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Cuprins

Introduction

In this paper I approach the evolution of gravitational tests from an epistemological perspective framed in the concept of rational reconstruction of Imre Lakatos, based on his methodology of research programmes. Unlike other works on the same subject, the evaluated period is very extensive, starting with Newton's natural philosophy and up to the quantum gravity theories of today. In order to explain in a more rational way the complex evolution of the gravity concept of the last century, I propose a natural extension of the methodology of the research programmes of Lakatos that I then use during the paper. I believe that this approach offers a new perspective on how evolved over time the concept of gravity and the methods of testing each theory of gravity, through observations and experiments. I argue, based on the methodology of the research programmes and the studies of scientists and philosophers, that the current theories of quantum gravity are degenerative, due to the lack of experimental evidence over a long period of time and of self-immunization against the possibility of falsification. Moreover, a methodological current is being developed that assigns a secondary, unimportant role to verification through observations and/or experiments. For this reason, it will not be possible to have a complete theory of quantum gravity in its current form, which to include to the limit the general relativity, since physical theories have always been adjusted, during their evolution, based on observational or experimental tests, and verified by the predictions made. Also, contrary to a widespread opinion and current active programs regarding the unification of all the fundamental forces of physics in a single final theory, based on string theory, I argue that this unification is generally unlikely, and it is not possible anyway for a unification to be developed based on current theories of quantum gravity, including string theory. In addition, I support the views of some scientists and philosophers that currently too much resources are being consumed on the idea of developing quantum gravity theories, and in particular string theory, to include general relativity and to unify gravity with other forces, as long as science does not impose such research programs.

In *Introduction*, after a very brief history of the concept of gravity from antiquity to the 17th century, I present various approaches in time of the methodologies of gravitational tests, and the concept of Lakatos' scientific rationality through research programmes. I present my proposal to extend the Lakatos methodology with two new terms, bifurcated programs and unifying programs, with their specific characteristics. In *Newtonian Gravity*, after an analysis of the methodology used by Newton, I talk about the negative heuristics (hard core) and the positive heuristics (development strategy) used in the elaboration of the law of universal gravity. There follows a period of proliferation of post-Newtonian theories of gravity, the tests proposed by Newton and those for the other theories, and then I highlight the anomalies accumulated by the theory and the saturation point, where the need is felt to develop another theory with greater heuristic power and to digest the anomalies of Newton's theory. The *General Relativity* section is approached in the same way, starting from an epistemological and methodological approach, the negative and positive heuristics of this research program, the proliferation of post-Einsteinian theories, and the description of the parameterized post-Newtonian formalism used to analyze, evaluate and compare the models of gravity based on the gravity tests specific to these theories. The final part of the section is dedicated to the anomalies that appear in general relativity and to highlight the saturation point that requires a new approach to gravity. In Quantum Gravity the same epistemological and methodological issues are addressed, with emphasis on canonical quantum gravity (including loop quantum gravity) and string theory, highlighting the methodological problems of these theories and the tests that are proposed for their experimental verification. I conclude the section with the evaluation of the attempts to obtain the unification of all the forces in a final theory. A shorter section on *Cosmology* follows, in which I analyze the research program of cosmology from the perspective of gravity theories. In the *Conclusions* I present, condensed, my opinions and arguments developed throughout the work.

Gravity

Gravity has a universal character, but its strength rapidly decreases with distance, being the weakest of the four fundamental forces of physics[1]. In the 4th century BC, the Greek philosopher Aristotle considered as the cause of the fall of heavy bodies their tendency to move to their natural place[2]. In Book VII of *De Architectura*, the Romanian engineer and architect Vitruvius argues that

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[1] The four "fundamental" forces are the electromagnetic force, the "weak" nuclear force responsible for radioactive decay, "strong" nuclear force linking the constituent elements of the nuclei, and gravitational force.

[2] Edward Grant, *The Foundations of Modern Science in the Middle Ages: Their Religious, Institutional and Intellectual Contexts* (Cambridge ; New York: Cambridge University Press, 1996), 60–61.

gravity does not depend on the "weight" of a substance, but rather on its "nature"[3]. Indian astronomer and mathematician Brahmagupta argued that the Earth is spherical and attracts objects[4]. In the seventeenth century, Galileo discovered that, contrary to Aristotle's teachings, all objects were accelerating equally when they fell[5]. After Newton's count of gravity as a force, general relativity considers gravity to be a consequence of the curvature of spacetime due to mass distribution. According to the current main theory, gravity appeared with the birth of the Universe, during the Planck era (10^{-43} seconds after the Big Bang). Currently, there are attempts to develop a quantum theory that unifies gravity with the other three fundamental forces in nature. Quantum mechanics with quantum field theory[6] and general relativity are the fundamental theories in which gravity is approached.

Gravitational tests

Allan Franklin and Slobodan Perovic, in *Experiment in Physics*[7], state that theories in science in general, and in physics in particular, are confirmed (temporarily) by experiments that verify the assertions and predictions of theories, thus laying the groundwork for scientific knowledge. Francis Bacon was the first to support the concept of a crucial experiment, which can decide the validity of a hypothesis or theory. Later, Newton argued that scientific theories are directly induced by experimental results and observations, excluding untested hypotheses. Hobbes stated, on the contrary, that human reason preceded experimental techniques, criticizing Boyle's

[3] Vitruvius Pollio, *De architectura* (Torino: Giulio Einaudi, 1997), 215.

[4] Muḥammad ibn Aḥmad Bīrūnī, "Alberuni's India," text, 1910, 272, http://www.columbia.edu/cu/lweb/digital/collections/cul/texts/ldpd_5949073_001/index.html.

[5] Stillman Drake, *Galileo at Work: His Scientific Biography* (Courier Corporation, 2003).

[6] Quantum field theory is the common framework for light and electron theory in the form of fields (quantum electrodynamics), weak nuclear forces theory, and quarks and gluons theory. The standard model of particle physics combines these approaches and describes the internal structure of atoms through quantum fields.

[7] Allan Franklin and Slobodan Perovic, "Experiment in Physics," in *The Stanford Encyclopedia of Philosophy*, ed. Edward N. Zalta, Winter 2016 (Metaphysics Research Lab, Stanford University, 2016), https://plato.stanford.edu/archives/win2016/entries/physics-experiment/.

optimism about the role of the experimental method[8]. In the 20th century, logical positivism separates observational deductions from theoretical ones. Thomas Kuhn and Paul Feyerabend criticized this view, saying that all experiments are based on a theoretical framework and therefore cannot independently confirm a theory[9]. Ian Hacking agreed with this idea, but says the comments remain reliable through independent confirmations. In the case of a single viable experimental system, Allan Franklin and Slobodan Perovic propose specific strategies for validating the observation, which, together with Hacking's strategy, constitute an epistemology of the experiment:

1. Experimental verification and calibration, with the help of known phenomena.
2. Reproduction of previously known artifacts.
3. Elimination of plausible sources of error and alternative explanations of the result ("Sherlock Holmes strategy").
4. Using the results to argue their validity.
5. Using a well-corroborated independent theory of phenomena to explain the results.
6. Using an apparatus based on a well-corroborated theory.
7. Use of statistical arguments. [10]

But applying these strategies does not guarantee the correctness of the results. Because of this, physicists use several strategies, depending on the experiment.

Peter Galison, in *How Experiments End* (1987), states that experiments end in a subjective way, when experts believe they have reached a valid result[11]. Most experiments are based on the traditions in the field and the personal experience of the researcher (including his theoretical assumptions), both in designing the experiment and in accepting a theory that "allows" the conduct of experiments. The theoretical assumptions of the experimenters are accepted.

Harry Collins has developed an argument called "experimenters' regress[12]," according to which there are no formal criteria that you can apply to decide whether an experimental device

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[8] Steven Shapin and Simon Schaffer, *Leviathan and the Air-Pump: Hobbes, Boyle, and the Experimental Life* (Princeton University Press, 1989).

[9] Ian Hacking, "Do We See Through a Microscope?," *Pacific Philosophical Quarterly* 62, no. 4 (1981): 63: 305–322.

[10] Franklin and Perovic, "Experiment in Physics."

[11] Peter Galison, "How Experiments End," *Journal of Philosophy* 87, no. 2 (1990): 235.

[12] Harry M. Collins, *Changing Order: Replication and Induction in Scientific Practice*, Reprint edition (Chicago: University of Chicago Press, 1992), 79–111.

works properly or not. What actually matters is negotiation within the scientific community, which depends on factors such as the career, social and cognitive interests of scientists and perceived usefulness for future work, but which is not decided by what we may call epistemological criteria or rationalized judgment[13].

Pickering also argues that the reasons for accepting the results are their subsequent usefulness in scientific practice, and their agreement with existing community commitments[14]. He states that an experimental system rarely produces valid experimental results unless it is adjusted accordingly, and that the theory of apparatus, as well as the theory of phenomena, determines the production of a valid experimental result[15]. Later, he concludes that "the outcomes depend on how the world is"[16]: "In this way, then, how the material world is leaks into and infects our representations of it in a nontrivial and consequential fashion. My analysis thus displays an intimate and responsive engagement between scientific knowledge and the material world that is integral to scientific practice." [17]

Hacking claims that, despite appearances, constructivists, such as Collins, Pickering or Latour, do not believe that facts do not exist or that there is no reality. He cites Latour and Woolgar that the result is a consequence of scientific work rather than its cause[18] [19], in a relative consensus with the scientific community.

Franklin and Perovic state that the accumulation of a large amount of data in an experiment may require a selection, by the technique of reduction used by physicists, of the data that will be used. This may be an important epistemological concern regarding the selection of data considered

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13 Franklin and Perovic, “Experiment in Physics.”

14 Andrew Pickering, “The Hunting of the Quark,” *Isis* 72, no. 2 (1981): 216–36.

15 Pickering, “The Hunting of the Quark.”

16 Andrew Pickering, *The Mangle of Practice: Time, Agency, and Science*, 1 edition (Chicago: University of Chicago Press, 1995), 182.

17 Pickering, 183.

18 Bruno Latour, Steve Woolgar, and Jonas Salk, *Laboratory Life: The Construction of Scientific Facts, 2nd Edition*, 2nd edition (Princeton, N.J: Princeton University Press, 1986), 180.

19 Ian Hacking, *The Social Construction of What?*, Revised edition (Cambridge, Mass: Harvard University Press, 2000), 80–81.

useful, minimizing the probability of unexplored results[20]. In such cases, physicists apply a robustness analysis in testing hypotheses, checking the equipment used, and establishing working algorithms.

In the case of the solutions of Einstein's equations of general relativity and of the modeling of quantum gravity theories, due to the complexity of these approaches, simulations of computer experiments are attempted. Currently, there is an ongoing dispute to what extent these simulations are experiments, theories or some kind of hybrid methods of doing science. [21]

Between 1965 and 1990 many experiments were developed for testing gravitational theories, including[22]

- High precision measurements of the effects of electromagnetic radiation in the gravitational field, confirming the GR for the weak gravitational field.
- Detection of the non-linear gravitational interaction of the masses at a pulsar in the gravitational field of a neutron star.
- Indirect confirmation of gravitational radiation by observing two nearby neutron stars, confirming GR.
- Attempts, so far failed, to ascertain the violation of the principle of equivalence or the existence of a fifth force.

During this period most experiments confirmed the general relativity with the help of the newly developed technologies. A technological basis for gravitational wave astronomy has been created. Cryogenic barogenic antennas and laser interferometric antennas were built, associated with the theoretical analysis of the experiments with the test masses, resulting in the sensitivity of the experiments depending on the thermal insulation, if the device continuously records the coordinates the antenna sensitivity is limited, and the sensitivity can be increased if there are used

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[20] Allan Franklin, *Shifting Standards: Experiments in Particle Physics in the Twentieth Century*, 1 edition (Pittsburgh, Pa: University of Pittsburgh Press, 2013), 224–25.

[21] Eric Winsberg, *Science in the Age of Computer Simulation* (Chicago: University of Chicago Press, 2010), 136.

[22] Vladimir B. Braginsky, "Experimental Gravitation (What Is Possible and What Is Interesting to Measure)," *Classical and Quantum Gravity* 11, no. 6A (June 1994): A1–A7, https://doi.org/10.1088/0264-9381/11/6A/001.

quantum procedures[23]. The antennas can help in observing the gravitational background radiation and testing the general relativity in the ultra-nonlinear case.

Regarding the sensitivity of gravitational measuring devices, Vladimir B Braginsky states that the current level of knowledge allows us to hope that the sensitivity of the antennas can increase, and no limit of sensitivity has been set in the gravitational experiments, it depends on the knowledge of the scientists. [24]

Currently, experimental gravity is an emerging field, characterized by continuous efforts to test the predictions of gravity theories.

The *classical limit* or the *limit of correspondence* is the ability of a physical theory to approximate the classical version when it is taken into account by the special values of its parameters[25]. The *principle of correspondence* formulated by Niels Bohr in 1920[26] states that the behavior of systems described by quantum mechanics reproduces classical physics within the limits of large quantum numbers[27]. This principle has two basic requirements: the reproduction of the Poisson brackets, and the specification of a complete set of classical observables whose operators, when acting through appropriate semiclassical states, reproduce the same classical variables with small quantum corrections[28].

Methodology of Lakatos - Scientific rationality

[23] Braginsky.

[24] Braginsky.

[25] David Bohm, *Quantum Theory*, Revised ed. edition (New York: Dover Publications, 1989).

[26] N. Bohr, "Über die Serienspektra der Elemente," *Zeitschrift für Physik* 2, no. 5 (October 1, 1920): 423–478, https://doi.org/10.1007/BF01329978.

[27] Paul A. Tipler and Ralph Llewellyn, *Modern Physics*, Sixth edition (New York: W. H. Freeman, 2012), 160–61.

[28] Abhay Ashtekar, Luca Bombelli, and Alejandro Corichi, "Semiclassical States for Constrained Systems," *Physical Review D*, 2005, https://www.academia.edu/587754/Semiclassical_states_for_constrained_systems.

Both general relativity and quantum mechanics are paradigms in Kuhn's sense[29]. Both coexist simultaneously. But in Kuhn's scheme there is no such situation in which two simultaneous paradigms coexist peacefully. Kuhn's paradigm is defined primarily from a sociological point of view[30]. In this sense, the "family" of relativists coexist peacefully with the "family" of quantum physics theorists for almost a hundred years, without much interaction between them. In universities, both paradigms are accepted. Both paradigms also have a common feature: the claim for completitude and universality Quantum theoreticians consider that the role of the observer and the corresponding statistical interpretation are properly described only in the framework of quantum theory. At the same time, the supporters of the theory of general relativity consider that gravitational interaction is universal and must be represented by curved, geometric space-time, which in turn influences gravity.

The two above paradigms are essentially incompatible from the point of view of the observational system[31]. Despite the incompatibility, the two paradigms are traditionally applied in different fields, namely macrophysics and microphysics. Both paradigms do not present decisive anomalies and are extremely efficient and respected. Also, there is no competition between the two paradigms. It turns out that *this contemporary situation in physics is not compatible with Kuhn's scheme for the structure of scientific revolutions*.

Lakatos proposed a methodology for investigating the evolution of science through research programs, a combination of Popper's falsifiability, Kuhn's scientific revolutions and Feyerabend's methodological tolerance[32]. Lakatos' concept takes into account a series of theories included in a research program, in which each new theory results by the addition of auxiliary clauses (or semantic reinterpretations) of existing theories to explain some anomalies. Such a new theory is theoretically progressive if it has an excess of empirical content over existing theories (if it predicts new facts),

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[29] Thomas S. Kuhn, *The Structure of Scientific Revolutions*, 3rd edition (Chicago, IL: University of Chicago Press, 1996).

[30] Kuhn, 10.

[31] Jürgen Audretsch, "Quantum Gravity and the Structure of Scientific Revolutions," *Zeitschrift Für Allgemeine Wissenschaftstheorie* 12, no. 2 (September 1, 1981): 322–39, https://doi.org/10.1007/BF01801202.

[32] Imre Lakatos, *The Methodology of Scientific Research Programmes: Volume 1: Philosophical Papers* (Cambridge University Press, 1980).

and it is empirically progressive if some of these predictions are confirmed (it produces new facts). A new theory is progressive both theoretically and empirically, and otherwise degenerate. It is considered "scientific" if it is at least theoretically progressive. A theory in the series is "falsified" when it is replaced by a theory with more corroborated content.

There is no time limit for the final evaluation of a program; so, this program obbeys to neither Popper's "refutation" nor Kuhn's "crises". A new research program (a new scientific concept, for example) benefits from a certain methodological tolerance. "Crucial" experiments can be considered decisive "after a long retrospective" only. As Lakatos states, “the discovery of an inconsistency - or of an anomaly - must *immediately* stop the development of a programme: it may be rational to put the incon sistency into some temporary, *ad hoc* quarantine, and carry on with the positive heuristic of the programme." Thus, Kepler's ellipses were admitted as crucial evidence for Newton and against Descartes one hundred years after Newton's *Principle*[33]. And the abnormal behavior of Mercury's perihelion has been known for decades as an anomaly in Newton's program, but only the development of Einstein's theory has transformed it into a "refutation" of Newton's research program.

For Lakatos, the history of science is a history of competing research programs ("paradigms"), but does not necessarily include Kuhnian periods of normal science, allowing the simultaneous coexistence of competing theories even if the new theory has, for a period of time that may take tens for years, a lower heuristic power.

Heuristics is a central concept of Lakatos philosophy. It tells us which research paths to avoid (negative heuristics) and which paths to follow (positive heuristics), giving a definition of the "conceptual framework" (and, consequently, language). The negative heuristic forbids us to point *modus tollens* to the "hard core" of the program. With the help of positive heuristics, you can articulate or even invent "auxiliary hypotheses" that form a protective belt around this nucleus, which must withstand tests and be adjusted, or even completely replaced, to defend the nucleus.

While theoretical progress (as described by Lakatos) may be immediate, empirical progress may not be verified for long time, and a long series of "refutations" may occur in a research program

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[33] Isaac Newton, “Philosophiæ Naturalis Principia Mathematica, I Ed.,” The British Library, 1687, https://www.bl.uk/collection-items/newtons-principia-mathematica.

before the auxiliary hypotheses in growth, with appropriate content, or revising false "facts," to turn the program into a success story. The positive heuristic ignores the real examples, the "available" data, based on the "models" predetermined by the researchers withn the research program, which can be modified and even replaced in the further development of the program. In this evolution, the "refutations" are irrelevant, being predictable and overcome by the research strategy.

