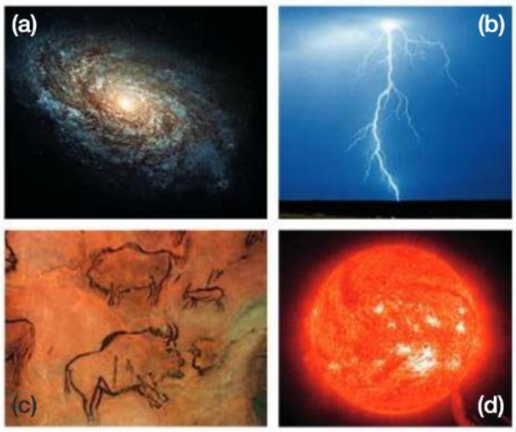
The Fundamental Forces

Physicists describe all phenomena in the Universe through four fundamental interactions, or forces. While we are quite familiar with two of them – gravity and electromagnetism – the other two – the 'strong' and 'weak' interactions – are specific to the world of the infinitely small.



Credit: a) NASA; b) H. van Tilborg; c) J.-M. Alibaud, Fotolia.com; d) ESA/NASA/SOHO

In our daily life, in order to move an object, we usually have to touch it and apply a contact force. Other forces can exert remotely, i.e. two magnets attracting or repelling each other.

All these forces are interpreted in terms of four fundamental forces, each transferred by one or several particles called 'mediator bosons'. Two particles, e.g. electrons, interact together by exchanging some of these mediator bosons. Depending on the mass of the bosons, the range of interaction will vary – the greater the mass, the shorter the range.

The four fundamental interactions

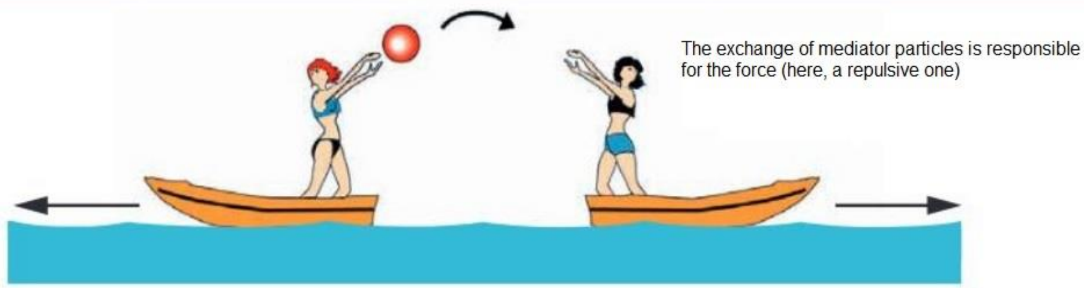
(a) Gravitation explains the evolution of galaxies as well as the fall of bodies. (b) The electromagnetic force combines electricity – here, lightning – and magnetism. (c) The weak interaction governs many radioactive decays, including that of Carbon-14, which is used to date parietal art, for example. (d) The strong interaction is responsible for nucleus cohesion, as well as fusion reactions within stars.

If two objects repel or attract each other electrically, it is because they both have an electric charge. Again, the same rule applies on the subatomic scale. A particle subjected to an interaction has an associated charge – which may not always be as simple as the electric charge.

Let's examine the four fundamental forces. Gravitation is the force we know best in our everyday life, but it is also the weakest interaction. It cannot be detected on the atomic scale, and scientists don't know yet how to include it in the quantum mechanics formalism describing the other three forces. Its mediator boson would be a zero-mass particle called a graviton, yet to be uncovered. Here the mass plays the role of a charge, and the force is always attractive.

The fundamental forces

Type	Relative intensity	Mediator particles	Prevails in
Strong force	~ 1	Gluons	Atomic nucleus
Electromagnetic force	~ 10^{-3}	Photons	Electrons around the nucleus
Weak force	~ 10^{-5}	Z^0, W^+, W^- bosons	Beta radioactive decay
Gravitation	~ 10^{-38}	Graviton (?) (not yet observed)	Celestial bodies



Credit: CERN

The electromagnetic force, perceptible on our scale, is conveyed by the photon, which is also the fundamental grain of light. Photons have zero mass and, therefore, act over very long distances. The associated charge is the electric charge, which can be positive or negative. Particles with no electric charge, such as neutrinos, are not subjected to this force.

The weak force only acts on very small scales. It is responsible for certain types of radioactivity, and it is because of its low intensity that radioactive elements have very long lifetimes. There are three mediator bosons for this force, two are electrically charged (W^+ and W^- bosons) and one neutral (Z^0 boson). These are very heavy particles, which makes this force extremely weak on our scale.

The strong force is responsible for the cohesion of protons and neutrons, which are made up of quarks, and is involved in the formation of atomic nuclei. It is carried by bosons called gluons and has a very short range. The short range isn't due to the gluon's mass – null – but to another property related to the charge of the force, poetically called colour. Among the matter particles, only quarks carry a colour charge, which comes in three varieties, conventionally named 'red', 'green', and 'blue'. There are also three varieties of opposite strong charges, carried by antiquarks. In nature only objects with a total strong charge equal to zero ('white' objects) can be found; they can be obtained either by combining a charge and its opposite, or by combining three charges of each variety.

Characteristics of the different forces

The four forces affecting fundamental particles are sorted in the table by descending order. The numbers in the second column are relative: they compare the intensity of a force with the most intense force (fittingly named the strong interaction), conventionally set to 1. The electromagnetic force is a thousand times weaker than the strong interaction, which explains, in particular, why the repulsion between protons (all positively charged) isn't enough to break nucleus cohesion. The weak interaction is even less intense but plays a major role on the scale of particles. As for gravitation, the force is negligible here. All these forces are based on the exchange of mediator particles, bosons.

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