Study claims all observables in nature can be measured with a single constant: The second

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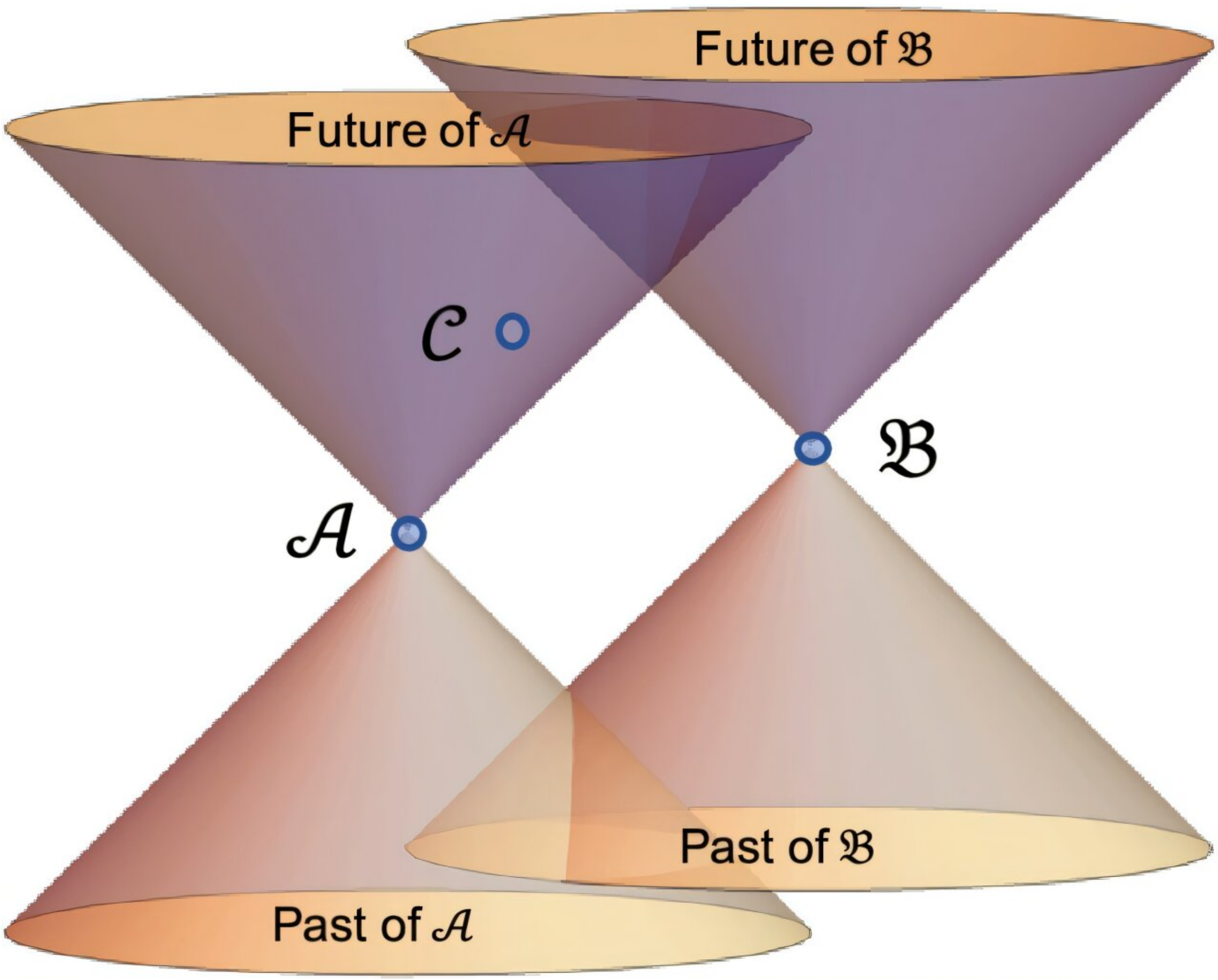

The figure illustrates three events in Minkowski spacetime. Event □□ is neither in the past nor in the future of □□, □□ ~ □□, and event □□ is neither in the past nor in the future of □□, □□ ~ □□. Despite this, □□ ≁ □□. Indeed, □□ is in the future of □□: □□ ≻ □□. Credit: *Scientific Reports* (2024). DOI: 10.1038/s41598-024-71907-0

A group of Brazilian researchers has presented an innovative proposal to resolve a decades-old debate among theoretical physicists: How many fundamental constants are needed to describe the observable universe? Here, the term "fundamental constants" refers to the basic standards needed to measure everything.

The study is published in the journal *Scientific Reports*.

The group argues that the number of fundamental constants depends on the type of space-time in which the theories are formulated; and that in a relativistic space-time, this number can be reduced to a single constant, which is used to define the standard of time. The study is an original contribution to the controversy sparked in 2002 by a famous article by Michael Duff, Lev Okun and Gabriele Veneziano published in the *Journal of High Energy Physics*.

