The Unification of Forces

Physics seeks laws that explain natural phenomena. With each advance, the landscape becomes more simple – distinct phenomena have in fact the same origin – at the cost of a more complex formalism. Will this process eventually result in the unification of the four forces governing Nature?

Two famous physicists

Isaac Newton (1643-1727)

James Clerk Maxwell (1831-1879)

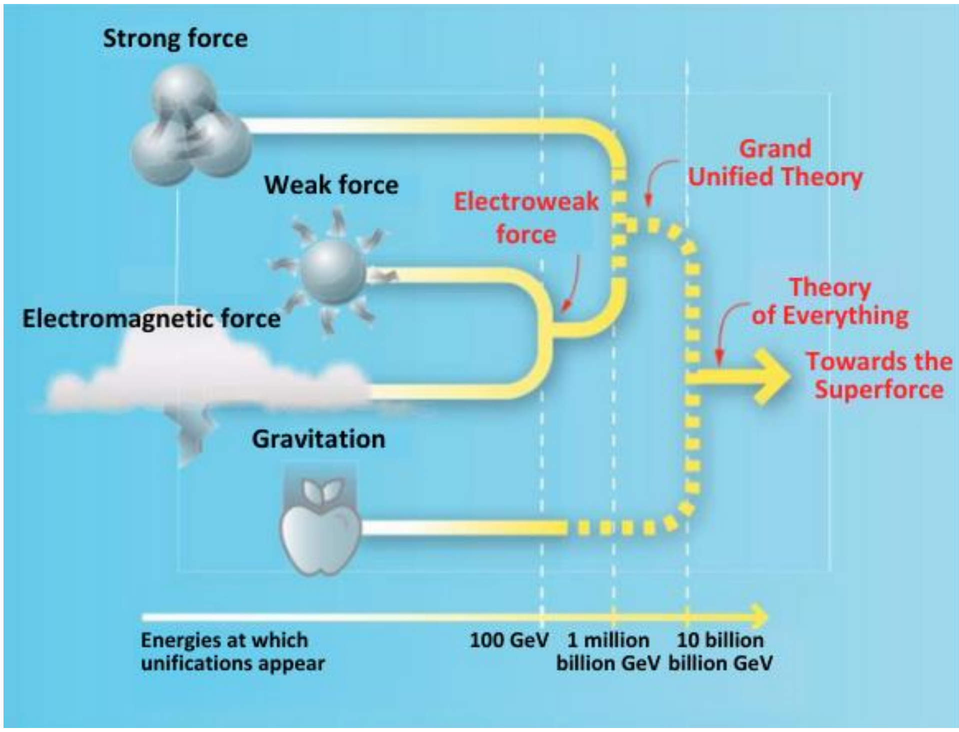
Credit: R. Maraï

Newton and Maxwell made significant contribution to the unification of the laws of physics. Newton showed that the fall of objects to Earth and the motion of celestial bodies stem from the same principle: the law of universal gravitation. Maxwell succeeded in describing electricity and magnetism within a single framework: electromagnetism.

Physics is based on the intuition that all phenomena in the Universe can be explained by laws that are known or may yet be discovered. Under this hypothesis, the infinite variety of phenomena can be reduced to a limited set of rules. The smaller the number of rules, the better the explanation, the further we move away from empiricism towards theory. Thus, the unification of the forces in Nature interweaves with the history of physics.

It all started with Newton's theory of universal gravitation (1687), which unified terrestrial mechanics, describing the fall of bodies to the Earth, and celestial mechanics, describing the movement of stars in the sky. Two centuries later, Maxwell unified electricity and magnetism, two phenomena that had until then been considered as completely distinct.

The next step was the Standard Model of particle physics, which is valid down to the scale of a billionth billionth metre and which combines two major advances of the 20th century, special relativity and quantum mechanics. Before the Standard Model was formulated, the infinitely small was described using a few hundred particles subject to three forces: electromagnetism, and the weak and strong nuclear forces. The Standard Model retains only twelve elementary particles classified into three families, and unifies the electromagnetic and weak forces. Although these two interactions are clearly separate at our level, they share a common origin – the electroweak force. The link between them appears on smaller scales of distance – or, in other words, on greater scales of energies – than those which can be observed ordinarily. But this unification has consequences that are perfectly verified during high-energy collisions in particle accelerators.



Credit: A. Dugan, adapted

Could this unification of forces extend at even smaller distances, at even greater energies? The unification of the strong nuclear force with the electroweak force is anticipated to occur at scales vastly beyond current experimental capabilities – by a factor of a trillion. Researchers are still striving to develop a satisfactory formulation of this 'grand unified theory', whose predictions must align with experimental results.

The ultimate step would be the unification of the three forces describing the world of elementary particles and gravitation, which is too weak to have effects at the level of the infinitely small but governs the infinitely large via the theory of general relativity. This phenomenon would occur at even more distant energies/distances, and it is currently difficult to imagine how a hypothetical 'theory of everything' could be tested. Nonetheless, tracing the history of the Universe back to the Big Bang suggests that such conditions might have existed in the past.

A scenario of unification of the fundamental forces

As energy increases, the four fundamental forces are believed to gradually unify. So far, only the unification of the weak and electromagnetic interactions has been observed. The subsequent stages – incorporating the strong interaction, and, eventually, gravitation – would occur at such high energies that their effects remain unobservable in current colliders.

Translated from 'L'unification des forces',* Passeport pour les deux infinis, *IN2P3/Dunod, https://pass2i.ijclab.in2p3.fr/ (French); updated with ICHEP2024 conference (https://ichep2024.org) for IPPOG