According to Lakatos, “This methodology offers a new rational reconstruction of science. It is best presented by contrasting it with falsificationism and conventionalism.” [34] The history of science is, in Lakatos's opinion, the history of research programs rather than theories, which is a partial justification for the idea that the history of science is the history of conceptual frameworks or scientific language. . "A program advances theoretically if the new theory resolves the anomaly and is independently verifiable by making new predictions, and it advances empirically if at least one of these new predictions is confirmed. A program can progress, both theoretically and empirically, even if every theory produced within it is rejected. A program degenerates if its successive theories are not theoretically progressive (because they do not predict new facts) or are not empirically progressive (because new predictions are rejected)." [35]

The models within the research programs are sets of idealized conditions but increasingly closer to the reality, and possibly observational theories, used during the program to help its development. The refutation of these models is foreseen within the development strategy (positive heuristics), being irrelevant and "digested" by the next model. Thus, the difficulties of a program are rather mathematical than empirical. The refutations of the models are rather checkings (corroborations) of the approximation of the model to the reality, and of its heuristic power. According to the methodology, the first models are so idealized that it may not correspond to reality at all.

According to Barry Gholson and Peter Barker, Lakatos' methodology suggests that research programs evolve from an initial state that resembles to instrumentalism, to a mature state that resembles to realism. In particular, in Newton's research program, Lakatos states that the first

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[34] Lakatos, *The Methodology of Scientific Research Programmes*, 110.

[35] Nicolae Sfetcu, “Reconstructia Rationala a Stiintei Prin Programe de Cercetare” (2019), http://doi.org/10.13140/RG.2.2.24667.21288.

theory in a program was be so idealized that it represents nothing (the distinguishing sign of instrumentalism)[36]. Replacing the theory with new successive theories as the program progresses, he changes the initial model into an increasingly plausible candidate for reality. An important part of the heuristic program consists of recommendations for the incorporation of new features, absent in the initial theory, but which are necessary for real world representations. Thus, the instrumentalist and realistic features of the Lakatos research program are incompatible with the mutually exclusive categories presented by the logical empiricists.[37]

Lakatos describes a research program as follows:

> "It consists of a developing series of theories. Moreover, this developing series has a structure. It has a tenacious hard core, like the three laws of motion and the law of gravitation in Newton's research programme, and it has a heuristic, which includes a set of problem-solving techniques... Finally, a research programme has a vast belt of auxiliary hypotheses based on which we establish initial conditions... I call this belt a protective belt because it protects the hard core from refutations: anomalies are not taken as refutations of the hard core but of some hypothesis in the protective belt. Partly under empirical pressure (but partly planned according to its heuristic) the protective belt is constantly modified, increased, complicated, while the hard core remains intact."[38]

The natural extension of the Lakatos methodology

Research programs allow the development of more complex theories. Barry Gholson and Peter Barker believe that the terms can be applied to both individual theories and programs. If it is applied to the theories of a research program, I consider that they in turn become research programs, which we can call *research subprograms*.

Unlike Kuhn's scientific revolutions, Lakatos assumed that the simultaneous existence of several research programs is the norm. Science is currently facing such an unusual situation: two incompatible theories, but both accepted by the scientific community describe the same reality in

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[36] Lakatos, *The Methodology of Scientific Research Programmes*, 50–51.

[37] Barry Gholson and Peter Barker, "Kuhn, Lakatos, and Laudan: Applications in the History of Physics and Psychology," *American Psychologist* 40, no. 7 (1985): 755–69, https://doi.org/10.1037/0003-066X.40.7.755.

[38] Lakatos, *The Methodology of Scientific Research Programmes*, 179.

two different ways. Quantum mechanics governs phenomena at small dimensions of elementary particle physics, at speeds much lower than the speed of light and high energies, and general relativity deals with the macro universe, at speeds close to the speed of light and small energies. Thus, a problem of underdetermination in physics appeared. The quantum gravity attempts to complete the scientific revolution in physics started in the 19th century, for the unification of all fundamental forces, by merging the two frameworks of quantum physics and general relativity. From the efforts of physicists in this attempt resulted a rich variety of approaches, techniques and theories, of which the most known are string theory and loop quantum gravity. But the evolution in this direction is very slow and littered with many uncertainties and disputes.

The problem of underdetermination implies that more than one theory is compatible with empirical data. Underdetermination may be relative to the currently available data (transient, or scientific underdetermination), in which case theories may differ in unverified predictions, or underdetermination between theories or theoretical formulations regarding all possible data (a "permanent underdetermination"), when all their predictions are identical. A permanent underdetermination disappears (it does not have a real significance) in the case of the instrumentalist approach if the theories are individualized only in terms of their empirical content. But if we assume that the formulations of alternative theories describe different scenarios, the underdetermination must be considered real.

Quine states that two logically incompatible theories can be both compatible with the data but, if there is a mapping between the theoretical formulations, they do not in fact describe different theories, they are different variants of the same theory ("reconstruction of predicates"). Matsubara states that the formulations can represent two true alternative theories despite the structural similarity, as there are relevant semantic differences that are lost in mapping of the logically or mathematically formalized theory.

Research programs may at one time compete with single theories, single theories between them, or research programs between them. We can speak of a "*research unit*" as a singular theory or a research program.

Bifurcated programs

Barry Gholson and Peter Barker state that Lakatos' basic methodology is not an effective way to represent the underlying metaphysics identified by Kuhnians and Popperians, due to the simultaneous existence of several Lakatos-type theories that exemplify the same set of fundamental commitments. According to them, the research program consists of a series of successive theories that form chains, but never groups or families of linked theories that can compete.

It is a wrong statement, in my opinion. Lakatos has never denied such sequences. Moreover, such a group theory, called by these "clusters", can naturally develop within Lakatos' methodology. Later, Laudan developed this idea of a series of theoretical chains included in a single historical entity determined by the dominance of a certain set of metaphysical commitments. In some cases, contradictory theories can be developed based on the same basic commitments.

Lakatos' methodology does not exclude these situations; even more, they can result in a very natural way, if we consider that such theories start from the same hard core (same negative heuristic) but using a different development strategy (positive heuristic). I call these theories "*bifurcations*", respectively *bifurcated theories* or even *bifurcated programs* within a long-term approach.

Lakatos himself notes that a research program can be bifurcated at a given moment:

> "But one should not forget that *two specific theories, while being mathematically (and observationally) equivalent, may still be embedded into different rival research programmes, and the power of the positive heuristic of these programmes may well be different*. This point has been overlooked by proposers of such equivalence proofs (a good example is the equivalence proof between Schrodinger's and Heisenberg's approach to quantum physics)."

Unifying programs

Immediately after 1900, Planck's quantification questioned all classical physics. Until then, physics had developed through the application, extension, modification or reinterpretation of established physical theories, in a one-dimensional chain. But physics - especially Newtonian mechanics and Maxwell-Lorentzian electrodynamics - were no longer valid according to Planck's results. A new theory was needed, but that could no longer be obtained from the extension or modification of the existing physical theories, because they seemed to be fundamentally wrong. Thus, Einstein was forced to invent a new fundamental theory, trying to unify the current theories. This is how special relativity appeared, out of necessity.

Subsequently, the unification of all forces, through a quantum approach of the general relativity, became the main concern of quantum gravity. There are precedents in this regard: from classical electromagnetic theory and classical mechanics, two new independent unifying theories have emerged, special relativity and quantum mechanics; from special relativity and quantum mechanics the quantum field theory resulted; and at present it is hoped to arrive at a new unifying theory, from general relativity (a generalization of special relativity) and quantum field theory. These unified theories combine the theories from which they formed into a new common framework.

Within the Lakatos methodology, about these *unifying theories* it can be stated that they belong to a new research program with negative and positive heuristics different from those of the *unified research programs*, but the corresponding theory is reduced to the *unified theories* under certain conditions. I call such a program a "*unifying program*" ("*unifier*"), resulted within the concept of unification.

To be accepted, a unifying program must have a greater heuristic (theoretical or experimental) power than its unified programs.

Thus, the string theory attempts to unify the general theory of Einstein's relativity with quantum mechanics, in a way in which the explicit connection with both quantum theory and the reduced energy description of space-time in general relativity is maintained. At low energies, it naturally gives rise to general relativity, gauge theories, scalar fields and chiral fermions. String theory incorporates several ideas that do not yet have experimental evidence, but which would allow the theory to be considered a unifying candidate for physics beyond the standard model.

Matsubara appreciates Lakatos' methodology in Hacking's interpretation, but he also notes the lack of a fusion of different research programs in Lakatos's methodology, giving as examples of unified theories Schrodinger's wave mechanics and Heisenberg's matrix mechanics. He also considers the possibility of a fusion of ideas from string theory and some of its competitors, such as loop quantum gravity.

Due to the complexity and the wide variety of phenomena at the cosmological level, scientists build models based on individualized research programs, depending on the specific phenomenon (specific to black holes, for example), taking as the hard core of these programs the principles of general relativity or quantum mechanics. Subsequently, these research programs are trying to unify within some research programs such as black holes, or even larger ones, for gravitational or space-time singularities. For each phenomenon there are several alternative research programs, finally gaining recognition only those that have a higher heuristic power, but often there are smaller groups of researchers who do not give up even the alternatives with a lower heuristic power.

The unifying research programs can be developed simultaneously with the programs that will be unified (and in this case we can speak of the unified programs as "*research subprograms*"), or later, choosing from several programs the ones that best fit with the unifying program. This is a widely used way in recent years. When a concept evolves over a long time through independent research programs, without a unifying program to include them, we are not talking about a methodology of a certain research program, but a *rational reconstruction* of the science to which these independent programs compet.

1. Newtonian gravity

In certain research programs, such as the mechanistic theory of the universe according to which the universe is a huge clock (and a system of vortices) with the push as the sole cause of movement, the particular Cartesian metaphysics functioned as a powerful heuristic principle: it discouraged scientific theories, such as the "essentialist" version of Newton's action at a distance, which were incompatible with it (*negative heuristics*). And it encouraged the auxiliary hypotheses that could have saved it from apparent contradictions, such as the Keplerian ellipses (*positive heuristics*).

The first edition of Newton's *Principia* contains only two additional comments on the methodology: the notification that the purpose of the paper is to explain "how to determine the true motions from their causes, effects, and apparent differences, and, conversely, how to determine from motions, whether true or apparent, their causes and effects"[39]; and, in the Scholium at the end of Book 1, Section 11, Newton asserts that his distinctive approach makes possible a safer argumentation in natural philosophy.

In the second edition (1713) Newton introduces separate sections for the phenomena and rules involved in determining the universal gravity[40], and at the end of the General Scholastic of the third edition, 1726, includes the most famous methodological statement:

> "I have not as yet been able to deduce from phenomena[41] the reason for these properties of gravity, and I do not feign hypotheses. For whatever is not deduced from the phenomena must be called a hypothesis; and hypotheses, whether metaphysical or physical, or based on occult qualities, or mechanical, have no place in experimental philosophy. In this experimental philosophy, propositions are deduced from the phenomena and are made general by induction. The impenetrability, mobility, and the impetus of bodies, and the laws of motion and the law of gravity have been found by this method. And it is enough that gravity really exists and

[39] Newton, "Philosophiæ Naturalis Principia Mathematica, I Ed.," para. XIV.

[40] Isaac Newton, *Philosophiae Naturalis Principia Mathematica, II Ed.*, 1713, https://www.e-rara.ch/zut/338618.

[41] In contemporary philosophy "deduction from phenomena" is known as "eliminatory induction" and "demonstrative induction".

> acts according to the laws that we have set forth and is sufficient to explain all the motions of the heavenly bodies and of our sea." [42]

adding later, "unless as conjectures or questions proposed to be examined by experiments." [43]

Newton warns in the *Principia* that he uses mathematical theory in a new way, with the forces treated abstractly, independently of the mechanism, only mathematically. Clarke and Berkeley in the 18th century assert that these passages express strict causal agnosticism. Newton writes that, using terms such as "attraction," he does not intend to define a "species or mode of action or a physical cause or reason." [44]

Referring to Newton's claim to "deduce" the law of universal gravity from the phenomena of orbital motion, Lakatos claimed that this statement is at least misleading and, at worst, a subterfuge. Only a hypothetical-deductive construct of its demonstration of universal gravity makes sense.

According to Andrew Janiak, the anti-metaphysical reading of the mathematical treatment of Newton's force is a reasonable one. Anti-metaphysical interpretation can be supported by the famous methodological statement of the *Principia*, "*hypotheses non fingo*", "I feign no hypotheses." [45] As the mathematical treatment of force can be interpreted as expressing strict causal agnosticism, focusing exclusively on empirical descriptions of the movements in the solar system, "Newton's methodology can be interpreted as expressing a more general metaphysical agnosticism." [46]

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[42] Isaac Newton, "Philosophiae Naturalis Principia Mathematica, III Ed.," *Science* 177, no. 4046 (1726): 943, https://doi.org/10.1126/science.177.4046.340.

[43] Isaac Newton, *An Account of the Book Entitled Commercium Epistolicum Collinii & Aliorum, de Analysi Promota*, 1715, 312.

[44] Andrew Janiak, *Newton as Philosopher* (Cambridge University Press, 2010), 16.

[45] Lakatos states that the best rational reconstruction of Newton's famous phrase "*hypotheses non fingo*" is likely; "I reject the degenerating problemshifts that are designed to retain some theories that are syntactically metaphysical," cf. Imre Lakatos, "Criticism and the Methodology of Scientific Research Programmes," *Proceedings of the Aristotelian Society* 69, no. 1 (1968): 180.

[46] Janiak, *Newton as Philosopher*, 17.

For Newton, science, "experimental philosophy," involves explanatory sentences that can be "deduced from phenomena." What cannot be deduced in this way is merely a hypothesis. But Newton does not circumvent hypotheses, he only does not include them into science, considering them purely speculative. Their place is reserved in *Opticks* Queries[47], and in explicit annotations in the *Principia*. The hypotheses are developed by Newton when he does not have independent empirical support for those assertions. In the General Scholium, he states: ""For whatever is not deduced from the phenomena must be called a hypothesis; and hypotheses, whether metaphysical or physical, or based on occult qualities, or mechanical, have no place in experimental philosophy" [48]

From Newton's point of view, gravity is not mechanistic; but he also admits that he does not know the "reason" for the properties of gravity expressed in the law of universal gravity, namely that he does not have a physical explanation of this force, refusing to make assumptions on this subject. Unlike Leibnitz, he explicitly states that a certain causality in nature is non-mechanical, thus challenging the prevailing mechanistic philosophy at that time. In this regard, Stein and DiSalle assert that Newton was a radical empiricist in metaphysical debates: he not only rejects the mechanistic philosophy of Descartes, Leibniz, and Huygens, but transforms the metaphysical questions considered by them as purely *a priori* into empirical issues, whose answers depend on the development of physics. [49]

Newton is willing to hold metaphysical positions, such as in the structure of space and time or causality, but he rejects Cartesian *a priori* approaches, putting physics ahead of metaphysics, which makes him, according to Stein and DiSalle, not an antimetaphysician, but an empirical metaphysician, with a principial empirical attitude towards metaphysical questions.

In order to understand movement in a manner consistent with its laws, Newton postulates absolute space[50], thus allowing it to conceive the movement as a change in absolute space. This

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[47] Isaac Newton, *Opticks : Or, A Treatise of the Reflections, Refractions, Inflections and Colours of Light* (London : Printed for William Innys at the West-End of St. Paul's, 1730), http://archive.org/details/opticksortreatis1730newt.

[48] Newton, "Philosophiae Naturalis Principia Mathematica, III Ed.," 943.

[49] Janiak, *Newton as Philosopher*.

[50] In Scholium, Newton explicitly states that absolute space is not perceptible (Newton, "Philosophiæ Naturalis Principia Mathematica, I Ed.," 414.) being aware that true motion is difficult to detect if it is absolute motion.

idea allows Newton to save the perceptible effects of acceleration of bodies as real movements in absolute space[51].

Newton's natural philosophy can only be understood if we consider his conception of God:

> "Newton invoked God in the action at a distance for a specific reason, to support gravity in the universe, warning against a vision of the universe as a mere machine. He thus tried to develop a concept about God that would provide a stable, organized and predictable model of the natural world, a God who projects on rational and universal principles, accessible to all people ... he appeals to God to explain the mechanisms he cannot explain otherwise, including the action at a distance." [52]

Newton's theory of gravity was fundamentally rejected by his contemporaries for violating the norms of mechanistic philosophy. According to Andrew Janiak, Newton was forced to defend his mathematical treatment of force and movement on a fundamental metaphysical basis[53]. After the revolution in physics in the 17th century, from the neo-Aristotelian ("scholastic") philosophy to Cartesianism, Newton caused a new paradigm shift by replacing the mechanistic philosophy with the natural philosophy. This second schism occurred in the absence of a conceptual continuity. Although without a metaphysical system of his own, Newton defended himself by articulating a compelling relationship between mathematical and metaphysical physics in disputes about space and time, matter, laws of motion, the nature of forces, and the relationship of God with the world.

Principia has triggered a broad discussion among Newton's contemporaries about the methodology to be adopted when studying the natural world.

As Andrew Janiak states, for Newton force was the main concept that explained the movement and its causes in nature. He conceived forces as ephemeral actions, like quantities, through the connection between mass and acceleration, providing a means of measuring forces. In Book III of *Principia*, Newton identifies the centripetal force that maintains planetary orbits with the force of gravity, which causes the free fall of objects on earth. Hence the conclusion, in Book

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51 Newton, "Philosophiae Naturalis Principia Mathematica, III Ed.," 423.

52 Nicolae Sfetcu, *Isaac Newton despre acţiunea la distanţă în gravitaţie - Cu sau fără Dumnezeu?* (MultiMedia Publishing, 2018), http://doi.org/10.13140/RG.2.2.24577.97122.