The whole story had begun ten years earlier, in the summer of 1992, when the three scientists met on the terrace of the cafeteria at CERN, the European Organization for Nuclear Research. During an informal conversation, they discovered that they disagreed on the number of fundamental constants.

"In the summer of 2001, we returned to the subject and discovered that our opinions were still different. So we decided to explain our positions," the three write in the abstract of their article.

In short, Okun stated that three basic units—meter (length), kilogram (mass), and second (time)—were necessary to measure all physical quantities. In other words, he reaffirmed the so-called MKS system (M, for meter; K, for kilogram; S, for second), which was later incorporated into the International System of Units (SI). Veneziano, for his part, argued that in certain contexts two units would suffice: one for time and one for length. Duff was equivocal, stating that the number of constants could vary depending on the theory in question.

Explaining the new article, Matsas says, "The goal is to find the most fundamental description of physics possible. The question raised by Okun, Duff and Veneziano is by no means trivial. As physicists, we're faced with the need to understand what's the minimum number of standards we need to measure everything."

The Brazilian researchers claim that the number of fundamental constants depends on the space-time in which the physical quantities are considered. They analyze two types of space-time: Galilean, on which Isaac Newton (1642-1727) built classical mechanics; and relativistic, which provides the substrate for Albert Einstein's (1879-1955) theory of general relativity.

There are several relativistic space-times that correspond to different solutions of Einstein's equations. The simplest of these is Minkowski space-time, named after the German-born Jewish-Lithuanian mathematician Hermann Minkowski (1864-1909). It is a space-time that is empty (free of particles and everything else), homogeneous (in which all points have the same properties), and isotropic (in which all spatial directions are equivalent). For simplicity, the article in question uses Minkowski space-time. However, the authors point out that their conclusions can be generalized to any relativistic space-time.

"In Galilean space-time, you need rulers and clocks to measure all the physical variables. In relativistic space-time, however, clocks are sufficient. This is because in relativity, space and time are so interrelated that a single unit is sufficient to describe all quantities. High-precision clocks, such as the atomic clocks used today, are capable of meeting all measurement needs," says Matsas.

As you can see from the previous sentence, even in Galilean space-time, a simplification of fundamental quantities is already possible that leaves out mass.

"Historically, based on a standardization effort adopted during the French Revolution (1789-1799), the kilogram was defined as the mass of one liter of pure water at a given pressure and temperature. In practical terms, it's very convenient to have a mass standard, but from a fundamental point of view, it's not necessary," says Vanzella. "The mass of a body is given by the acceleration with which a particle is attracted when it's at a certain distance from the mass."

In its current version, the International System of Units (SI) uses seven basic units: meter (length), second (time), kilogram (mass), kelvin (temperature), ampere (electric current), candela (light intensity), and mole (number of molecules or atoms).

"But these units are only basic because they serve practical purposes. For example, if someone needs to buy a light bulb, the number of candelas tells them how much light intensity the bulb should provide. However, it has long been known that these units have redundancies. That is, many of them can be defined based on others. After a review carried out in 2019, these units are now associated with constants of nature, such as the speed of light [c] and Planck's constant [h]," says Matsas.

According to the criteria used by Duff, Okun and Veneziano, the number of fundamental constants is related to the minimum number of independent standards needed to express all physical quantities. To repeat, in Galileo's space-time, all observables can be expressed in terms of units of time and space, which are usually the "second" and the "meter." In relativistic space-time, the unit of time—that is, the "second"—is sufficient to express any observable.

And the definition of "second" is currently based on a natural constant: the energy difference between two specific levels of the electronic layer of caesium-133. One second (1s) corresponds to the time of 9,192,631,770 oscillations of the radiation emitted when an electron passes between these two states of caesium-133.

"Any artifact capable of regularly counting 9,192,631,770 oscillations of this radiation will have measured 1s and can be considered an honest clock," explains Matsas.

In short, in relativistic space-time (which is the space-time in which the study in question considers us to live), any physical quantity can be measured in terms of the "second," which is the unit of time. Time is a variable because it is constantly changing, but the "second" is defined by a constant associated with a certain energy level in the electronic layer of the caesium-133 atom.

"The verdict that an observable is or isn't a constant of nature is absolute because it's proclaimed by honest clocks, which must exist for the very concept of space-time to make sense. But the choice of which 'fundamental constant' is used to define them is a social and historical construction that depends on convenience," comments Vanzella.

The study included George Matsas and Vicente Pleitez, both from the Institute of Theoretical Physics at São Paulo State University (IFT-UNESP), as well as Alberto Saa, from the Institute of Mathematics, Statistics and Scientific Computing at the State University of Campinas (IMECC-UNICAMP), and Daniel Vanzella, from the São Carlos Institute of Physics at the University of São Paulo (IFSC-USP).

More information: George E. A. Matsas et al, The number of fundamental constants from a spacetime-based perspective, *Scientific Reports* (2024). DOI: 10.1038/s41598-024-71907-0

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