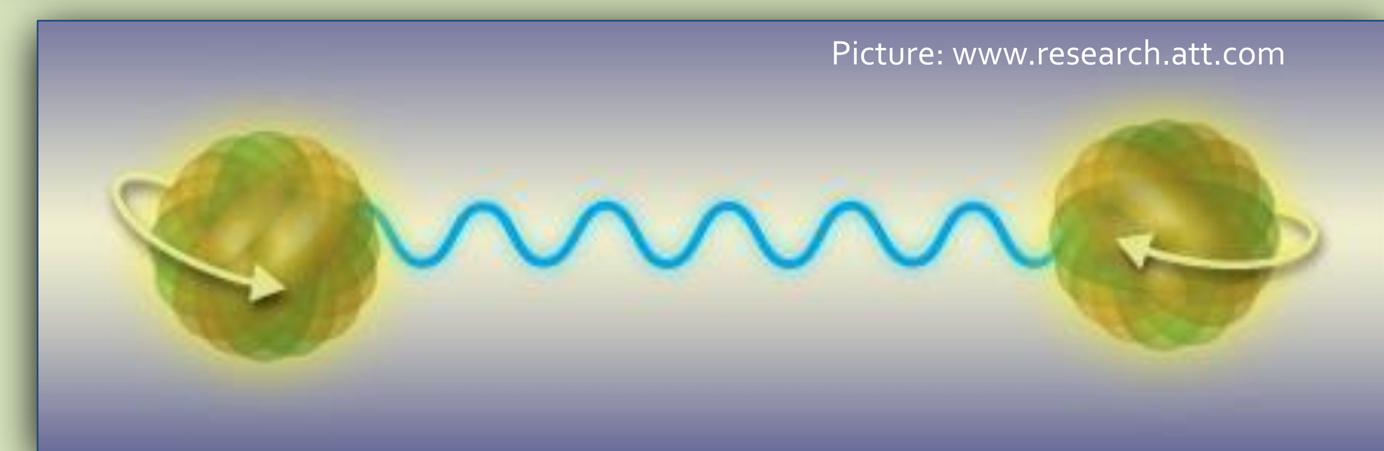
What is *Entanglement*?

Entanglement is an essential feature of quantum mechanics, our best theory for describing the microscopic world. It is best understood by considering a pair of particles produced together but travelling away from each other, as in the picture below.

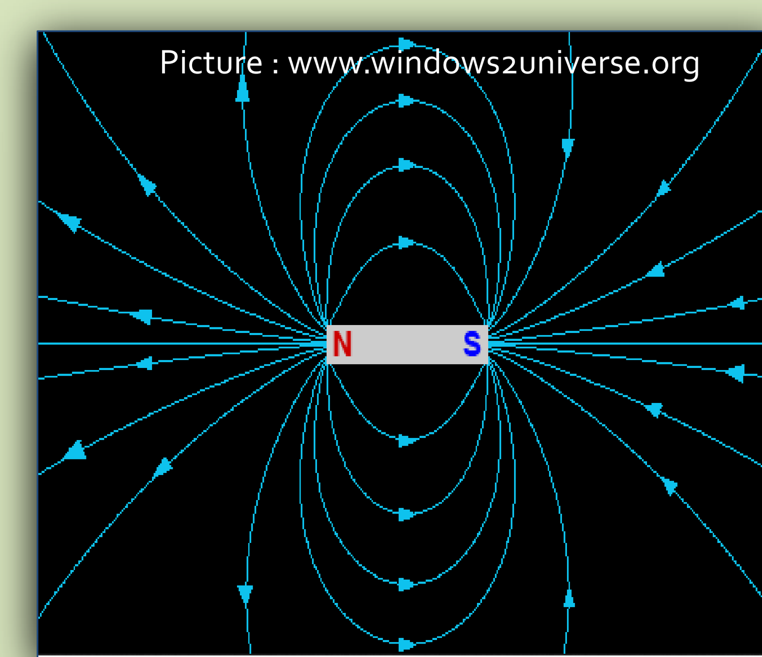

Picture: www.research.att.com

Quantum mechanics predicts that the two particles cannot really be considered as separate objects, but are **intrinsically connected** or "**entangled**" with each other. For example, performing a measurement on one, such as measuring the particles spin as in the diagram above, **instantaneously** affects the result of measuring the other. This phenomena occurs even if the particles are very far apart in space, so far that even light could not travel between them in the time it takes for the other particle to be affected. This is at the heart of what Einstein called the "**spooky non-locality**" of quantum mechanics:

Quantum particles are intrinsically entangled!

Entangled Fields

In physics, a **field** is an object that **extends throughout space**. To describe the system we therefore have to specify how it is behaving at every single point in space. Examples of fields include magnetic fields as in the picture on the right, and the height of the surface of a body of water as in the picture below. In both cases **a number is associated to every point in space**, describing the value of the field there.