53 Janiak, *Newton as Philosopher*.

III, that all bodies are attracted to each other in proportion to their amount of matter (universal gravity). He acknowledges, however, that he does not know the cause of gravity: "I have not as yet been able to discover the reason for these properties of gravity from phenomena, and I do not feign hypotheses." [54]

By the seventh sentence of Book III of Principles, Newton came to the following conclusion: "Gravity acts on all bodies universally and is proportional to the quantity of matter in each." [55]

The methodology of *Principia* of discovering the forces present in nature was controversial, including for the action at a distance. In the second edition of 1713, he added other methodological observations, called by him "*regulae philosophandi*", or the rules of philosophy. The first two rules refer to causal reasoning, and the third rule, much debated by contemporaries, referred to an induction problem: we have perceptions and experiments for knowledge, but on what basis can we generalize? Newton gives a partial answer in proposition seven of the Third Book of Principle, in Rule 3:

> "Those qualities of bodies that cannot be intended and remitted [i.e., increased and diminished] and that belong to all bodies on which experiments can be made should be taken as qualities of all bodies universally." [56]

Newton links this third rule to his laws of motion:

> "That all bodies are movable and persevere in motion or in rest by means of certain forces (which we call forces of inertia) we infer from finding these properties in the bodies that we have seen. The extension, hardness, impenetrability, mobility, and force of inertia [This is a potentially confusing way to refer to the specific mass, which we would call the inertial mass of a body. See the third definition in the *Principia*[57].] of the whole arise from the extension, hardness, impenetrability, mobility and force of inertia of each of the

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[54] Alexandre Koyre, *From the Closed World to the Infinite Universe* (Johns Hopkins University Press, 1957), 229.

[55] Newton, "Philosophiae Naturalis Principia Mathematica, III Ed.," 810.

[56] Newton, *Philosophiae Naturalis Principia Mathematica, II Ed.*

[57] Newton, "Philosophiae Naturalis Principia Mathematica, III Ed.," 404–5.

> parts; and thus we conclude that every one of the least parts of all bodies is extended, hard, impenetrable, movable, and endowed with a force of inertia. And this is the foundation of all natural philosophy." [58]

Leibniz asserted that Newton's three-dimensional Euclidean space allows distinct states, but indistinguishable if the absolute positions of all material bodies are changed, while retaining their relative positions[59]. The same laws of motion are valid in all inertial frames, so it would be impossible, by applying Newton's laws, to determine what the inertial framework is. Leibniz concludes that we should use the principle of parsimony to reject such "metaphysical" entities.

But Newtonian mechanics does not satisfy the principle of relativity for absolute acceleration and absolute rotation, only for inertial frames. In accelerated or rotated systems, Newtonian laws are no longer valid. It would result that absolute acceleration and rotation have physical significance, resulting in a dilemma, as discussed by Michael Friedman. Basically, the combined theory of Newtonian space and time and Maxwell's electrodynamics prove to be false[60]. Einstein resolved this paradox in 1905, keeping Maxwell's laws intact but changing the transformations that link inertial frames.

Newton introduced the term "experimental philosophy" in 1712, in a passage at the General Scholium of *Principia* where he set out his methodology against hypotheses. His purpose was to defend his theory of gravity against critics, especially Leibniz's:

> “Experimental Philosophy reduces Phaenomena to general Rules & looks upon the Rules to be general when they hold generally in Phaenomena.... Hypothetical Philosophy consists in imaginary explications of things & im- aginary arguments for or against such explications, or against the arguments of Experimental Philosophers founded upon Induction. The first sort of Philosophy is followed by me, the latter too much by Cartes, Leibnitz & some others." [61]

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[58] Newton, 95–96.

[59] Michael Friedman, *Foundations of Space-Time Theories: Relativistic Physics and Philosophy of Science* (Princeton University Press, 1983).

[60] Friedman.

[61] Newton, “Philosophiæ Naturalis Principia Mathematica, I Ed.”

As Alan E. Shapiro states, the term rather refers to empirical science. It was also added to the second edition of the *Principia* in 1713, where he stated that he demonstrated the existence of gravity even though he could not find its cause, listing the different properties of gravity. Newton also exposes his methodology in Query 31 of *Opticks*, where he is concerned with force and natural philosophy. Newton's experimental philosophy is considered to have two essential elements: the exclusion of hypotheses from natural philosophy; and the requirement that sentences in experimental philosophy be "duced from the phenomena and are made general by induction." Newton thus rejects the hypothesis without experimental support. Those with experimental support, but insufficient to help demonstrate scientific principles, are allowed but distinct from established principles, like the queries in Optics. This type of hypothesis can suggest new experiments and help explain the properties and principles already discovered.

In the second English edition of *Principia*, 1717, Newton detailed the term "experimental philosophy" and introduced the induction method:

> "This Analysis consists in making Experiments and Observations, and in drawing general Conclusions from them by Induction, and admitting of no Objections against the Conclusions, but such as are taken from Experiments, or other certain Truths. For Hypotheses are not to be regarded in experi- mental Philosophy. And although the arguing from Experiments and Obser- vations by Induction be no Demonstration of general Conclusions; yet it is the best way of arguing which the Nature of Things admits of, and may be looked upon as so much the stronger, by how much the Induction is more general. And if no Exception occur from Phaenomena, the Conclusion may be pronounced generally. But if at any time afterwards any Exception shall occur from Experiments, it may then begin to be pronounced with such Exceptions as occur." [62]

Thus, the existence of gravity "has been proved mathematical demonstrations grounded upon experiments phaenomena of nature: & Mr Leibnitz himself cannot deny they have been proved."

Confirmation is, according to Newton, first by mathematical demonstration and secondly by experiment. He was convinced that a deductive mathematical approach leads to certainty and

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[62] Newton, *Philosophiae Naturalis Principia Mathematica, II Ed.*, 404.

the experiment may provide some foundations needed for a science, but until the 18th century he did not assign to the experiment the leading place in his methodology.

According to Laudan[63], Newton considered that one of the central purposes of natural philosophy is to show the Creator's hand in the details of his creation, because "to discourse of [God] from the appearances of things, does certainly belong to Natural Philosophy." [64] The theories, according to Newton, can be certain or very probable. Between two rival theories, Newton would probably have chosen what would have promoted his cognitive goals, as in the case of mechanistic philosophy. But it must to take into account that some of Newton's cognitive purposes differ from those of today. Therefore, according to Laudan we can evaluate their rationality by determining whether their actions have promoted some goals, and their actions can be determined as rational only with reference to the corresponding weighted product of their cognitive utilities.

According to Robert Disalle, Newton offers inductive arguments for a metaphysical conclusion, while Einstein uses epistemological analyzes to decompose metaphysical notions. But Newton's arguments have the same basic form and purpose as Einstein's. Newton's thought experiments on the bucket of water are, in essence, arguments for a way to connect physical processes with the structures of space and time. [65]

Until at least the second half of the century, Locke and Newton's systems were perceived as being based on very similar principles and methods, composed of natural and moral philosophy. Locke and Newton share a similar conception of the scientific method, based on rational and regular experiments and observations and the use of generalization and deduction. Thus G. A. Rogers writes:

> "What Locke found in the *Principia* was the exemplification of a method to which he himself already subscribed. He already believed that a combination of observation, generalization or induction, and deduction was the only route to knowledge of nature and that the *Principia* exhibited just that method in its most fruitful

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[63] L. Laudan, *Progress and Its Problems: Toward a Theory of Scientific Growth* (University of California Press, 1977).

[64] Newton, "Philosophiae Naturalis Principia Mathematica, III Ed."

[65] Robert Disalle, "Spacetime Theory as Physical Geometry," *Erkenntnis* 42, no. 3 (1995): 317–337.

> manner... It confirmed for him all his own methodological conclusions... The *Principia* was for Locke the vindication of a general methodological approach to which he had subscribed for perhaps twenty years." [66]

Hume also explicitly associates his work with the Newton's method, although there is a clear distinction between Hume's inductivism and Locke's conception of the methodology of natural science. [67]

1.1 Heuristics of Newtonian gravity

The classic example of a successful research program is Newton's gravitational theory, probably the most successful Lakatosian research program. Initially, Newton's gravitational theory faced a lot of "anomalies" ("counterexamples") and contradicted the observational theories that supported these anomalies. But supporters of the Newtonian gravity research program have turned every anomaly into corroborating cases. Moreover, they themselves pointed to counterexamples which they then explained through Newtonian theory[68]. According to Lakatos, "In Newton's programme the negative heuristic bids us to divert the *modus tollens* from Newton's three laws of dynamics and his law of gravitation. This 'core' is 'irref utable' by the methodological decision of its proponents: anomalies must lead to changes only in the 'protective' belt of auxiliary, 'observational ' hypotheses and initial conditions." [69]

Newton established the positive heuristic of his research program through a strategy of successive approaches[70]. Newton's first three laws of motion regulated inductive reasoning, along with Newton's view of a fundamental taxonomy based on physical forces (interactions). It started

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[66] G. A. J. Rogers, "Locke's Essay and Newton's Principia," *Journal of the History of Ideas* 39, no. 2 (1978): 217–32, 229.

[67] Graciela de Pierris, "Hume and Locke on Scientific Methodology: The Newtonian Legacy," *Hume Studies* 32, no. 2 (2006): 277–329.

[68] Pierre-Simon Marquis De Laplace, *Exposition du systéme du monde*, 2nd ed. (Cambridge; 2009: Cambridge University Press, 2009).

[69] Lakatos, *The Methodology of Scientific Research Programmes*, 48.

[70] Lakatos, "Criticism and the Methodology of Scientific Research Programmes."

from an idealized solar system, with a punctual Sun and a single planet circling around the Sun. Then he considered that the orbit of the planet is an ellipse, deriving the proportionality between the gravitational force and the inverse of the square of the distance between the planet and the Sun.

The inductive generalization of Newton considered an elementary motion with a static force included in the deduced law of gravity, and the idea that planetary movements can be generalized. These were his working hypotheses on the basis of which he proceeded to his inductive generalizations. They offer immediate protection of the hard core of the Newtonian research program (negative heuristics), by requiring that the evidence developed from the data be of high quality[71]. The deduction of the law of gravity fulfilled this requirement to a greater extent than its demonstrative reasoning, but the "deduction" was primarily based on the motion of only five planets in a short astronomical period.

Newton acknowledges the risk of introducing such taxonomic working hypotheses into inductive generalization, in the most famous methodological passage in *Opticks*, in discussing the "analysis and synthesis" methods in the next paragraph of the final query, which was added in 1706. He has considered that the success obtained from unrestricted generalizations is the best protection against the risk introduced by the inevitable taxonomic hypotheses that enter into induction. [72]

This model contradicted the law of action and reaction that Newton included in the hard core, so he developed a more complex model, in which the sun and the planet revolved around their center of common weight. It did not generate any anomaly, but it was difficult to deduce from it the real laws of motion for several bodies. Thus, Newton developed a new theory, for several planets, with interactions between each planet and the Sun but neglecting the interactions between planets.

After the intermediate verification of this theory, Newton developed a more complex theory, considering that the Sun and the planets are not punctual, but spheres with dimensions other than zero, since in theory he had to take into account the density of bodies, and could not accept

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[71] I. Bernard Cohen and George E. Smith, *The Cambridge Companion to Newton* (Cambridge University Press, 2006).

[72] Cohen and Smith.

that a point body has infinite density. He also took into account the rotational motion of the bodies around their own axes. In the following model it took into account the non-spherical shape of the Earth and the variation of the gravity of the surface with the latitude, the orbit of the Moon, the tides, the precession of the equinoxes and the trajectories of comets. Through this positive heuristic he tried to protect himself against the risks that appear in the inductive leap, immediately pushing the theory to analyze all relevant phenomena, and using it as a research tool for the problems encountered[73]. At the same time, the deductions in the case of the Earth allowed him to generalize from the celestial gravity to the universal gravity, as well as the precession of the equinoxes indirectly, taking into account the forces (interactions) between the planets, calculating the resulting perturbations. The tide and the precession of the equinoxes allowed the generalization from simple centripetal forces to an interactive gravity, as did the study of the orbits of Jupiter and Saturn. And the study of comets has allowed the extension of the law of gravity to bodies possible from a very different matter.

He published the results of his research program only when he considered that he had obtained as much as possible from observations and mathematics. The process of comparison with phenomena and arguments for the universality of gravity extends throughout Book 3.

Newton's inductive generalization for universal gravity introduced an important falsifiable conjectural element, which was subsequently verified, providing the most convincing evidence in his favor. The basic idea was that any discrepancy between Newtonian theory and observation would prove to be physically significant and would tell us something more about the physical world. By this, the taxonomic working hypotheses that underlie Newton's inductive step toward universal gravity remain intact, as theory advances.

Based on additional questionable assumptions, and suggestions regarding the movements of Jupiter and Saturn, Newton initiated his own sequence of successive approximations according to the *Principia*. Even after the third edition of the *Principia* appeared, almost forty years later, each of these *Principia* subjects was still being studied. Newton's argument for universal gravity was only completed a century after the publication of the first edition of the *Principia*.

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[73] Cohen and Smith.

Newton foresaw the further developments of his models from the first fully idealized model. He understood that the intermediate models would contain anomalies, but he had to go through them in order to develop the mathematical apparatus by confronting the models and modifying the theory along the way so as to eliminate the anomalies.

Newton asserted that *Principia* illustrated a new approach to empirical inquiry. But, besides the remark about the derivation of forces from the phenomena of movement and then of the movements of these forces in the Preface to the first edition, and the remark about comparing a generic mathematical theory of centripetal forces with phenomena to find out the conditions of action of the force, from the end Book 1, Section 11, the only notable remark about the methodology is the famous passage from the general Scholium added in the second edition as a final statement[74].

The unprecedented success of Newton's theory of gravity has stimulated interest in the methodology of *Principia* for use in other fields. Two aspects of the methodology are obvious to George Smith[75]: Newton has opposed his method to the "hidden" assumptions, and the requirement that questions be considered open as long as empirical considerations have not yet given them answers (a requirement in perfect agreement with tolerance methodology proposed by Lakatos in the research programs). The purpose of the method was to limit the theoretical claims to "inductive generalizations".

Each successive model in Newton's program predicts a new fact, it is an increase of the empirical content: it constitutes a consistent progressive theoretical change. And each prediction is finally verified, though previously it could have been instantly "refuted".

The central idea of the Newtonian inductive method is that universal laws inductively derive from the "manifest qualities" or "phenomena" observed, and only the observed phenomena can lead us to the revision of these laws. Newton explicitly opposes purely hypothetical explanations of mechanistic philosophy. Leibniz and Huygens accepted Newton's demonstration

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[74] George Smith, "Newton's Philosophiae Naturalis Principia Mathematica," in *The Stanford Encyclopedia of Philosophy*, ed. Edward N. Zalta, Winter 2008 (Metaphysics Research Lab, Stanford University, 2008), https://plato.stanford.edu/archives/win2008/entries/newton-principia/.

[75] Smith.

that the orbits of the satellites of the large astronomical bodies in the solar system obey the inverse-square law, but they rejected Newton's law of universal gravity because they were related to mechanistic philosophy. The rules III and IV of Newton were added to the second (1713) and third (1726) editions of the *Principia* in response to the objections of the mechanistic philosophers:

> Rule III: "Those qualities of bodies that cannot be intended and remitted [i.e. qualities that cannot be increased and diminished] and that belong to all bodies on which experiments can be made should be taken as qualities of all bodies universally." [76]

> Rule IV: "In experimental philosophy, propositions gathered from phenomena by induction should be considered either exactly or very nearly true notwithstanding any contrary hypotheses, until yet other phenomena make such propositions either more exact or liable to exceptions." [77]

These rules state that the inductive universalization method must be applied without interference of hypotheses. Newton explicitly states that the mechanistic philosophy assumptions obstruct his method. He illustrates here the use of his method by first describing the inductive inference of universal law that all bodies are extended.

Bernard Cohen thus describes Newton's positive heuristics, in Chapter 5 of The Cambridge Companion to Newton as the "Newtonian style" stages[78]: (1) the "one-body" problem, (2) the "two-body" problems, (3) the problems of three or more interacting bodies. Thus, Newton must approach the complexity of a real orbital motion in a succession of successive approximations, each approximation being an idealized movement, and with systematic deviations, providing evidence for the next stage of the sequence.

In his idealized models, Newton imposed two restrictions on successive approximations[79]. In each case in which he deduces some characteristics from the celestial gravitational forces, he argued that the consequence of the "if-then" deduction still maintains closeness as long as the antecedent has closeness. And the mathematical results established in Book 1 allow him to identify

[76] Newton, "Philosophiae Naturalis Principia Mathematica, III Ed.," 795.

[77] Newton, 796.

[78] Cohen and Smith, *The Cambridge Companion to Newton*.

[79] Domenico Meli, "The Relativization of Centrifugal Force," *Isis: A Journal of the History of Science* 81 (1990): 33.

the specific conditions under which the phenomenon from which the deduction is made would have not only proximity, but also accuracy. It follows that Newton's "deductions" from phenomena involve trying to address the complexity of real-world movements in a sequence of increasingly complex progressive idealizations, with systematic deviations from idealizations, each model serving as the basis for the next more complex model. Systematic deviations are called "secondary phenomena" when they are not observable *per se*, but theoretically deduced[80]. This respects Newton's first rule for natural philosophy - that no more causes than both true and enough causes should be admitted explaining a phenomenon.

Newton's law of gravity provides an explanation of Kepler's rules and idealized orbital movements for each previously idealized model, so it has greater heuristic power than any previous model. By this law one can explain why these idealizations are valid at least in the proximity.

From the perspective of Lakatos, in the 17th century three scientific systems were in competition: the research program of Aristotle, that of Descartes, and Newton's program appeared as a rival of Descartes's program. Both Descartes and Newton's programs were progressive compared to Aristotle's and could explain the movements of comets and tides. The Cartesians could explain why the moon always kept the same face to the ground and why all the planets rotate in the same direction, while the Newtonians could explain how the planets influence one another[81]. Explanatory differences resulted from different hard cores. The core of the Cartesian program specified contact action and explicitly forbade the concept of action at a distance.

Newton's program also includes elements of the older Cartesian program, such as contact action. This is an example of a fruitful exchange between programs. But the empirical evidence ultimately led to the failure of the Cartesian program.

