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13-17 minutes

But what IS a force field?

The 17th century witnessed the emergence of the concept of the force field in physics. This notion was meant to explain the interaction of bodies at a distance. How does the Earth know, e.g., to circle the sun? 17th century physics explained this phenomenon in the following manner: the sun, by virtue of having a mass, does something to the space around it; it creates a gravitational force field. The force field imbues each point in space with a mathematical quantity, the potential for the force. The potential can be probed by other massive bodies, such as the Earth, and tells them how to react to the presence of the sun at a distance. Several centuries later, the same concept of a force field was invoked to explain the repulsion of two electrons. Not gravity, but electromagnetism is at work here. The role of mass in electromagnetism is played by electromagnetic charge. While the force field concept proved powerful for performing calculations and making physical predictions, e.g. regarding the orbits of the planets, its nature remained mysterious. What did "imbuing each point in space with a mathematical quantity" correspond to in terms of physical reality? What property of space was being altered by the presence of this field? These questions gave rise to many, both philosophical and scientific, ruminations, until physicists in the middle of the 20th century settled the issue definitively in the case of the electromagnetic force, and subsequently also for the strong and weak nuclear forces, which had been discovered in the meantime.

Forces conveyed by particles

The force field was identified as an effective description of a more fundamental physical phenomenon: the exchange of force-conveying particles, called gauge bosons. An electron circling an atomic nucleus is, in terms of the 17th century field concept, probing the electromagnetic field generated by the nucleus. It knows about the presence of the nucleus because the nucleus has changed the space around it (imbued it with a mathematical quantity) by creating a force field. In the modern approach, the electron is exchanging the gauge boson of the electromagnetic field, the photon, with the nucleus: exchanging the photon back and forth is the means of communication between electron and nucleus, and responsible for their interaction. There is no longer a need to explain a mysterious modification of space. The theoretical framework formalizing these ideas is called quantum field theory. As we understand the universe today, it is governed by 4 types of forces: the electromagnetic force, the strong and weak nuclear force, and the gravitational force. Of these, the first three are convincingly described through the exchange of the respective gauge bosons in the framework of quantum field theory. It thus appears natural to attempt to embed gravity in this framework as well, and introduce the corresponding gauge boson, the graviton. However, Nature has revealed itself to be more sophisticated than that.

Gravity as odd man out

At the beginning of the 20th century, in parallel to the advancement of our understanding of the microscopic behavior of nature culminating in the formulation of quantum field theories, Albert Einstein introduced a completely new way of thinking about gravity. His ideas make the notion of space changing around a gravitating body precise, while simultaneously essentially eliminating the need for the concept of a gravitational force! Recall from high school physics that the concept of force was introduced by Newton to explain why a body deviates from its natural state of motion, which is with constant velocity along a straight path. Einstein's insight was to redefine what is meant by a straight path. In our intuition, we can replace the notion of straight path by that of the shortest distance between two points. But if we are constrained to move on the surface of a globe, we see that the shortest distance notion of the concept of a straight path is more general. Surfaces of different geometry will thus entail different notions of what constitutes a straight path. According to Einstein, particles always move on a straight path. Our observations, in apparent contradiction to this axiom, are explained by a modification to the geometry of space-time caused by gravity. Three comments are in order. First, we can visualize surfaces (2 dimensional spaces) of different geometry, but not 3 dimensional spaces of different geometry. This is a limitation of our visualization capabilities: we think of the 2 dimensional surface as embedded in 3 dimensions, and deform it within this ambient space. Mathematically, there is no need for the ambient space as a crutch: one can study the geometry of a 2 dimensional or any higher dimensional space directly. Secondly, why space-time? The Newtonian natural state of motion involved a straight path and constant velocity. To geometrize the second notion, it is necessary and very natural to weaken the distinction between space and time. And thirdly, I would like to emphasize that Einstein's ideas demanded a dramatic re-thinking of 2000 years of thought concerning the nature of space and time. The notion of space-time having a non-trivial geometry dictated by gravity runs counter to our intuition. But observations and experiments have proved Einstein right. In light of these developments, it is perhaps not surprising that the quantum field theoretic approach, explaining forces via exchange of gauge bosons, runs into problems when applied to gravity. In quantum field theory, the status of space is that of a stage on which dynamics takes place, and time is its ancient ticking self. In Einstein's theory, space and time combine to the notion of space-time, which participates in the dynamics. If one chooses to ignore these objections and forges ahead with trying to naively apply the methods of quantum field theory to a theory of the graviton, the alleged gauge boson for gravity, the theory one obtains fails to allow for sensible calculations: all quantities one wishes to compute yield infinities from which physical predictions cannot be extracted. A novel approach is needed.