Picture : www.windows2universe.org

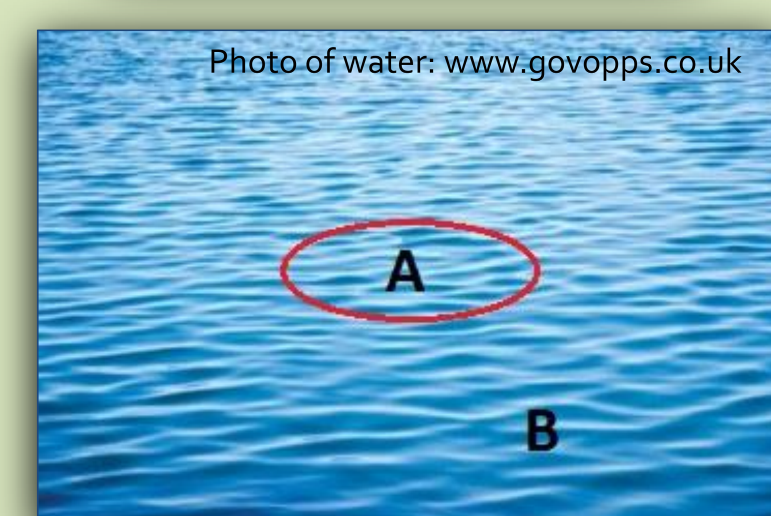


Photo of water: www.govopps.co.uk

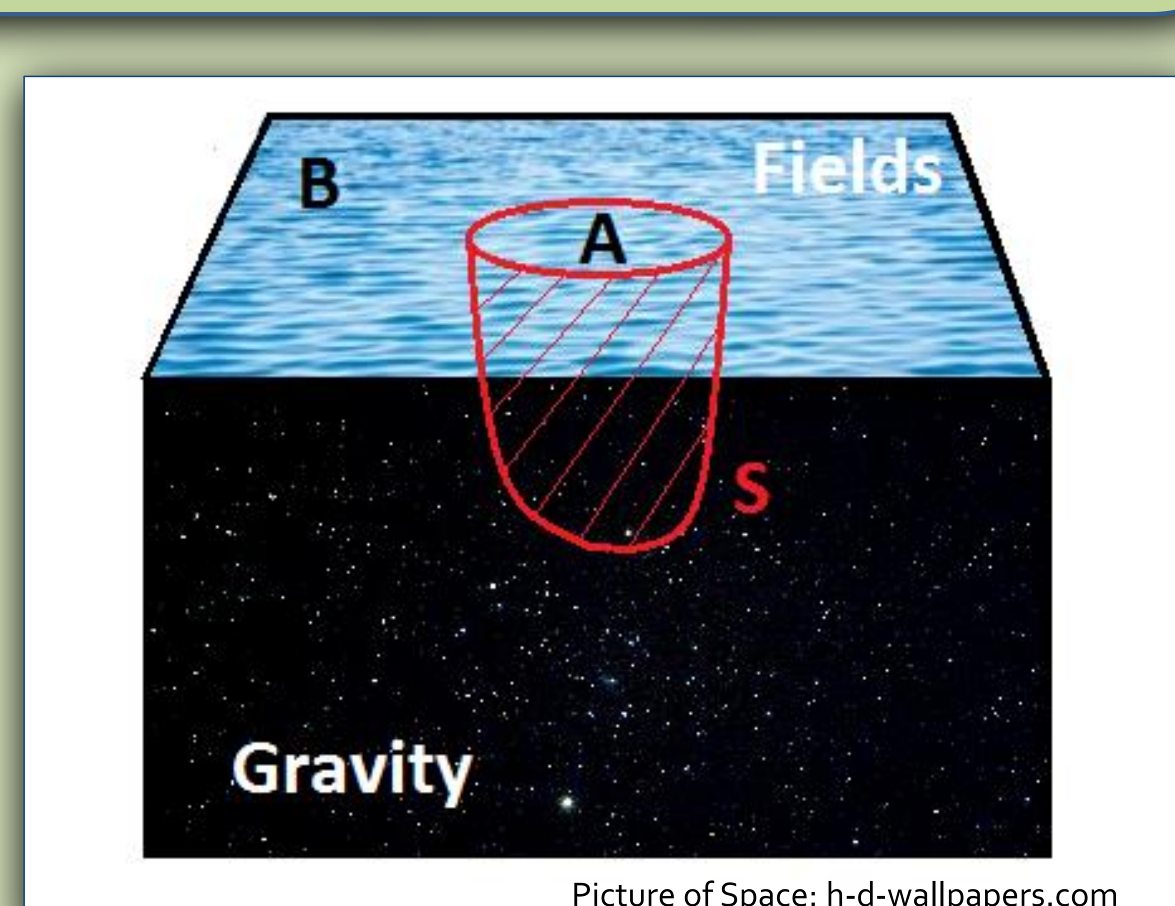
We can study the **entanglement of fields** just as for particles. Here, the entanglement is occurring between the field at different positions in space. The way that entanglement is usually studied in field theory is by **splitting the space** into two regions A and B as in the picture on the left, and studying the so-called "**entanglement entropy**" between the field contained in A with the field contained in B.

Looking at Entangled Fields through the Hologram

My research involves using **holography** to study the entanglement of **quantum fields**. Quantum field theories provide our most successful and fundamental descriptions of nature; it is a natural and important question to ask how quantum entanglement applies to field theories, since entanglement is a fundamental property of all quantum systems.

Holography states that a **quantum field theory** in ***d*-dimensions** (known as the "**boundary theory**") is **equivalent** to a **theory of gravity** in ***d*+1-dimensions** (known as the "**bulk theory**"); for example, a quantum field theory in 2D is equivalent to gravity in 3D. It is often **mathematically simpler** to perform calculations in gravity than it is to perform calculations in quantum field theory, and thus holography admits **a new way of calculating the entanglement of fields.**

As an example, consider the problem mentioned above of calculating the field entanglement between regions A and B. Holography claims that this is given by the **area of a particular surface S** that ends on the curve that separates the regions, as in the picture on the right. This surface extends in the full 3-dimensions of the bulk theory since the presence of gravity "drags it" into the bulk. We also see this is closely related to the **area law** for the **entropy of black holes** that motivated holography in the first place!



Picture of Space: h-d-wallpapers.com

Entanglement is a central part of quantum theory and one that is being increasingly studied in experimental situations. Holography allows us to gain deeper insight and understanding into how it works in the context of quantum field theories!