Lorentz's program reached a dominant position at the beginning of the 20th century, then being overtaken by Einstein's, both theoretically and empirically, almost immediately after its

[80] Cohen and Smith, *The Cambridge Companion to Newton*.

[81] E. J. Aiton, *Vortex Theory of Planetary Motions*, First Edition edition (London; New York: American Elsevier Publishing Co., Inc., 1972).

initiation in 1905[82]. Although Lorentz's program was also progressive, relativity's program overcame, being consistently more progressive and assimilating the Lorentz transformations. [83]

In the success of Einstein's program, several research programs were involved: the Newtonian program, caused by a program supported by Lorentz[84] that made electromagnetism accepted as more fundamental than mechanics; a second rival program supported by Ostwald and Mach through which an attempt was made to develop a purely phenomenological physics, with energy as a basic concept[85]; Einstein's program which involved the theories of relativity; and the program of quantum physics initiated by Bohr and developed by the theories of Heisenberg, Schrodinger and Dirac.

In the first two decades of the 20th century, quantum physics overcame the phenomenological program and replaced Newtonian physics, but the mathematics and ontology of the new program were incompatible with the mathematics and ontology of Einstein's program. However, these programs coexist today. The rivalry between these programs stagnated in the 1940s and 1950s, reviving with the advent of radio astronomy, which allowed new empirical progress.

Lakatos' methodology offers a powerful conceptual framework, which, as in Kuhn's case, derives from the analysis of historical episodes in physics. But unlike Kuhn, Lakatos presented a methodology that avoids the problems of incommensurability[86] and irrationalism and demonstrates that empirical evidence is the ultimate arbiter of competing research programs. [87]

1.2 Proliferation of post-Newtonian theories

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[82] Elie Zahar, "Why Did Einstein's Programme Supersede Lorentz's? (II)," *British Journal for the Philosophy of Science* 24, no. 3 (1973): 211–75.

[83] Gholson and Barker, "Kuhn, Lakatos, and Laudan."

[84] Zahar, "Why Did Einstein's Programme Supersede Lorentz's?"

[85] Niles Holt, "Wilhelm Ostwald's 'The Bridge,'" *British Journal for the History of Science* 10, no. 2 (1977): 146–150.

[86] Two theories are incommensurable if they are embedded in a strongly contrasting conceptual framework, whose languages do not overlap enough to allow scientists to directly compare theories or to cite empirical evidence favoring one theory over the other.

[87] Gholson and Barker, "Kuhn, Lakatos, and Laudan."

Theoreticians have formulated a set of fundamental criteria that any theory of gravity should satisfy, two purely theoretical and two that are based on experimental evidence[88]. Thus, a theory must be:

- *complete* (capable of analyzing from the "first principles" the result of any experiment of interest).
- *self-consistent* (its prediction for the outcome of each experiment must be unique)
- *relativistic* (at the limit when gravity is neglected compared to other physical interactions, non-gravitational laws of physics must be reduced to special relativity laws)
- *with the correct Newtonian limit* (within the limits of weak gravitational fields and slow motions, they must reproduce Newton's laws)

The main theories of gravity from 1686-1900, until the development by Lorentz of his own theory and then was elaborated the theories of relativity by Einstein, are

- *Newton's Law of Universal Gravity* (1686): Newton's theory is considered to be exactly within the limits of low gravity fields and low velocities, and all other theories of gravity must reproduce Newton's theory within the appropriate limits.
- *Mechanistic explanations* (1650-1900): Bifurcated theories having as hard core the mechanistic theory; they failed because most led to an unacceptably high value of aether dragging, which is unconfirmed, violates the law on energy conservation and is incompatible with modern thermodynamics[89].
    - René Descartes (1644) and Christiaan Huygens (1690) used vortexes to explain the mechanistic gravity[90]. Newton opposed the theory arguing with the lack of deviations of the orbits due to the fluid-dynamic resistance, the sometimes-different direction of the natural satellites from the direction of the vortex, and of Huygens's circular explanations.
- *Electrostatic models* (1870-1900): They tried to combine Newton's laws with those of electrodynamics (Weber, Carl Friedrich Gauss, Bernhard Riemann, James Clerk Maxwell), trying to explain the perihelion precession of Mercury. There were partial successes, in 1890 Lévy and in 1898 Paul Gerber, but the models were rejected because were based on assumptions that later proved to be wrong[91].

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[88] Clifford M. Will, *Theory and Experiment in Gravitational Physics, Revised Edition*, Revised edition (Cambridge England ; New York, NY, USA: Cambridge University Press, 1993).

[89] Grant, *The Foundations of Modern Science in the Middle Ages*, 60–61.

[90] Christiaan Huygens, *Discours de La Cause de La Pesanteur*, 1885, 443–88.

[91] J. Zenneck, "Gravitation," in *Encyklopädie der Mathematischen Wissenschaften mit Einschluss ihrer Anwendungen: Fünfter Band in Drei Teilen Physik*, ed. A. Sommerfeld (Wiesbaden: Vieweg+Teubner Verlag, 1903), 25–67, https://doi.org/10.1007/978-3-663-16016-8_2.

- Robert Hooke (1671) and James Challis (1869) assumed that each body emits waves whose effect is the attraction between bodies. Maxwell argued that this theory requires constant production of waves, which must be accompanied by infinite energy consumption. Challis himself acknowledged that he did not reach a precise result due to the complexity of the processes[92].
- Including Isaac Newton (1675), and later Bernhard Riemann (1853) proposed a theory that aetheric flows move all bodies to one another[93]. As with Le Sage's theory, the theory violates the law of energy conservation. There are also problems related to the interaction of bodies with aether.
- Nicolas Fatio de Duillier (1690) and Georges-Louis Le Sage (1748) proposed a corpuscular model, using some sort of screening or shading mechanism - a bifurcation of Newton's law that respects the law of inverse squares. It was re-invented, among others, by Lord Kelvin (1872) and Hendrik Lorentz (1900), and criticized by James Clerk Maxwell (1875) and Henri Poincaré (1908) in particular for thermodynamic anomalies. Le Sage's theory was studied by Radzievskii and Kagalnikova (1960), Shneiderov (1961), Buonomano and Engels (1976), Adamut (1982), Jaakkola (1996), Tom Van Flandern (1999) and Edwards (2007). A variety of Le Sage models and related topics are discussed in Edwards, et al. [94]
- Newton proposed a second theory based on aether (1717) developed later by Leonhard Euler (1760), in which the aether loses its density near mass, leading to a net force directed toward bodies[95]. James Clerk Maxwell pointed out that in this "hydrostatic" model "the state of stress... which we must suppose to exist in the invisible medium, is 3000 times greater than that which the strongest steel could support."
- Later, a similar model was created by Hendrik Lorentz, who used electromagnetic radiation instead of corpuscles.
- Lord Kelvin (1871) and Carl Anton Bjerknes (1871) considered that each body pulsates, which could be an explanation of gravity and electrical charges. This hypothesis was also studied by George Gabriel Stokes and Woldemar Voigt. But the theory forces the assumption that all pulsations in the universe are in phase,

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[92] James Challis, *Notes on the Principles of Pure and Applied Calculation: And Applications of Mathematical Principles to Theories of the Physical Forces.* (University of Michigan Library, 1869).

[93] B. Riemann, *Neue Mathematische Prinzipien Der Naturphilosophie* (Leipzig: Dedekind, R.; Weber, W., 1876).

[94] Matthew R. Edwards, ed., *Pushing Gravity: New Perspectives on Le Sage's Theory of Gravitation*, y First edition edition (Montreal: Apeiron, 2002).

[95] Leonhard Euler, *Briefe an eine deutsche Prinzessin, aus dem Französischen übersetzt* (Junius, 1773), https://books.google.ro/books?id=FaMAAAAAMAAJ.

> which seems highly unlikely. And the aether should be incompressible. Maxwell argued that this process must be accompanied by new production and permanent destruction of aether.

Clifford M. Will explains, in *Theory and experiment in gravitational physics*, the motivations of some of these theories, including the elaboration of general relativity and quantum theory[96], which include bifurcations of Newton's initial theory, or do not meet the current criteria of a gravitational theory, with the observation that it is possible that, in the case of the modification of the present forms, some of these theories may subsequently meet these criteria:

- Newtonian theory of gravity: it is not relativistic
- Milne's kinematic relativity[97]: it was initially designed to solve certain cosmological problems. It is incomplete - it does not predict gravitational redshift.
- The various vector theories of Kustaanheimo[98] [99] contain a vector gravitational field in flat space-time. They are incomplete - they cannot be coupled with the other laws of non-gravitational physics (Maxwell's equations), unless we impose a flat space-time. They are inconsistent - they give different results in the propagation of light for the corpuscular and undulatory aspects of light.
- Poincare's theory (generalized by Whitrow and Morduch): the theory of action at a distance in flat space-time. It is incomplete or inconsistent in the same way as Kustaanheimo's theories[100].
- Whitrow-Morduch vector theory (1965): contains a vector gravitational field in flat spacetime. It is incomplete or inconsistent in the same way as Kustaanheimo's theories[101].
- Birkhoff's Theory (1943): contains a tensor gravitational field used to construct a metric. It violates the Newtonian limit by the specific conditions imposed[102].

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96 Will, *Theory and Experiment in Gravitational Physics, Revised Edition*.

97 E. A. Milne, *Kinematic Relativity* (Facsimile Publisher, 2015), 566–78.

98 Paul Edwin Kustaanheimo and V. S. Nuotio, *Relativistic Theories of Gravitation* (Helsingin Yliopisto. Department of Applied Mathematics, 1967).

99 G. J. Whitrow and G. E. Morduch, "Relativistic Theories of Gravitation : A Comparative Analysis with Particular Reference to Astronomical Tests," *Vistas in Astronomy* 6 (1965): 1–67, https://doi.org/10.1016/0083-6656(65)90002-4.

100 Whitrow and Morduch, "Relativistic Theories of Gravitation."

101 Whitrow and Morduch.

102 George D. Birkhoff, "Matter, Electricity and Gravitation in Flat Space-Time," *Proceedings of the National Academy of Sciences* 29, no. 8 (August 1, 1943): 231–39, https://doi.org/10.1073/pnas.29.8.231.

- Yilmaz's Theory (1971, 1973): contains a tensor gravitational field used to construct a metric. It is mathematically inconsistent - the functional dependence of the metrics on the tensor field is not well defined[103].

Other alternative historical theories developed over time have been refuted by experimental checks or replaced by better corroborated theories:

- In 1690, Pierre Varignon assumed that all bodies are exposed to thrusts of aether particles from all directions, with a limitation to a certain distance from the Earth's surface, under which bodies would experience greater attraction to Earth[104].
- In 1748, Mikhail Lomonosov assumed that the effect of aether is proportional to the complete surface of the elemental components of which matter is composed[105].
- In 1821, John Herapath tried to apply the co-developed model of kinetic gas theory to gravity. He assumed that the aether is heated by bodies and density decreases occur that push the bodies in that direction[106]. Taylor showed that the low density due to thermal expansion is compensated by the increased velocity of the heated particles; therefore, no attractions appear.
- Ritz gravity theory[107], Weber-Gauss electrodynamics applied to gravity. Classical promotion of perihelions[108].
- Nordström's theory of gravity (1912, 1913), an early competitor of general relativity.
- Kaluza Klein's Theory (1921) [109]
- Whitehead's theory of gravity (1922), another early competitor to general relativity.

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[103] Hüseyin Yilmaz, "New Approach to Relativity and Gravitation," *Annals of Physics* 81, no. 1 (November 1, 1973): 81, https://doi.org/10.1016/0003-4916(73)90485-5.

[104] Pierre (1654-1722) Auteur du texte Varignon, *Nouvelles Conjectures Sur La Pesanteur , Par M. Varignon,...*, 1690, https://gallica.bnf.fr/ark:/12148/bpt6k74179x.

[105] Mikhail Vasil'evich Lomonosov, *Mikhail Vasil'evich Lomonosov on the Corpuscular Theory*, First edition. edition (Cambridge, Mass: Harvard University Press, 1970), 224–233.

[106] J Herapath, "On the Causes, Laws and Phenomena of Heat, Gases, Gravitation I, II, III, in Annals of Philosophy, or Magazine of Chemistry, Mineralogy, Mechanics, Natural History, Agriculture and the Arts 1 Pp. 273–293," Atticus Rare Books, 1821, 273–93, https://www.atticusrarebooks.com/pages/books/761/john-herapath/on-the-causes-laws-and-phenomena-of-heat-gases-gravitation-i-ii-iii-in-annals-of-philosophy-or.

[107] Walther Ritz, "Recherches critiques sur l'électrodynamique générale," *Annales de chimie et de physique*, 1908, 267–71.

[108] Ritz, 267–271.

[109] Theodor Kaluza, "Zum Unitätsproblem in Der Physik | BibSonomy," 1921, 966–972, https://www.bibsonomy.org/bibtex/19218e3a965ffaefa3af2d4c14bb5ae52/zhaozhh02.

Lorentz aether theory was developed from Hendrik Lorentz's "electron theory", between 1892 and 1895 considering it as a completely immobile aether[110]. It introduced an ad-hoc hypothesis to cancel the failure of negative first order aether deviation experiments in v/c by introducing an auxiliary variable called "local time". The negative result of the Michelson-Morley experiment resulted in the introduction of another ad-hoc hypothesis, length contraction, in 1892. But neither did the subsequent experiments confirm the theory, which became a degenerate theory according to Lakatos. Lorentz tried to revitalize it in 1899 and 1904 by introducing the Lorentz transformation. But neither the new theoretical models solved the problem of aether. Henri Poincaré corrected the errors in 1905 and incorporated the non-electromagnetic effects into the theory, calling it "New mechanics" and using for the first time the expression "the principle of relativity." [111] He also criticized Lorentz for introducing too many helpful assumptions into his theory. Later, Minkowski (1908) and Arnold Sommerfeld (1910) also tried to develop a Lorentz invariant gravity law[112]. Poincaré's theory resisted a period due to his greater heuristic power, but he was defeated by the special relativity of Albert Einstein, who also took over some of the ideas of this theory. Lorentz acknowledged in 1914 that his theory was incompatible with the principle of relativity and rejected it[113]. At present some physicists consider the Lorentz theory developed later by Poincaré as a special, "Lorentzian" or "neo-Lorenzian" interpretation of special

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110 Hendrik A. Lorentz, "Considerations on Gravitation," in *The Genesis of General Relativity*, ed. Michel Janssen et al., Boston Studies in the Philosophy of Science (Dordrecht: Springer Netherlands, 2007), 559–574, https://doi.org/10.1007/978-1-4020-4000-9_13.

111 Henri Poincaré, "Les Relations Entre La Physique Expérimentale et La Physique Mathématique, in Revue Générale Des Sciences Pures et Appliquées," issue, Gallica, 1900, 1163–1175, https://gallica.bnf.fr/ark:/12148/bpt6k17075r.

112 Scott Walter, "Breaking in the 4-Vectors: The Four-Dimensional Movement in Gravitation, 1905–1910," in *The Genesis of General Relativity*, ed. Michel Janssen et al., Boston Studies in the Philosophy of Science (Dordrecht: Springer Netherlands, 2007), 193–252, https://doi.org/10.1007/978-1-4020-4000-9_18.

113 Eduard Prugovecki, "Historical and Epistemological Perspectives on Developments in Relativity and Quantum Theory," ResearchGate, 1992, https://www.researchgate.net/publication/300434048_Historical_and_Epistemological_Perspectives_on_Developments_in_Relativity_and_Quantum_Theory.

relativity[114]. Since both use Lorentz transformations and the same mathematical formalism, it is not possible to distinguish between the two theories by experiment. The difference between them is that Lorentz assumes the existence of an undetectable aether.

Modified Newtonian Dynamics (**MOND**) is a theory that proposes to modify Newton's law of universal gravity with the intention of taking into account the observed properties of galaxies. MOND is trying to eliminate the controversial theory of dark matter. It was developed in 1982 and published in 1983 by Israeli physicist Mordehai Milgrom[115]. Milgrom introduced the hypothesis that the gravitational force experienced by a star in the outer regions of a galaxy is proportional to the square of centripetal acceleration (as opposed to simple proportionality, from Newton's second law) or, alternatively, that the gravitational force in these cases vary inversely proportional to radius (as opposed to the inverse square of radius in Newton's law of gravity). In the MOND, the modification of Newton's laws takes place only for the movement of galaxies, at extremely small accelerations.

MOND successfully predicted galactic phenomena unexplained by the theory of dark matter[116], but fails to confirm the properties of galaxy clusters, nor to develop a cosmological model that competes with the current ΛCDM model[117]. Accurate measurement of the speed of gravitational waves in comparison to the speed of light in 2017 did not exclude MOND theories.

A large variety of astrophysical phenomena are corroborated by the MOND, [118] [119] such as:

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[114] Quentin Smith, *Einstein, Relativity and Absolute Simultaneity*, ed. William Lane Craig, 1 edition (London: Routledge, 2007).

[115] M. Milgrom, "A Modification of the Newtonian Dynamics as a Possible Alternative to the Hidden Mass Hypothesis," *The Astrophysical Journal* 270 (July 1983): 371–389, https://doi.org/10.1086/161130.

[116] Stacy S. McGaugh, "A Tale of Two Paradigms: The Mutual Incommensurability of ΛCDM and MOND," *Canadian Journal of Physics* 93, no. 2 (April 21, 2014): 250–259, https://doi.org/10.1139/cjp-2014-0203.

[117] Pavel Kroupa, *The Vast Polar Structures around the Milky Way and Andromeda*, 2013, https://www.youtube.com/watch?v=UPVGDXNSBZM.

[118] Benoit Famaey and Stacy McGaugh, "Modified Newtonian Dynamics (MOND): Observational Phenomenology and Relativistic Extensions," *Living Reviews in Relativity* 15, no. 1 (December 2012): 10, https://doi.org/10.12942/lrr-2012-10.

[119] Mordehai Milgrom, "MOND Laws of Galactic Dynamics," *Monthly Notices of the Royal Astronomical Society* 437, no. 3 (January 21, 2014): 2531–41, https://doi.org/10.1093/mnras/stt2066.