String theory as a theory of quantum gravity

The initial formulation of string theory, called the perturbative string (we will return to the notion of perturbation theory below), was found by accident -- the theoretical physics equivalent of the discovery of penicillin: a candidate for a theory of the strong interaction exhibited a boson in its spectrum of spin 2, the hallmark of the graviton. Ignoring the historical narrative, one can motivate the structure underlying the perturbative string by outlining how it addresses the difficulties quantum field theory encounters when attempting to incorporate gravity. Infinities: Where do the infinities in quantum field theory come from? Underlying this theory is the notion of point particle: both the gauge bosons (such as the photon) and the matter particles (such as the electron) can be localized at a single point in space. Interactions are equally localizable, e.g. the point in space-time at which an electron emits a photon. This notion of localization is inherently prone to give rise to infinities: the strength of the gravitational interaction increases with distance to the source as 1 over the distance squared. If the source is truly a point, as the distance to this point tends to 0, the interaction strength will tend to infinity. String theory eliminates the notion of point-like (i.e. 0-dimensional) elementary particles: the elementary excitations underlying matter and its interactions are postulated to be one-dimensional tiny loops moving through space-time -- hence the string in string theory. The status of space-time: As a closed string, a loop, propagates through space-time, it traces out a 2-dimensional surface called the worldsheet of the string (think of the image it would leave on the photographic film of yore at long exposure times). The worldsheet takes central stage in the perturbative string. First comes the worldsheet, devoid of an ambient space-time. The theory is formulated in terms of mathematical structures that are associated to this worldsheet, and it is these that describe space-time and how the string moves in it. Space-time is elevated from stage to actor participating in the dynamics. Simplicity: Aside from addressing the problem of infinities, the passage from point particles to strings provides a bonus: points carry no geometric information. In quantum field theory, one thus introduces different types of points to correspond to the zoo of elementary particles one observes, such as electrons, positrons, etc. In contrast, a 1-dimensional object such as a string can vibrate. And indeed, each vibrational mode corresponds to a different elementary particle. Hence, only one type of string is needed to incorporate the zoo of observed particles.

Perturbative string theory and the search for non-perturbative foundations

Two strings coming in from past infinity, interacting with each other, and moving off to future infinity form one worldsheet: it is described by two cylinders that join and then split apart again. The strings can interact in a more complicated fashion, joining and separating again any number of times. The worldsheet becomes increasingly complicated the more interactions take place. A measure of this complexity is the genus: how many holes the worldsheet has (in the sense that a doughnut has one hole, and a pretzel three). Each splitting and joining gives rise to a new hole, and increase the genus by one. Worldsheets with all possible genera must be considered when describing the interaction of two strings with each other. The importance of each such contribution is governed by a quantity called the string coupling constant. If this constant is large (one speaks of the strong coupling regime), all possible worldsheets must be incorporated to obtain a physical result. This is generally not feasible computationally. If on the other hand, the constant is small (the weak coupling regime), the larger the number of holes in the worldsheet (i.e. the more splitting and joining), the less the process will contribute to the total interaction cross-section. This is the regime in which perturbative string theory can be used to compute physical cross-sections. It gives rise to a perturbation series: an infinite sequence of contributions, ordered by the genus of the worldsheet underlying the computation, but of ever decreasing size. This is the origin of the qualifier perturbative in perturbative string theory. Calculating the leading contributions to the perturbation series provides an approximation to the true answer. Such perturbation series are commonly encountered in physics: if a difficult problem one cannot solve exactly is related to a simpler problem that one can solve, and this relation involves a small parameter -- e.g. an interacting theory related to a free (i.e. non-interacting) theory via a small coupling constant -- then one can calculate the quantity of interest in the simpler theory together with an infinite series of corrections, scaling with ever increasing powers of the small parameter and hence of ever decreasing magnitude. Perturbative string theory gives an algorithm for calculating the perturbation series, based on worldsheets of ever higher genus, but without specifying the equations to which the perturbation theory is an approximation to. The challenge of finding the underlying equations is referred to as the search for a non-perturbative definition of string theory, and is at the frontier of fundamental research in string theory.

Compactification studies

The mathematical framework of string theory is very predictive. Many of the parameters that are ours for the choosing in other theories are fixed in string theory. A prominent example is the dimension of space-time. In Newtonian physics, we compute the trajectory of cannonballs in three spatial dimensions, because this is the case of relevance to Earthly warfare. The formalism of the theory permits the same calculation in any number of dimensions. String theory on the other hand is less flexible; it dictates the number of spatial dimensions, and it dictates this number to be 9! This lack of flexibility is a property sought after in a fundamental theory: the fewer choices possible, the more predictive the theory. The predictions, of course, must be in accord with observation. Contrary to our intuition, the prediction of 9 spatial dimensions by string theory passes this test without difficulty. Einstein taught us, as I reviewed above, that space has a non-trivial geometry. If the 6 unexpected additional spatial dimensions have particular geometries, if they are e.g. very small circles, then we cannot observe them when firing cannons. Many fundamental observables however will depend sensitively on the particular geometry of these so-called internal dimensions, e.g. the spectrum of elementary particles that we encounter in our everyday lives, such as electrons and positrons, and in collider experiments, such as the W-boson, or most recently, the Higgs particle. The process of working out the 4 dimensional consequences of the choice of geometry of the internal 6 dimensions is called compactification. The higher dimensional perspective provides another unifying principle to the zoo of particles and interactions that must be listed one by one from a four dimensional point of view. Indeed, this powerful idea predates string theory. Kaluza and Klein already suggested considering a 5 dimensional space-time to unify classical electromagnetism and gravity in the 1920s. The re-emergence of this idea in the theory of quantum gravity provided by string theory is another instance in which string theory adheres to the principle of simplicity.