- Concrete relationship between the total baryonic mass of the galaxy and the asymptotic rotation speed according to the MOND prediction.
- MOND predicts a much better correlation between characteristics in the distribution of the nonbarionic mass and the rotation curve than the dark matter hypothesis, observed in several spiral galaxies.
- MOND predicts a specific relationship between the acceleration of stars at any distance from the center of a galaxy and the amount of dark matter in this radius that would be deduced in a Newtonian analysis, an observationally verified prediction.
- Confirms the stability of disk galaxies for galaxy regions within the deep MOND regime.
- For particularly massive galaxies, MOND predicts that the rotation curve should decrease by 1/r, according to Kepler's law, confirmed by observations of elliptical galaxies with large masses.

From the initial MOND theory, several competing theories have been branched off that are based on the same hard core (negative heuristics) but with different development strategies (positive heuristics):

- AQUAL was developed in 1984 by Milgrom and Jacob Bekenstein, generating MOND behavior by modifying the gravitational term in the classical Lagrangian[120].
- QUMOND introduces a distinction between the MOND acceleration field and the Newtonian acceleration field[121].
- TeVeS starts from the behavior of the MOND but considers a relativistic framework. TeVeS has been successful in gravitational lens observations and structure formation but fails to explain other cosmological aspects[122].

There are other alternative relativistic generalizations of the MOND, such as BIMOND and the generalized Einstein-Aeter theories[123].

The external field effect implies a fundamental break of MOND by the principle of strong equivalence (but not necessarily by the principle of weak equivalence), this being recognized as a crucial element of the MOND paradigm.

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[120] J. Bekenstein and M. Milgrom, "Does the Missing Mass Problem Signal the Breakdown of Newtonian Gravity?," *The Astrophysical Journal* 286 (November 1984): 7–14, https://doi.org/10.1086/162570.

[121] Mordehai Milgrom, "Quasi-Linear Formulation of MOND," *Monthly Notices of the Royal Astronomical Society* 403, no. 2 (February 4, 2010): 886–95, https://doi.org/10.1111/j.1365-2966.2009.16184.x.

[122] Jacob D. Bekenstein, "Relativistic Gravitation Theory for the MOND Paradigm," *Physical Review D* 71, no. 6 (March 14, 2005): 069901, https://doi.org/10.1103/PhysRevD.71.069901.

[123] Famaey and McGaugh, "Modified Newtonian Dynamics (MOND)."

Supporters of MOND theory have proposed several observational and experimental tests to help establish the best-corrected theory[124] between MOND models and dark matter, such as: the existence of abnormal accelerations on Earth that could be detected in a precision experiment[125]; testing in the solar system using the LISA Pathfinder mission by observing the tides predicted by the MOND and a Sun-Earth saddle point of Newtonian gravitational potential[126]; measuring the MOND corrections to the precession of the perihelion of the planets in the Solar System[127]; an astrophysical test to investigate the behavior of isolated galaxies, and non-Newtonian behavior in binary star systems; testing using the redshift dependence of radial acceleration[128].

The "**Fifth Force**" is a theory that changes Newton's law of universal gravity. The initial experiments gave contradictory results: one claimed the existence of the fifth force, while the other contradicted this theory. After numerous repetitions of the experiment, the discord was resolved, and the consensus was reached that the Fifth Force does not exist[129].

1.3 Tests of post-Newtonian theories

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[124] John F. Wallin, David S. Dixon, and Gary L. Page, "Testing Gravity in the Outer Solar System: Results from Trans-Neptunian Objects," *The Astrophysical Journal* 666, no. 2 (September 10, 2007): 1296–1302, https://doi.org/10.1086/520528.

[125] V. A. De Lorenci, M. Faundez-Abans, and J. P. Pereira, "Testing the Newton Second Law in the Regime of Small Accelerations," *Astronomy & Astrophysics* 503, no. 1 (August 2009): L1–4, https://doi.org/10.1051/0004-6361/200811520.

[126] Christian Trenkel et al., "Testing MOND/TEVES with LISA Pathfinder," *ArXiv:1001.1303 [Astro-Ph]*, January 8, 2010, http://arxiv.org/abs/1001.1303.

[127] Luc Blanchet and Jerome Novak, "Testing MOND in the Solar System," *ArXiv:1105.5815 [Astro-Ph, Physics:Gr-Qc]*, May 29, 2011, http://arxiv.org/abs/1105.5815.

[128] Sabine Hossenfelder and Tobias Mistele, "The Redshift-Dependence of Radial Acceleration: Modified Gravity versus Particle Dark Matter," *International Journal of Modern Physics D* 27, no. 14 (October 2018): 1847010, https://doi.org/10.1142/S0218271818470107.

[129] Michele Cicoli, Francisco G. Pedro, and Gianmassimo Tasinato, "Natural Quintessence in String Theory," *Journal of Cosmology and Astroparticle Physics* 2012, no. 07 (July 23, 2012): 044–044, https://doi.org/10.1088/1475-7516/2012/07/044.

1.3.1 Newton's proposed tests

In the first edition of *Principia*, Newton considered that the experiments with the **pendulum** would allow him to decipher the different types of resistance force and their variation with speed. It recognizes the failure of these experiments, in the second and third editions, then appealing to the vertical fall of objects with the forces of resistance due to the inertia of the environment. His intention was to approach the other types using the differences between observations and this law[130]. But this approach was also wrong, since there is no distinct species of resistance force, but only a result of the interaction with the inertial and viscous environment. This interaction being very complex, Newton could not deduce a law for the force of resistance, it only determined empirically relations for bodies of different forms. [131]

Newton argues in the law of gravity the strict proportionality of the "quantity of matter" with weight, but the pendulum experiments only indicate that the inertial mass is proportional to the weight. [132] The mass of an object is an intrinsic feature of it, while the weight is an extrinsic feature, depending on the gravitational fields generated by other objects. The experiments with the pendulum are described in detail in Book III, Proposition 6, where Newton states: "All bodies gravitate toward each of the planets, and at any given distance from the center of any one planet the weight of any body whatever toward that planet is proportional to the quantity of matter which the body contains," [133] and then describes his experiments. [134]

Newton states, in contradiction with the Cartesian view, that each of the universal and essential properties of matter - i.e. extension, mobility, hardness, impenetrability and mass - is known "only through the senses". But from his assertion that the properties of matter are known "only through experiments," it follows that Newton does not accept a naive-empirical view, but rather a sophisticated double conception of the epistemology of matter, [135] denying the Cartesian view that we can determine the universal properties of matter only *a priori* or only by reason, and arguing that conceptually guided experiments in physical theory are necessary to determine the properties of matter: "It [mass] can always be known from a body's weight, for – by making very accurate

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[130] Newton, "Philosophiae Naturalis Principia Mathematica, III Ed.," 749.

[131] L. D. Landau and E. M. Lifshitz, *Fluid Mechanics: Volume 6*, 2 edition (Amsterdam u.a: Butterworth-Heinemann, 1987), 31–36, 168–79.

[132] Newton, "Philosophiae Naturalis Principia Mathematica, III Ed.," 701, 806–9.

[133] Newton, 806.

[134] Newton, 806–7.

[135] Janiak, *Newton as Philosopher*.

experiments with pendulums – I have found it to be proportional to the weight." [136] Newton's concept of matter involved a fundamental rejection of mechanistic philosophy. The experiments with the pendulum are also described in Proposition 24 of Book 2, in corollaries five and seven.

In the experiments with the pendulum, comparing the number of oscillations of the bob of the solid pendulum and the empty pendulum, Newtom tried to determine how an ether that acts not only on the surface of a body but also on its interior parts, affects these pendulums. This is how Newton came to believe that there is no ether and he favored the idea in the Preface of *Principia* of the universality of gravity. [137]

To discuss the effects that distinguish absolute motion from relative motion, Newton uses the "**water bucket**" thinking experiment, described in a paragraph on the effects that distinguish absolute motion from relative motion. Newton states here that "the true and absolute circular motion of the water, which is here directly contrary to the relative, becomes known, and *may be measured by this endeavor*." [138] Hang a bucket of water with a rope and twist the bucket in one direction; then let the rope recover. The bucket is rotating now, and the water surface will initially be flat, but in relation to the bucket it rotates. By rubbing with the rotating bucket, the water gradually starts to rotate, eventually balancing the speed of the bucket, so that the movement towards the bucket gradually reaches zero. But, as the relative rotation of the water relative to the bucket decreases, "endeavor to recede from the axis of motion" increases accordingly. Newton observes that acceleration (for example, rotation) is empirically detectable by the presence of inertial effects, even in the absence of a change in object relations. Also, Newton argues, contrary to Descartes, that we cannot understand the true movement of water in the bucket as a change in the relationship between water and the surrounding body (in this case, the bucket). The relationship between the water and the bucket remains the same, even though the water has a real movement, as indicated by the presence of inertial effects. So, the true movement of a body cannot be understood in terms of changes in its relations with other objects. Absolute space allows us to capture what is the true movement, according to Newton. [139]

For Newton, it seems that centrifugal force is the criterion and measure of absolute rotation. He defines absolute rotation as producing such an effect, criticizing Descartes' definition of "motion in the philosophical sense" as a movement of a body in relation to neighboring bodies. The experiment shows that the dynamic effect is independent of the relative motion between the water

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[136] Newton, "Philosophiae Naturalis Principia Mathematica, III Ed.," 404.

[137] Newton, 382–83.

[138] Newton, *Philosophiae Naturalis Principia Mathematica, II Ed.*, 21.

[139] Janiak, *Newton as Philosopher*.

and the bucket. [140] Newton finally demonstrates that, because it depends on identifiable physical forces, its definition can be applied consistently even in the absence of observable reference bodies, because if two bodies connected by a cord are alone in an otherwise empty universe, the tension on cable still offers a criterion and a measure of the amount of true circular motion. [141]

Another Newtonian thought experiment involved **two bodies connected by a cord**, [142] which rotate around their center of common weight, in the absence of other bodies that can influence their movements. "The endeavor of the balls to recede from the axis of motion could be known from the tension of the cord, and thus the quantity of circular motion could be computed." Respectively, the absolute rotation of a body is not only independent of its rotation with respect to the contiguous bodies but is independent of any relative rotation.

According to Ernst Mach, two hundred years after Newton, if Newton neglected neighboring bodies, he referred all movements to "fixed stars." But if we can deduce from Newton's laws how bodies will behave in the absence of fixed stars, we cannot deduce whether, in these circumstances, they will remain valid anyway. For Einstein, under Mach's influence, Newton's argument illustrates the "epistemological defect" inherent in Newtonian physics. [143]

In Propositions 26-29, Book 3, of *Principia*, 1687, [144] Newton developed a special treatment of the influence of the Sun's gravitational force on the **motion of the Moon** around the Earth. Tycho Brahe had discovered a bi-monthly variation in lunar velocity after an expected lunar eclipse disappeared. Remarkably, Newton did not consider the actual motion of the Moon, which is known to be approximated by Horrocks' model of an ellipse precession with the Earth in one focus. He considered an idealized model in which the Moon rotates in a circular orbit around the Earth in the absence of solar disturbance. He calculated the orbit change due to this disturbance and obtained results that were in accordance with Brahe's observation. This was one of the great triumphs of Newton's gravitational theory, further developed by Euler[145], and G. Hill[146].

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[140] Newton, *Philosophiae Naturalis Principia Mathematica, II Ed.*, 21.

[141] Newton, 22.

[142] Cohen and Smith, *The Cambridge Companion to Newton*, 44.

[143] Cohen and Smith, *The Cambridge Companion to Newton*.

[144] Newton, "Philosophiæ Naturalis Principia Mathematica, I Ed."

[145] Leonhard Euler, *Sol et Luna I: Opera Mechanica Et Astronomica Vol 23*, ed. Otto Fleckenstein, 1956 edition (Basileae: Birkhäuser, 1956), 286–289.

[146] G. W. Hill, "The Collected Mathematical Works of G. W. Hill," *Nature* 75, no. 1936 (December 1906): 284–335, https://doi.org/10.1038/075123a0.

Newton's theory was most successful when it was used to predict **Neptune**'s existence based on Uranus movements, which could not be explained by the actions of other planets. The calculations of John Couch Adams and Urbain Le Verrier predicted the general position of the planet, and the calculations of Le Verrier led Johann Gottfried Galle to the discovery of Neptune. [147]

Newton's theory of gravity is better than Descartes's theory because Descartes's theory has been refuted (proved to be false) in explaining the motion of the planets. Newton's theory was in turn refuted by Mercury's abnormal perihelion. Even if the Keplerian ellipses rejected Cartesian vortex theory, only Newton's theory forced us to reject it; and even though Mercury's perihelion rejected Newtonian gravity, only Einstein's theory made us reject it. A refusal merely indicates the urgent need to revise the current theory, but it is not a sufficient reason to eliminate the theory.

1.3.2 Tests of post-Newtonian theories

Usually, the "laboratory" of gravitational tests was the celestial bodies, the astrophysical systems. But such tests are disturbed by non-gravitational effects. The most used such "laboratory" was the solar system. Recently, scientists have focused on observing binary pulsars for the verification of gravitational theories, by observing the variations of the orbital period, thus providing indirect evidence for the emission of gravitational radiation.

But the experimenter cannot "arrange the lab" according to his needs, nor trigger certain events when he needs them. But the current technological development is beginning to allow pure laboratory experiments. Thus, resonant detectors (harmonic oscillators) with very low dissipation levels were reached. In these laboratory tests, one type of experiments is the one for checking the post-Newtonian gravitational effects. For this purpose, a body of laboratory dimensions is moved (by rotation or vibration) to produce in its vicinity a "post-Newtonian gravitational field" (Newtonian-type gravitational fields produced by kinetic energy or pressure). The movement of the mass is modulated so that the desired post-Newtonian signal resonantly drives the oscillations of the detector and the experimenter monitors the changes resulting in the movement of the detector. [148]

Through these experiments, only certain types of post-Newtonian effects can be examined. Some post-Newtonian effects (such as nonlinear gravitational effects) are completely negligible. But it is possible to check the gravitational influences of speed and pressure. In these post-Newtonian

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[147] John Couch Adams, “On the Perturbations of Uranus (1841-1846). | StJohns,” 1846, 265, https://www.joh.cam.ac.uk/w16-manuscripts-john-couch-adams-perturbations-uranus-1841-1846.

[148] Carlton Morris Caves, “Theoretical Investigations of Experimental Gravitation” (phd, California Institute of Technology, 1979), http://resolver.caltech.edu/CaltechTHESIS:03152016-161054898.

experiments, the elimination of "Newtonian noise", the Newtonian gravitational field effects of the laboratory source that are much larger than the largest post-Newtonian effects, is attempted.

1.4 Newtonian gravity anomalies

Newton's law of gravity is precise enough for practical purposes. The deviations are small when the dimensional quantities $\varphi/c^2 << 1$ and $(v/c)^2 << 1$, where φ is the gravitational potential, v is the speed of the studied objects and c is the speed of light[149]. Otherwise, general relativity must be used to describe the system. Newton's law of gravity is the gravitational limit of general relativity under the conditions specified above.

Regarding Newton's law, there are still current theoretical concerns: there is still no consensus regarding the mediation of gravitational interaction (whether there is action at a distance). Also, Newton's theory involves an instantaneous propagation of gravitational interaction, otherwise an instability of planetary orbits would appear.

Newton's theory could not explain the exact precession of the orbit of the planets, especially for Mercury, which was detected long after Newton died. [150] The difference of 43 arcseconds per century appears from the observations of the other planets and from the precession observed with advanced telescopes in the 19th century.

The angular deflection of light rays due to gravity, calculated using Newton's theory, is half the deflection observed by astronomers. General relativity predicts values much closer to observational ones.

In spiral galaxies, the orbit of the stars around their centers seems to not exactly respect Newton's law of universal gravity. Astrophysicists have introduced some ad-hoc hypotheses to agree this phenomenon with Newton's laws, assuming the existence of large amounts of dark matter.

Newton himself was disturbed by the concept of "action at a distance" that his equations involved. In 1692, in his third letter to Bentley, he wrote:

> "That gravity should be innate, inherent, and essential to matter, so that one body may act upon another at a distance, through a vacuum, without the mediation of anything else, by and through which their action and force may be conveyed from one to another, is to me so great an absurdity, that I believe no man who has in philosophical matters a competent faculty of thinking can ever fall into it. Gravity must be caused by an agent

[149] Charles W. Misner, Kip S. Thorne, and John Archibald Wheeler, *Gravitation* (W. H. Freeman, 1973), 1049.

[150] Max Born, *Einstein's Theory of Relativity*, Revised edition edition (New York: Dover Publications Inc., 1962), 348.

> acting constantly according to certain laws; but whether this agent be material or immaterial, I have left to the consideration of my readers." [151] [152]

Newton failed to issue a phenomenological theory, to be confirmed experimentally, on how gravity acts, although he suggested two mechanical hypotheses in 1675 and 1717. In the General Scholium in the second edition of the *Principia* of 1713, he said: "I have not yet been able to discover the cause of these properties of gravity from phenomena and I feign no hypotheses...." [153]

1.5 Saturation point in Newtonian gravity

At the end of the 20th century and the beginning of the 21st century, the contradictions between Newtonian mechanics and Maxwell's electrodynamics (between the Galilean invariance and the idea of the constant speed of light) became evident. An initially proposed solution was the ether concept. Einstein rejected this solution, interpreting Newton's and Maxwell's theories as so fundamental, each with its rival model, that the only solution was the development of a new unifying theory, with another hard core and a specific positive heuristic: special relativity.

Nicholas Maxwell[154] discusses six discrepancies in Newtonian mechanics highlighted by Einstein[155] (which might be called anomalies in the Lakatos program), namely:

1. the arbitrariness of inertial reference frames and the concept of absolute space;
2. two distinct fundamental laws, (a) the law of motion ($F = ma$) and (b) the expression of gravitational force ($F = Gm_1m_2/d^2$);
3. the arbitrariness of (b) being given (a), there being an infinite number of possibilities as good for (b);
4. the possibility that the law of force is determined by the structure of space and the failure to exploit this possibility;
5. the ad-hoc character of the equality of the inertial mass with the gravitational one; and
6. the unnatural nature of energy being divided into two forms, kinetic and potential.

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[151] I. Bernard Cohen, "Isaac Newton's Papers & Letters on Natural Philosophy and Related Documents," *Philosophy of Science* 27, no. 2 (1960): 209–211.

[152] Sfetcu, *Isaac Newton despre acţiunea la distanţă în gravitaţie - Cu sau fără Dumnezeu?*

[153] Newton, *Philosophiae Naturalis Principia Mathematica, II Ed.*

[154] Nicholas Maxwell, "The Need for a Revolution in the Philosophy of Science," *Journal for General Philosophy of Science* 33, no. 2 (December 1, 2002): 381–408, https://doi.org/10.1023/A:1022480009733.

[155] Albert Einstein, "Autobiographische Skizze," in *Helle Zeit — Dunkle Zeit: In memoriam Albert Einstein*, ed. Carl Seelig (Wiesbaden: Vieweg+Teubner Verlag, 1956), 27–31, https://doi.org/10.1007/978-3-322-84225-1_2.

Einstein explains why attempts to solve anomalies by ad-hoc hypotheses fail, and concludes: "Accordingly, the revolution begun by the introduction of the field was by no means finished. Then it happened that, around the turn of the century ... a second fundamental crisis set in," the crisis generated by the beginnings of quantum theory, the first being particle/field dualism in classical physics. [156]

In addition, Lorentz's classical program was progressive until 1905 - the year that Einstein published his theory of special relativity.

Nugayev claims that the research program supported by Einstein was much broader, including relativity, quantum theory and statistical mechanics, for the unification of mechanics and electrodynamics. [157]

Most of the explanations for Einstein's victory over Lorentz's research refer to the Michelson-Morley experiment. [158] Elie Zahar[159], based on Lakatos' methodology[160], states that Lorentz's etheric theories and Einstein's special and general theories of relativity have been developed in different competing programs. According to Zahar, Lorentz's program was replaced by Einstein's relativity program only in 1915 by explaining the precession of Mercury's perihelion. But with the development of the GR, Einstein's program predicted observations that could not be derived from Lorentz's. [161]

Nugayev, arguing against Zahar's extension of Lakatos' methodology, intends to explain the success of Einstein's research program on Lorentz's by a different extension of Lakatos's methodology, including different ones proposed by me. Thus, for two different theories trying to explain the same experimental data, the process of jointly applying the two theories to solve a problem will be called a "theories' cross", while these will be called "cross-theories". The set of statements that describes the relationships between crossings will be called "crossbred theory"[162]. Nugayev also addresses the idea of a theory that I have called "unifying" when the theories go

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[156] Einstein, 27–31.

[157] R. M. Nugayev, "The History of Quantum Mechanics as a Decisive Argument Favoring Einstein Over Lorentz," *Philosophy of Science* 52, no. 1 (1985): 44–63.

[158] Gerald Holton, "Einstein, Michelson, and the 'Crucial' Experiment," *Isis: A Journal of the History of Science* 60 (1969): 132–97.

[159] Zahar, "Why Did Einstein's Programme Supersede Lorentz's?"

[160] Lakatos, *The Methodology of Scientific Research Programmes*.

[161] Nugayev, "The History of Quantum Mechanics as a Decisive Argument Favoring Einstein Over Lorentz."

[162] Nugayev.

through "cross-contradictions". Nugayev calls the new theory "global". According to him, there would be two logical ways of elaborating the global theory: "reductionist" and "synthetic".

Nugayev states that Lakatos' hard nuclei are obtained by convention. I do not agree with him here. The hard core is established by the initiator of the research program which also establishes the strategy of program development according to the negative heuristic. The hard core is what it wants to remain unwavering, being absolutely convinced that it is right. When they would change the hard core, they would practically abandon that research program and start another program.

2. General relativity

Early philosophical interpretations of the general theory of relativity are very diverse, each trying to identify Einstein as a follower of that philosophy. Mach's supporters highlighted Einstein's attempt to implement a "relativization of inertia" in general relativity (GR), and his operationalist approach to simultaneity. Kantians and neo-Kantians have shown the importance of synthetic "intellectual forms" in GR, especially the principle of general covariance. Logical empiricists have emphasized the methodology of theory, the conventions to express the empirical content. [163]

Bertrand Russell noted that

> "There has been a tendency, not uncommon in the case of a new scientific theory, for every philosopher to interpret the work of Einstein in accordance with his own metaphysical system, and to suggest that the outcome is a great accession of strength to the views which the philosopher in question previously held. This cannot be true in all cases; and it may be hoped that it is true in none. It would be disappointing if so fundamental a change as Einstein has introduced involved no philosophical novelty." [164]

Most of Einstein's early work reveals that he is a supporter of Ludwig Boltzmann, rather than Ernst Mach, in the debate on atomism[165]. However, in 1912, Einstein's name was displayed among those who joined Mach in a call to form a "Society for Positivist Philosophy." At the end of his life, Einstein wrote about the "profound influence" exerted on him by Mach's School of Mechanics, and about the very high influence from youth of "Mach's epistemological position." [166] The occasional epistemological and methodological statements seem to indicate agreement with the essential parts of Mach's positivist doctrine[167]. Mach's idea that the mass and inertial motion of the body results from the influence of all other surrounding masses was probably the strongest motivation for developing a relativistic theory of gravity. [168]

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[163] Thomas A. Ryckman, "Early Philosophical Interpretations of General Relativity," in *The Stanford Encyclopedia of Philosophy*, ed. Edward N. Zalta, Spring 2018 (Metaphysics Research Lab, Stanford University, 2018), https://plato.stanford.edu/archives/spr2018/entries/genrel-early/.

[164] Bertrand Russell, *Relativity: Philosophical Consequences, in Encyclopaedia Britannica: Thirteenth Edition Volume 31* (ENCYCLOPAEDIA BRITTANICA PRESS, 1926), 331.

[165] Thomas Ryckman, *Einstein*, 1 edition (London ; New York: Routledge, 2011), chap. 3.

[166] Einstein, "Autobiographische Skizze," 21.

[167] Albert Einstein, *Über die spezielle und die allgemeine Relativitätstheorie*, 23. Aufl. 2001. Nachdruck (Berlin: Springer, 2002).

[168] Ryckman, "Early Philosophical Interpretations of General Relativity."

A passage from Einstein's first full exposition showed that his general covariance requirement for the equations of the gravitational field (meaning that they remain unchanged under arbitrary, but continuously adequate change of spacetime coordinates), "takes away from space and time the last remnant of physical objectivity". Josef Petzoldt, a Machian philosopher, noted that Einstein is best characterized as a relativist positivist[169]. Contemporary philosophy has shown that Einstein's remarks were merely elliptical references to an "hole argument," according to which if a theory is in general covariant, the empty points of the spacetime manifestation cannot have an inherent primitive identity, and therefore no independent reality[170]. Thus, for a general covariant theory, no physical reality accumulates in the "empty space" in the absence of the physical fields, ideas that it is not a support for positivist phenomenalism.

The relativization of all inertial effects ("Mach's principle"), together with the principle of general relativity interpreted by Einstein as the principle of general covariance, and with the principle of equivalence, were considered by Einstein the three pillar principles on which his theory was based.

The retrospective portraits of Einstein's methodology in the genesis of general relativity focus on the idea of a strategy that takes into account mathematical aesthetics[171]. The positivists and the operationalists have argued with Einstein's analysis of simultaneity as a fundamental methodological element of the theory of relativity.

The Kantian philosophers did not pay much attention to the theory of relativity. Cassirer sees the general theory of relativity as a confirmation of the fundamental principles of transcendental idealism[172]. Natorp[173] appreciated the principle of relativity as being consistent with Kantianism by distinguishing between ideal, purely mathematical transcendental concepts of space and time and their relative physical measurements. From this relativization, says Natorp, it follows that " events are ordered, not in relation to an absolute time, but only as lawfully determined phenomena in mutual temporal relation to one another, a version of Leibnizian relationism." [174] Also, the

[169] Joseph Petzoldt, Giora Hon, and Ernst Mach, *Der Verhältnis der Machschen Gedankenwelt zur Relativitätstheorie, an appendix to Die Mechanik in ihrer Entwicklung: Historisch-kritisch dargestellt* (Xenomoi Verlag, 1921), 516.

[170] John D. Norton, "General Covariance and the Foundations of General Relativity: Eight Decades of Dispute," *Reports of Progress in Physics* 56 (1993): 791–858.

[171] Thomas Ryckman, "A Believing Rationalist," The Cambridge Companion to Einstein, May 2014, 377–420, https://doi.org/10.1017/CCO9781139024525.014.

[172] Ernst Cassirer, W. C. Swabey, and M. C. Swabey, *Substance and Function and Einstein's Theory of Relativity* (Courier Corporation, 2003), 172–73.

[173] Paul Natorp, *Die logischen Grundlagen der exakten Wissenschaften* (Sändig Reprint, H. R. Wohlwend, 1910), 399–404.

[174] Ryckman, "Early Philosophical Interpretations of General Relativity."

constancy of the speed of light, considered an empirical presupposition, "reminded that absolute determinations of these measures, unattainable in empirical natural science, would require a correspondingly absolute bound." [175] Natorp considered the invariant requirement of the laws of nature regarding Lorentz transformations as "perhaps the most important result of Minkowski's investigation." [176]

A number of neo-Kantian positions, including Marburg's and Bollert's[177], have argued that relativity theory has clarified the Kantian position in transcendental aesthetics by showing that not space and time, but spatiality (determinism in the positional order) and temporality (in the order of succession).) are *a priori* conditions of physical knowledge. This revision of the conditions of objectivity is essential for critical idealism.

The most influential neo-Kantian interpretation of general relativity was Ernst Cassirer's *Zur Einsteinschen Relativitätstheorie*[178], in which the theory is considered to be a crucial test for *Erkenntniskritik* (the epistemology of the physical sciences of Marburg's transcendental idealism). Recognizing the requirement of general covariance, Cassirer stated that the general theory of relativity, with the coordinates of space and time, represents only "labels of events ("coincidences"), independent variables of the mathematical (field) functions characterizing physical state magnitudes." [179] The general covariance would be the most recent refinement of the methodological principle of the "unit of determination" which determines the physical knowledge by moving from concepts of substance to functional and relational concepts. Cassirer concluded that the general theory of relativity presents "the most determinate application and carrying through within empirical science of the standpoint of critical idealism." [180]

E. Sellien[181] stated that Kant's views on space and time refer only to intuitive space, and thus were impervious to the space and time measurable of Einstein's empirical theory.

The logical empiricism of the philosophy of science has emerged largely as a result of Einstein's two theories of relativity, favoring conventionalism à la Poincaré over neo-Kantianism and Machian positivism. The philosophy of logical empiricism of science itself is considered to have

[175] Ryckman.

[176] Natorp, *Die logischen Grundlagen der exakten Wissenschaften*, 403.

[177] Karl Bollert, *Einstein's Relativitätstheorie und ihre Stellung im System der Gesamterfahrung* (T. Steinkopf, 1921).

[178] Ernst Cassirer, *Zur Einstein'schen relativitätstheorie: Erkenntnistheoretische betrachtungen* (B. Cassirer, 1921), 1–125.

[179] Ryckman, "Early Philosophical Interpretations of General Relativity."

[180] Cassirer, Swabey, and Swabey, *Substance and Function and Einstein's Theory of Relativity*, 412.

[181] Ewald Sellien, *Die erkenntnistheoretische Bedeutung der Relativitätstheorie* (Christian-Albrechts-Universität zu Kiel, 1919).

been formed from the lessons learned from the theory of relativity. Some of the most characteristic doctrines of this philosophy (interpreting *a priori* elements in physical theories as conventions, dealing with the necessary role of conventions in developing theoretical concepts from observation, insisting on observational language in defining theoretical terms) were used by Einstein in modeling those two theories of relativity. [182]

Reichenbach developed the thesis of "the relativity of geometry", that an arbitrary geometry for spacetime can be developed if the laws of physics are modified accordingly by the introduction of "universal forces". But Reichenbach's first work on relativity[183] was written from a neo-Kantian perspective. According to Friedman[184] and Ryckman[185], Reichenbach modified the Kantian conception of synthetic *a priori* principles, rejecting the meaning of "valid for all time", while retaining the "constitutive of the object (of knowledge)", resulting in a specific "relativized *a priori*" theory. Thus, a transformation appears in the method of epistemological research of science whereby the method of analyzing science is proposed as "the only way that affords us an understanding of the contribution of our reason to knowledge." [186] The methodology of rationalization implies the clear distinction between the subjective role of the principles and the contribution of the objective reality. Relativity theory is a shining example of this method because it showed that the spacetime metric describes an "objective property" of the world, once the subjective freedom of coordinate transformation (the coordinating principle of general covariance) is recognized. [187] [188]

Einstein, in a January 1921 lecture entitled "Geometry and Experience", argued that the question of the nature of spacetime geometry is an empirical problem only with respect to certain stipulations. Reichenbach's conventional conception reached maturity in 1922. Reichenbach argued that problems regarding the empirical determination of the spacetime metric must take into account the fact that both geometry and physics support the observational test, this being the case in the Einstein's general relativity(Reichenbach's method has been called the "logical analysis of science.") Thus, the empirical determination of the spacetime metric by measurement requires the choice of "metric indicators" by establishing a coordinating definition. Einstein, together with

[182] Ryckman, "Early Philosophical Interpretations of General Relativity."

[183] Hans Reichenbach, *Relativitätstheorie Und Erkenntnis Apriori* (J. Springer, 1920).

[184] Michael Friedman, "Geometry, Convention, and the Relativized A Priori: Reichenbach, Schlick, and Carnap," Reconsidering Logical Positivism, July 1999, 21–34, https://doi.org/10.1017/CBO9781139173193.006.

[185] Thomas Ryckman, *The Reign of Relativity: Philosophy in Physics 1915-1925*, 1 edition (Oxford ; New York: Oxford University Press, 2005).

[186] Reichenbach, *Relativitätstheorie Und Erkenntnis Apriori*, 74.

[187] Reichenbach, 90.

[188] Ryckman, "Early Philosophical Interpretations of General Relativity."

Schlick and Reichenbach, developed a new form of empiricism, suitable for arguing general relativity against neo-Kantian criticism. [189] [190]

Einstein implemented a relational or relativistic conception of the movement, in accordance with Leibniz's relationalist attitude to space and time and in contrast to Newton's absolutist attitude. By this, constraints are placed on the ontology of the spacetime theories, limiting the field in which the quantifiers of the theories are located to the set of physical events, that is, in the set of spacetime points that are actually occupied by objects or material processes[191]. Reichenbachian relations, on the other hand, impose constraints on the ideology of spacetime theories, limiting the vocabulary to a certain set of preferred predicates, such as predicates defined in terms of "causal" relations.

Conventionalism, like relationalism, is skeptical of the structures postulated by spacetime theories. It raises the problem of geometric (metric) properties and relations defined in this field. Friedman asserts that conventionalism is closely linked to ideological relationalism. Basic conventionalism argues that certain incompatible description systems at first glance, such as Euclidean and non-Euclidean geometries, are in fact "equivalent descriptions" of the same facts, both of which may be true in relation to the various "coordinative definitions" chosen arbitrarily. This represents an epistemological problem in choosing between competing theories, resulting in a problem of theoretical underdetermination. Thus, Friedman asserts that relativity theory seems to be based on a conception of "equivalent descriptions" derived directly from the conventionalist strategy[192]. The development of relativity theory is based on a methodology from the perspective of the theoretical unification process.

A decade after the emergence of the general theory of relativity, there was talk of a reduction of physics to geometry[193], leading to distinct philosophical problems, of methodology but also of epistemology and metaphysics, along with technical issues. This implicit reduction of physics to

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[189] Moritz Schlick, "Kritizistische Oder Empiristische Deutung Der Neuen Physik?," *Société Française de Philosophie, Bulletin* 26, no. n/a (1921): 96.

[190] Hans Reichenbach, *Philosophie der Raum-Zeit-Lehre*, 1 Plate (De Gruyter, 1928).

[191] Friedman, *Foundations of Space-Time Theories*.

[192] Friedman.

[193] Oliver Lodge, "The Geometrisation of Physics, and Its Supposed Basis on the Michelson-Morley Experiment," News, Nature, 1921, 795–802, https://doi.org/10.1038/106795a0.

geometry was obtained crucial in the epistemological framework of what Hilbert called the "axiomatic method." [194]

After completing general relativity, Einstein attempted to develop a theory that unified gravity and electromagnetism, by generalizing Riemannian geometry or adding additional dimensions, but excluding the reduction of physics to geometry[195]. Until 1925 he invented the first geometric "unified field theories"[196]. None of these efforts were successful. In his research program for geometric unification, Einstein's research methodology underwent a dramatic change[197], relying more and more on "mathematical aesthetics, of "logical simplicity", and the inevitability of certain mathematical structures under various constraints, adopted essentially for philosophical reasons." [198]

The mathematician Hermann Weyl, in 1918, attempted to reconstruct Einstein's theory on the basis of epistemology of "pure infinitesimal geometry." [199]

In December 1921, the Berlin Academy published Theodore Kaluza's new proposal on the unification of gravity and electromagnetism based on a five-dimensional Riemannian geometry.

All attempts to geometry the physics in the unified program accepted the ability of mathematics to understand the fundamental structure of the outer world. Thus, the program of the geometrically unified field seems thus to be framed in a form of scientific realism called "structural realism", with a Platonic hue. A form of "structural realism" assumes that no matter the intrinsic character or

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[194] K. A. Brading and T. A. Ryckman, "Hilbert's 'Foundations of Physics': Gravitation and Electromagnetism within the Axiomatic Method," *Studies in History and Philosophy of Science Part B: Studies in History and Philosophy of Modern Physics* 39, no. 1 (January 1, 2008): 102–153, https://doi.org/10.1016/j.shpsb.2007.08.002.

[195] Marco Giovanelli, "The Forgotten Tradition: How the Logical Empiricists Missed the Philosophical Significance of the Work of Riemann, Christoffel and Ricci," *Erkenntnis* 78, no. 6 (December 1, 2013): 1219–1257, https://doi.org/10.1007/s10670-012-9407-2.

[196] Tilman Sauer, "Einstein's Unified Field Theory Program," The Cambridge Companion to Einstein, May 2014, 281–305, https://doi.org/10.1017/CCO9781139024525.011.

[197] Ryckman, *Einstein*, chaps. 9, 10.

[198] Ryckman, "Early Philosophical Interpretations of General Relativity."

[199] Hermann Weyl, Axel Hildebrand, and Dieter Schmalstieg, *Raum. Zeit. Materie: Vorlesungen über allgemeine Relativitätstheorie*, 7. (Berlin Heidelberg New York London Paris Tokyo: Springer, 1988), 115–16.

nature of the physical world, only its structure can be known. This version was supported by Russell, who included the general theory of relativity in this framework. [200]

In its contemporary form, structural realism has both an epistemic and an "ontic" form, in which the structural features of the physical world are ontologically fundamental[201]. Thomas A. Ryckman asserts that geometric unification theories fit this kind of realism. For Weyl and Eddington, "geometrical unification was an attempt to cast the harmony of the Einstein theory of gravitation in a new epistemological and so, explanatory, light, by displaying the field laws of gravitation and electromagnetism within the common frame of a geometrically represented observer-independent reality." [202]

Regarding the geometry of physics, there has been a permanent controversy over the conventions in science[203], and whether the choice of geometry is empirical, conventional or *a priori*. Duhem[204] states that hypotheses cannot be tested in isolation, but only as part of the theory as a whole (theoretical holism and underdetermination of choice of theory by empirical evidence). In a 1918 address to Max Planck, Einstein stated about underdetermination:

> "The supreme task of the physicist is ... the search for the most general elementary laws from which the image of the world must be obtained by pure deduction. No logical path leads to these elementary laws; it is only intuition that is based on an empathetic understanding of experience. In this state of methodological uncertainty, it can be believed that many, in themselves, equivalent systems of theoretical principles are possible; and this opinion is, in principle, certainly correct. But the development of physics has shown that, out of all the theoretical imaginable constructions, only one, at any given moment, proved superior unconditionally to all the others. None of those who have delved into this subject will deny that, in practice, the world of perceptions unequivocally determines the theoretical system, even if no logical path leads from perceptions to the basic principles of theory." [205]

Einstein considered that the physical real implies exclusively what can be constructed on the basis of the spacetime coincidences, the spacetime points being considered as intersections of the world

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[200] Bertrand Russell, *The Analysis of Matter*, First Paperback Edition edition (Nottingham: Spokesman Books, 2007), 395.

[201] Pierre Maurice Marie Duhem, Jules Vuillemin, and Louis de Broglie, *The Aim and Structure of Physical Theory*, trans. Philip P. Wiener, 9932nd edition (Princeton: Princeton University Press, 1991).

[202] Ryckman, "Early Philosophical Interpretations of General Relativity."

[203] Paul Arthur Schilpp, ed., *Albert Einstein, Philosopher-Scientist: The Library of Living Philosophers Volume VII*, 3rd edition (La Salle, Ill.: Open Court, 1998).

[204] Duhem, Vuillemin, and Broglie, *The Aim and Structure of Physical Theory*.

[205] Albert (Author) Einstein, "Motive des Forschens.," 1918, 31, http://alberteinstein.info/vufind1/Record/EAR000079148.

lines (the "point-coincidence argument")[206]. Coincidences thus have a privileged ontic role because they are invariable and therefore uniquely determined[207]. The force in the GR is also "geometrized"[208]. The spacetime metric in GR is reducible to the behavior of material entities (clocks, light beams, geodesics, etc.) [209]. It turns out that the measurement depends on the measuring instruments chosen as standards, and the metric relationships involve the chosen standards.

Paul Feyerabend, considers Einstein as a methodological "opportunist or cynic", respectively a methodological anarchist[210]. Arthur Fine states that Einstein adopts a vision close to the natural ontological attitude[211]. van Frassen considered Einstein a constructive empiricist[212]. Nicholas Maxwell asserts that aim-oriented empiricism, as a new method of discovery, is Einstein's mature vision of science[213] to overcome a severe scientific crisis: the disappearance of classical physics as a result of Planck's quantum theory of 1900. Aim-oriented empiricism claims that science makes permanent assumptions about the nature of the universe, independent of empirical considerations.

Popper[214], as well as Kuhn[215] and Lakatos[216], defend versions of standard empiricism in Einstein's case.

Vincent Lam and Michael Esfeld support the concept of ontic structural realism (OSR), in which "spacetime is a physical structure in the sense of a network of physical relations among physical

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[206] Don A. Howard, "Einstein's Philosophy of Science," in *The Stanford Encyclopedia of Philosophy*, ed. Edward N. Zalta, Fall 2017 (Metaphysics Research Lab, Stanford University, 2017), https://plato.stanford.edu/archives/fall2017/entries/einstein-philscience/.

[207] Nicolae Sfetcu, *Singularitățile ca limite ontologice ale relativității generale* (MultiMedia Publishing, 2018), http://doi.org/10.13140/RG.2.2.17470.18242.

[208] Adolf Grünbaum, *Philosophical Problems of Space and Time: Second, Enlarged Edition* (Springer Science & Business Media, 2012).

[209] Paul Feyerabend, *Against Method* (London: New Left Books, 1975).

[210] Michael Esfeld and Vincent Lam, "Moderate Structural Realism About Space-Time," *Synthese* 160, no. 1 (2008): 18, 56–57, 213n.

[211] Arthur Fine, *The Shaky Game: Einstein, Realism, and the Quantum Theory* (University of Chicago Press, 1986), 9.

[212] Fine, 108.

[213] Nicholas Maxwell, *Karl Popper, Science and Enlightenment* (London: UCL Press, 2017).

[214] Karl Popper, *Conjectures and Refutations: The Growth of Scientific Knowledge*, 2nd edition (London ; New York: Routledge, 2002).

[215] Kuhn, *The Structure of Scientific Revolutions*.

[216] Lakatos, *The Methodology of Scientific Research Programmes*.

relata (objects) that do not possess an intrinsic identity independently of the relations in which they stand," [217] which can take into account the fundamental GR characteristics of diffeomorphism invariance[218] and background independence[219]. The localization within the OSR is dynamic and background independent, being invariant diffeomorphic, thus well coding the GR characteristic of background independence.

According to Don A. Howard, "Einstein's own philosophy of science is an original synthesis of elements drawn from sources as diverse as neo-Kantianism, conventionalism, and logical empiricism, its distinctive feature being its novel blending of realism with a holist, underdeterminationist form of conventionalism." [220]

There are a few central ideas to Einstein's philosophy:

- Underdetermination of the theoretical option through evidence.
- Simplicity and choice of theory.
- Univocity in the theoretical representation of nature.
- Realism and separability.
- Distinction between the theories of the principles and the constructive theories.

For Einstein, *simplicity* is the main criterion in the theoretical choice when the experiments and observations do not give sufficiently clear indications[221]. *Univocity* in the theoretical representation of nature should not be confused with a denial of the *underdetermination* thesis. The principle of univocality played a central role in Einstein's formulation of general relativity, including in the elaboration of the "hole argument" which some physicists mistakenly considered. [222]

Many philosophers and scientists consider that Einstein's most important contribution to the philosophy of science was the distinction he made between principle theories and constructive theories. According to Einstein, a ***constructive theory*** offers a constructive model for phenomena of interest. A ***principle theory*** consists of a set of well-substantiated individual empirical generalizations. Einstein states that the final understanding requires a constructive theory, but

[217] Vincent Lam and Michael Esfeld, "The Structural Metaphysics of Quantum Theory and General Relativity," *Journal for General Philosophy of Science / Zeitschrift Für Allgemeine Wissenschaftstheorie* 43, no. 2 (2012): 243–258.

[218] The diffeomorphism is a smooth and bijective mapping between differentiated manifolds whose inversion is also smooth.

[219] Esfeld and Lam, "Moderate Structural Realism About Space-Time."

[220] Howard, "Einstein's Philosophy of Science."

[221] John Norton, *How Einstein Found His Field Equations: 1912-1915*, 1984, 21, 23.

[222] P. M. Harman and Peter Michael Harman, *The Natural Philosophy of James Clerk Maxwell* (Cambridge University Press, 2001).

progress in theory can be "impeded by premature attempts at developing constructive theories in the absence of sufficient constraints by means of which to narrow the range of possible of constructive." The role of principle theories is to provide constraints, and progress is made on the basis of such principles. *Einstein states that this was his methodology in discovering the theory of relativity as the main theory, the other two principles being the principle of relativity and the principle of light.*

It is worth noting the similarity between the idea of the "principle theories" as Einstein's constraints, and the "hard core" of Lakatos (negative heuristics) that would have been the sum of Einstein's "principle theories".

The distinction between principle theories and constructive theories has played an explicit role in Einstein's thinking. Harman noted that early versions of this distinction have been used since the 19th century, by James Clerk Maxwell. [223]

Einstein's equations are difficult to solve exactly, but there are currently several exact solutions, such as the Schwarzschild solution, the Reissner-Nordström solution and the Kerr metric, each corresponding to a certain type of black hole in an otherwise empty universe[224], and the Friedmann-Lemaître-Robertson-Walker and de Sitter universes, each describing an expanding cosmos[225]. Other exact solutions include the Gödel universe (with the possibility of spacetime travel), the Taub-NUT solution (a homogeneous but anisotropic universe) and the anti-de Sitter space (with the Maldacena conjecture) [226]. Due to the difficulty of these equations, solutions are currently being sought by numerical integration on a computer or by examining small perturbations of exact solutions. From the approximate solutions found by the disturbance theories is also part of the post-Newtonian extension, developed by Einstein, with a distribution of matter that moves slowly compared to the speed of light. A particularization of this extension is the *parameterized post-Newtonian formalism*, which allows quantitative comparisons between the predictions of general relativity and alternative theories.

By imposing the general covariance, all the spacetime checks assume a determination of the spacetime coincidences[227]. Schlick states that the passage from Einstein's 1916 paper dealing with

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223 Subrahmanyan Chandrasekhar, *The Mathematical Theory of Black Holes* (Clarendon Press, 1998).

224 Jayant Vishnu Narlikar, *Introduction to Cosmology* (Jones and Bartlett, 1983).

225 Albert Einstein, *The Principle of Relativity* (S.l.: BN Publishing, 2008), 78.

226 Stephen W. Hawking et al., *The Large Scale Structure of Space-Time*, New Ed edition (Cambridge: Cambridge University Press, 1975).

227 A. Einstein, "The Foundation of the General Theory of Relativity," in *The Principle of Relativity. Dover Books on Physics. June 1, 1952. 240 Pages. 0486600815, p. 109-164*, 1952, 117, http://adsabs.harvard.edu/abs/1952prel.book..109E.

this aspect represents the birth of the modern observation/theory distinction, and the beginning of empirical and truthful interpretations of later positivism[228].

Einstein hoped that general relativity would extend the relativity of motion from the Galilean equivalence to the equivalence of all states of motion, including rotation, based on the assumption that general covariance or equivalence of coordinate descriptions guarantees the desired equivalence. But by itself, general covariance is not such an argument, unable to solve the original problem of Einstein's relationship between movement. This problem is, in essence, one of geometric structure[229]. According to Disalle, Einstein made an epistemological confusion by accepting the idea that relative movements can be known independently of any spatial theory, in order to allow relative movements to have an epistemologically privileged position. Disalle concludes that classical relationalism, considered to be an epistemological critique of spacetime theory, is itself a spatial theory.

Riemann (1867) and Helmholtz (1870) stated that all geometric measurements depend on the physical assumptions underlying the measurement method, because empirical geometry must postulate not only a geometrical structure, but also a representation of an idealized physical process[230]. For Riemann, the connection between geometry and physics will have to be based on physical objects and more complicated processes. Such a connection implies a physical principle, an idea taken up by Einstein for the curvature of spacetime. [231]

Poincare stated that any measurement can agree with any geometry, if we eliminate the discrepancies by the hypothesis of a distorting force that affects the measuring instruments[232]. Reichenbach and Schlick systematized this concept by the notion of "coordinative definition", directing empiricism toward conventionalism, with a geometry with definitions that correlate

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[228] Moritz Schlick, *Space and Time in Contemporary Physics: An Introduction to the Theory of Relativity and Gravitation* (Mineola, N.Y: Dover Publications, 2005).

[229] Disalle, "Spacetime Theory as Physical Geometry."

[230] Bernhard Riemann and Hermann Weyl, *Über die Hypothesen, welche der Geometrie zu Grunde liegen* (Berlin Heidelberg: Springer-Verlag, 1919), 133–52, https://www.springer.com/gp/book/9783662423165.

[231] Albert Einstein, *Geometrie und Erfahrung: Erweiterte Fassung des Festvortrages Gehalten an der Preussischen Akademie der Wissenschaften zu Berlin am 27. Januar 1921* (Berlin Heidelberg: Springer-Verlag, 1921), 123–30, https://www.springer.com/de/book/9783642499036.

[232] Henri Poincare, *The Foundations of Science; Science and Hypothesis, the Value of Science, Science and Method* (Place of publication not identified: TheClassics.us, 2013), 81–84.

fundamental concepts with an empirical given object[233] [234]. Thus, Reichenbach stated that: "the philosophical significance of the theory of relativity consists in the fact that it has demonstrated the necessity for metrical coordinative definitions in several places where empirical relations had previously been assumed." [235]

An example of this is simultaneity. Newtonian physics considered the simultaneity of events as an empirical fact, while Einstein imposed simultaneity as a physical principle. Since the speed of light was considered invariant, it turned out that simultaneity is relative. Disalle states that Einstein's definition of simultaneity is circular, since it already implies a principle of time measurement. Einstein denied, saying that the definition does not imply anything about light, the invariance of the speed of light being not a hypothesis, but "a stipulation that I can make according to my own free discretion, in order to achieve a definition of simultaneity." [236] Disalle concludes that the problem of the nature of spacetime is not whether a theoretical entity provides a causal explanation for appearances, but whether physical measurement processes are in accordance with geometrical laws. In conclusion, Reichenbach denies the role of geometry in explaining the root cause of spatial relations. [237]

But Einstein links spacetime not only with a certain procedure, but with a system of natural laws, the laws of electrodynamics, which he considers to be fundamental invariants. Thus the coordinative definition of the states of motion is a more subtle process than Reichenbach has proposed, implying not choosing a resting frame but establishing the laws of motion. In practice, the laws of motion have thus become, through coordinative definitions, postulates of the space-time geometry. [238]

According to Lakatos, Einstein's theory is no better than Newton's because of the refutation of Newton's theory: there are also "anomalies" of Einstein's theory. But this represents a breakthrough compared to Newton's theory, because he explained everything that successfully explained Newton's theory, and also explained the anomalies of that theory. In addition, he successfully predicted events about which Newton's theory said nothing.

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[233] Hans Reichenbach, *The Philosophy of Space and Time*, 1st edition (New York, NY: Dover Publications, 1957).

[234] Moritz Schlick, *Allgemeine Erkenntnislehre: Abteilung I / Band 1*, ed. Hans Jürgen Wendel and Fynn Ole Engler, Abteilung I: Veröffentlichte Schriften (Wien: Springer-Verlag, 2009), https://www.springer.com/gp/book/9783211327685.

[235] Reichenbach, *The Philosophy of Space and Time*, 15.

[236] Einstein, *Über die spezielle und die allgemeine Relativitätstheorie*, 15.

[237] Disalle, "Spacetime Theory as Physical Geometry."

[238] Disalle.

2.1 Heuristics of the general relativity

The essential principle of coordination in GR is the principle of equivalence, including a negative heuristic. The argument "is not that all reference frames are equivalent, but that the classical coordination of uniform motion in a straight line with the paths of force-free particles cannot be carried out unambiguously or consistently." [239] The principle of equivalence states that the decomposition of the gravitational motion into a uniform motion and gravitational acceleration cannot be unique, since free fall is not distinguishable locally from uniform motion. However, such a decomposition implies a violation of the general covariance, because it represents an arbitrary choice of a coordinate system[240]. For any coordinate system, if we identify its lines with the geodesic lines, we can construct the gravitational field so that the difference between these geodesics and the actual motions can be differentiated. [241]

Einstein's special theory of relativity (SR) is built on two fundamental postulates. the postulate of light (the speed of light, in the "rest frame", is independent of the speed of the source), and the principle of relativity. The latter was explicitly adopted by Einstein as a means of restricting the form of laws, whatever their detailed structure. Thus, we have the difference between a "constructive" theory and a "principle" theory. The general theory of relativity was developed using as a nucleus a principle of symmetry: the principle of general covariance[242]. Initially, Einstein saw the principle of general covariance as an extension of the principle of relativity in classical mechanics, and in SR. For Einstein, the principle of general covariance was a crucial postulate in the development of GR. The freedom of the GR diffeomorphism (the invariance of the form of the laws under transformations of the coordinates depending on the arbitrary functions of space and time) is a "local" spacetime symmetry, as opposed to the "global" spacetime symmetries of the SR (which depend instead on the constant parameters).

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[239] Disalle.

[240] Einstein, "The Foundation of the General Theory of Relativity," 114.

[241] Einstein, 142–43.

[242] Katherine Brading, Elena Castellani, and Nicholas Teh, "Symmetry and Symmetry Breaking," in *The Stanford Encyclopedia of Philosophy*, ed. Edward N. Zalta, Winter 2017 (Metaphysics Research Lab, Stanford University, 2017), https://plato.stanford.edu/archives/win2017/entries/symmetry-breaking/.

In recent years, there have been numerous debates in physics and philosophy regarding certain types of symmetries that act in the space of theories. Such symmetries are interpreted as achieving an "equivalence" between two theories that are said to be related to a "dual symmetry" (in the case of a "symmetry" in the strict sense of an automorphism, these are called "self-dualities"). Katherine Brading[243] exemplifies with the dualities between quantum field theories (such as generalized magnetic/electrical duality), between string theories (such as T and S dualities) and between physical descriptions that are, such as a quantum field theory and a string theory, as in the case of gauge/gravity dualities[244]. Other examples are the position-momentum duality, the wave-particle duality, or the Kramers-Wannier duality of the two-dimensional Ising model in statistical physics. Dualities are transformations between theories, while symmetry is a mapping between solutions of the same theory. A symmetry can be exact (unconditional validity), approximate (valid under certain conditions) or broken (depending on the object considered and its context). The symmetries functioned normatively, like constraints, in Einstein's general covariance in establishing the equations of general relativity.

Elie Zahar said that Einstein's development of relativity was due to his vague metaphysical beliefs, corresponding to some of his own "heuristic prescriptions" that became a specific and powerful tool. Zahar states that Kuhn's scientific revolution does not apply to Einstein's case. According to him, two "heuristic devices" led to the discovery of the theory of relativity: the internal requirement of coherence, and the claim that, "since God is no deceiver, there can be no accidents in Nature." Natural symmetries are fundamental at the ontological level, and the heuristic rule takes precedence over a theory that does not explain symmetries as deeper manifestations. [245]

According to Newton, gravity is not a primary quality like inertia or impenetrability. Therefore, inertia and gravity are independent properties. But Newton states that the inertial mass is equal to the gravitational mass, without explaining the reason for this identity (there is a symmetry that contradicts the independence of the two properties). In Michelson's experience, by applying the ether as a universal medium, it is undetectable, which is a paradox. Einstein became

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[243] Katherine Brading and Harvey R. Brown, "Symmetries and Noether's Theorems," in *Symmetries in Physics: Philosophical Reflections*, ed. Katherine A. Brading and Elena Castellani (Cambridge University Press, 2003), 89–109.

[244] Brading, Castellani, and Teh, "Symmetry and Symmetry Breaking."

[245] Zahar, "Why Did Einstein's Programme Supersede Lorentz's?"

aware of this paradox. Einstein eliminates the asymmetry between gravity and inertia by proposing that all gravitational fields be inertial. He also had other objections to classical physics: Lorentz's electromagnetic theory faced a dualism between discrete charged particles governed by Newton's laws and a continuous field that respected Maxwell's equations; relativity applies to Lorentz mechanics, but not to electrodynamics; the idea of absolute space (there is a privileged inertial framework), although its elimination does not influence classical mechanics.

Einstein appreciated, on the principle of relativity, its universality and its unifying role for mechanics and electrodynamics, this being the first principle used to develop its general theory of relativity. The second principle is that of light but, epistemologically, Einstein's second starting point in developing the general theory of relativity was not the principle of light, but the idea that Maxwell's equations are covariant and express a law of nature. The principle of light results from this idea, as does the principle of relativity, according to Zahar. [246]

Basically, Einstein had the choice of developing general relativity based on Maxwell's equations or Newton's laws. But in the dualism between particles and fields, all attempts at mechanical explanation of field behavior failed.

According to Zahar, no "crucial" experiment could have been conceived between Lorentz theory and Einstein's in 1905. But Minkowski and Planck abandon the classical program for special relativity, contrary to Kuhn's methodology. Moreover, Einstein was at that time a quasi-stranger, while Lorentz was a recognized authority. And Lorentz's theory was very clear from that of Einstein, which involved a major overhaul of the notions of space and time. Also, there were no anomalies that Einstein's theory would have solved better than Lorentz. In addition, Lorentz himself was finally convinced of the new perspective[247]. Whittaker[248] regards Lorentz and Poincaré as the true authors of special relativity, Einstein's credit being that of developing general relativity. Thus, Lorentz's etheric program was not defeated by the program of relativity but was practically developed in it. Zahar contradicts it, based on the fact that the two programs have very different heuristics. [249]

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[246] Zahar.

[247] Zahar.

[248] Edmund Taylor Whittaker, *A History of the Theories of Aether and Electricity* (Harper, 1960).

[249] Zahar, "Why Did Einstein's Programme Supersede Lorentz's?"

In the case of the Copernican revolution, the Platonic program for modeling the phenomenon through circular and spherical movements was initially successful, with each planet on a real physical crystalline sphere in axial rotation. It was later discovered that the distance between the earth and the planets varies, so that additional assumptions were made through eccentricities, epicycles and screens, to explain the new observations. When one tried to determine the motion of the celestial bodies towards the earth due to the uneven movements, there appeared differences between phenomena and mathematical methods that allowed only circular motions with the earth in the center of the universe. Copernicus, although he considered the Sun fixed, did not resolve this difference, still using epicycles. Kepler was the one who abolished the epicycles and found the laws of the elliptical motion of the planets with the Sun in a focus. Lorentz used the Galilean transformations, eliminating the epicycles but giving the etheric frame a privileged status. Just as Copernicus was aware of the idealization of his planetary model, Lorentz later understood that the effective coordinates, not the Galilean ones, are the quantities measured in the moving frame. Einstein gave up the Galilean transformations and identified the actual coordinates measured as the only real ones. Einstein's heuristics are based on a general requirement of Lorentz covariance for all physical laws, requiring the renunciation of Galilean transformations.

Zahar claims that Lorentz and Einstein used different heuristics in their research programs[250]. The etheric program was practically replaced by a program with greater heuristic power, which is why Planck abandoned Lorentz's theory in favor of Einstein just before Einstein's program became progressively empirical. The two theories are similar in terms of the "hard core" (negative heuristics) and can be considered as bifurcated programs. The difference between the positive heuristics was what led to the choice of scientists of Einstein's program at the beginning of the last century. Lorentz's positive heuristic consisted in providing the ether with properties that would explain many physical phenomena, including the electromagnetic field and Newtonian mechanics. This approach allowed a rapid development of Lorentz's program, but by the end of the 19th century heuristics had reached a saturation point. A number of degenerate programmes have emerged as mechanical models to resolve ether anomalies. To explain certain electromagnetic

[250] Zahar.

phenomena, Lorentz introduced the postulate of the ether at rest, but subsequent calculations contradicted this hypothesis.

The differences between Lorentz and Einstein's views were metaphysical: Lorentz believed that the universe respects intelligible laws (there is a propagating environment, an absolute "now", etc.), while for Einstein the universe is governed by coherent mathematical principles. (covariant laws, etc.) Zahar states that all major scientific revolutions were accompanied by an increase in mathematical coherence accompanied by a (temporary) loss of intelligibility (Newtonian astronomy is more coherent than Ptolemaic, but remote action was not accepted before Newton, then accepted at the end of the 18th century and again rejected after Maxwell). In Lorentz's research programme, the behavior of the electromagnetic field had come to dictate the properties of the ether, even improbable (for example, resting ether and acting by zero net forces). Basically, Lorentz's heuristic strategy has reversed: instead to deduce a theory from the ether considered fundamental, he reaches the ether based on the field. Einstein's heuristics were based on the requirement that all physical laws be Lorentz-covariant (to take the same form regardless of the frame of reference), and classical law to emerge from the new law as a limit case.

In order to obtain a relativistic theory of gravity, Einstein maintained the principle of equivalence, decided to treat all coordinate systems equally and to impose a condition of general covariance on all laws. The empirical success of general relativity through the correct prediction of the behavior of Mercury's perihelion has proved crucial for the further development of the programme.

Since 1905, the program of relativity has proved to be heuristically superior compared to the classical one. But special relativity has failed to outperform the Lorentz program. Bucherer's experiment[251] confirmed both hypotheses, and Kaufmann's experiment[252] denied both. Before the emergence of general relativity, the scientific community spoke of Lorentz-Einstein's theory, considering them as equivalent from an observer's point of view. General relativity has succeeded empirically replacing the Lorentz program by successfully explaining the "abnormal precession"

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[251] A. H. Bucherer, "Die Experimentelle Bestätigung Des Relativitätsprinzips," *Annalen Der Physik* 333 (1909): 513–36, https://doi.org/10.1002/andp.19093330305.

[252] W. Kaufmann, "Über Die Konstitution Des Elektrons," *Annalen Der Physik* 324 (1906): 949, https://doi.org/10.1002/andp.19063240303.

of Mercury's perihelion. This prediction was an empirical progress. In addition, general relativity has been found to be more falsifiable.

Nicholas Maxwell proposes also a method for the unification of two "mutually contradictory principles." [253] The method proposed by him for establishing the unified theory is as follows: from the two theories, the common elements that do not contradict are chosen, the contradictory elements are removed, and on this basis the new theory is developed. He does not sufficiently exemplify, in my opinion, what would be those common elements in the case of classical mechanics and classical electrodynamics, considered by all scientists as two contradictory theories from which the special theory of relativity was born. Also, Nicholas Maxwell imposes the existence of a "crucial assumption", whose falsifiability allows the acceptance of the theory as a result of a method of discovery based on empirical purpose. In today's physics, there are countless examples of unifying theories (such as the M theory proposing the union of all fundamental forces, including gravity) that have not set out to become falsifiable by "crucial assumptions".

General relativity is the result of Einstein's unification of Newton's theory of universal gravity (with the instantaneous action at a distance of the gravity) and the special theory of relativity (with the limitation of any speed to the constant value of the speed of light, *c*). These two principles contradict each other. So, according to Maxwell, it should be removed from the future unifying theory.

2.2 Proliferation of post-Einsteinian gravitational theories

Right after the elaboration and success of general relativity (GR), alternative theories for gravity began to appear, which can fall into four broad categories: [254]

- Bifurcated theories (with the Lakatosian[255] hard core identical or very similar to that of general relativity) or directly related to general relativity but not bifurcated, such as Cartan, Brans-Dicke and Rosen bimetric theories.
- Unifying theories that try to unify quantum mechanics with general relativity (theories of quantum gravity), such as loop quantum gravity.

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[253] Maxwell, *Karl Popper, Science and Enlightenment*.

[254] Timothy Clifton et al., “Modified Gravity and Cosmology,” *Physics Reports* 513, no. 1–3 (March 2012): 1–189, https://doi.org/10.1016/j.physrep.2012.01.001.

[255] Lakatos, *The Methodology of Scientific Research Programmes*.

- Unifying theories that try to unify gravity with other forces, such as Kaluza-Klein.
- Unifying theories that try to unify several theories simultaneously, such as the M theory.

In developing these theories, many different strategies (positive heuristics) have been tried, by adding new hypotheses to GR, using a spacetime for which the universe is static, hypotheses that eliminate gravitational singularities, etc. In this competition, so far has won the Einstein's GR theory, proving by far a greater heuristic power than his rivals. Some of these theories have been abandoned, others are still being developed by various communities of researchers, trying to eliminate the anomalies found in GR, or to expand GR by bifurcation or as unifying theories.

After 1980, when the scientific community agreed that GR is confirmed, generally, only theories that include GR as a particular case have survived. Particular attention began to be paid to theories of quantum gravity, in particular string theory. Most of the newer non-quantum gravity theories try to solve various cosmological anomalies, such as cosmic inflation, dark matter, dark energy, and so on. The proliferation of GR anomalies lately, including in the Pioneer case, has led to a revival of alternatives to this theory.

Most of the theories in the first category listed above include a Lagrangian density, an "action" (which guarantees the existence of conservation laws, and whose gravitational component is deduced from the Lagrangian density by integration) [256], and a metric.

Metric theories can be classified into (from the simplest to the most complex):

- Theories using scalar fields (including conformally flat theories and stratified theories with conformally flat space slices)
- Quasilinear theories (including linear fixed gauge)
- Tensor theories
- Scalar-tensor theories
- Vector-tensor theories
- Bimetric theories
- Other metric theories

More important *non-metric theories* include

- Belinfante-Swihart
- Einstein-Cartan theory
- Kustaanheimo
- Teleparallelism

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[256] Franz Mandl and Graham Shaw, *Lagrangian Field Theory, in Quantum Field Theory* (John Wiley & Sons, 2013), 25–38.

- Gravity based on gauge theory

Some of these theories are based on Mach's principle (the frame of reference comes from the distribution of matter in the universe[257], considered to be an intermediary between Newton (absolute space and time) and Einstein (there is no absolute frame of reference). Experimental evidence shows that the Mach's principle is wrong, but the related theories were not entirely excluded.

In order to verify and classify all these theories, specific tests have been developed, based on self-consistency (among the non-metric theories includes the elimination of theories that allow tachyons, ghost poles and higher order poles, and those that have problems with the behavior at infinite), and on completeness (to allow the analysis of the result of each experiment of interest). For example, any theory that cannot predict from the first principles the motion of the planets or the behavior of atomic clocks is considered incomplete.

Three *tests* are considered "classics" for the ability of gravity theories to manage relativistic effects:

- gravitational redshift
- gravitational lenses (around the Sun)
- abnormal advance of the perihelion of the planets.

To these tests was added, in 1964, the fourth test, called the Shapiro delay. Each theory should confirm these tests.

The *Einstein equivalence principle* (EEP), which is also tested for relativistic theories of gravity, has three components:

- uniqueness of the free fall (weak equivalence principle): the inertial mass is equal to the gravitational mass;
- Lorentz invariance: in the absence of gravitational effects, the speed of light is constant;
- local position invariance: the result of any local non-gravitational experiment is independent of where and when it is performed.

Schiff's conjecture states that any complete, self-consistent theory of gravity that checks the principle of weak equivalence necessarily also checks the principle of Einstein's equivalence (if the theory has a complete conservation of energy).

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[257] Alfred North Whitehead, *The Principle Of Relativity With Applications To Physical Science* (Whitefish, Mont.: Kessinger Publishing, LLC, 2008).

Metric theories satisfy the EEP. Only some non-metric theories satisfy the EEP.

The main general non-quantum post-relativity theories are Brans-Dicke theory, Fifth force, and Geometrodynamics.

Brans-Dicke theory is a scalar-tensor theory, in which gravitational interaction is mediated by a scalar field, and by the tensor field of general relativity[258]. The theory is considered to be in general agreement with the observations. The source of the gravitational field is, as in RG, the stress-energy tensor or the matter tensor. In Brans-Dicke theory, in addition to metrics (a rank two tensor field), there is a scalar field that changes the actual gravitational constant depending on the location (this is a key feature of the theory, being part of the Lakatosian hard core). The Brans-Dick theory, compared to GR, admits several solutions. It predicts the deflection of light and the precession of the perihelion of the planets, and general relativity can be derived from the Brans-Dicke theory as a particular case, but Faraoni argues that this is not valid in all situations allowed by the theory[259], and some physicists claim that it does not meet the powerful principle of equivalence.

The fifth force is a theory that involves, in addition to gravitational, electromagnetic, strong nuclear and weak nuclear forces, a fifth force to explain various anomalous observations that do not match existing theories. One hypothesis of this theory is that dark matter could be related to an unknown fundamental force. Others speculate that a form of dark energy called quintessence might be a fifth force[260]. Such a new, weak, fundamental force is difficult to test. In the late 1980s, some researchers[261] reported that they discovered this force while re-analyzing Loránd Eötvös results from the turn of the century, but other experiments failed to replicate this result. One of the tests that can be undertaken to prove the theory is supposed to be based on the strong principle of equivalence (the fifth force would manifest through an effect on the orbits of the solar system, called the Nordtvedt effect) with Lunar Laser Ranging and very long baseline interferometry. Other tests may consider additional dimensions; the mantle of the earth as a giant particle detector,

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[258] C. Brans and R. H. Dicke, "Mach's Principle and a Relativistic Theory of Gravitation," *Physical Review* 124, no. 3 (November 1, 1961): 925–935, https://doi.org/10.1103/PhysRev.124.925.

[259] Valerio Faraoni, "Illusions of General Relativity in Brans-Dicke Gravity," *Physical Review D* 59, no. 8 (March 22, 1999): 084021, https://doi.org/10.1103/PhysRevD.59.084021.

[260] Cicoli, Pedro, and Tasinato, "Natural Quintessence in String Theory," 44.

[261] E. Fischbach et al., "Reanalysis of the Eotvos Experiment," *Physical Review Letters* 56 (January 1, 1986): 3–6, https://doi.org/10.1103/PhysRevLett.56.3.

focusing on geoelectrons[262]; pulsation rate of cepheid variable stars in 25 galaxies[263]; and so on. Various additional hypotheses have been proposed in recent years to strengthen the theory, but no results have been conclusive so far.

Geometrodynamics is an attempt to describe spacetime and associated phenomena in terms of geometry. This is a unifying theory, trying to unify the fundamental forces and reformulate the general relativity. It's a theory initiated by Einstein but still active. In a way, the term geometrodynamics is synonymous with general relativity, in which case it is more precisely referred to as Einstein's geometrodynamics to denote the initial formulation of the value of general relativity. John Wheeler promoted this theory in the 1960s, trying to reduce physics to geometry in a fundamental way, with a dynamic geometry with a variable curve over time. Basically, Wheeler tried to integrate three concepts: mass without mass, charge without charge, field without field. [264]

2.3 Post-Newtonian parameterized formalism (PPN)

In the field of experimental gravity, one of the important applications is formalism. For the evaluation of gravity models, several sets of tests have been proposed. Post-Newtonian formalism considers approximations of Einstein's gravity equations by the lowest order deviations from Newton's law for weak fields. Higher terms can be added to increase accuracy. At the limit, post-Newtonian expansion is reduced to Newton's law of gravity. The post-Newtonian parametric formalism (PPN) details the parameters that differentiate the theories of gravity, in the weak gravitational field and speeds much lower than the speed of light. PPN can be applied to all gravity metric theories in which all bodies satisfy the Einstein equivalence principle (EEP). The speed of light remains constant in the PPN formalism and it is assumed that the metric tensor is always symmetrical. PPN is used to compare and classify alternative metrics of gravity. With the help of this formalism, many theories previously considered viable have been eliminated.

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[262] Jacob Aron, "Earth's Mantle Helps Hunt for Fifth Force of Nature," New Scientist, 2013, https://www.newscientist.com/article/dn23202-earths-mantle-helps-hunt-for-fifth-force-of-nature/.

[263] Bhuvnesh Jain, Vinu Vikram, and Jeremy Sakstein, "Astrophysical Tests of Modified Gravity: Constraints from Distance Indicators in the Nearby Universe," *The Astrophysical Journal* 779, no. 1 (November 25, 2013): 39, https://doi.org/10.1088/0004-637X/779/1/39.

[264] John A. Wheeler, "On the Nature of Quantum Geometrodynamics," *Annals of Physics* 2, no. 6 (December 1, 1957): 604–14, https://doi.org/10.1016/0003-4916(57)90050-7.

In *beta-delta notation*, the behavior of the weak gravitational field in general relativity is completely characterized by ten post-Newtonian parameters. In the notation of Will's[265], Misner et al. [266], they have the following values:

- γ: g_{ij} space curvature produced by unit rest mass
- β: nonlinearity in superposition law for gravity g_{00}
- β_1: gravity produced by unit kinetic energy $\rho_0 v^2/2$
- β_2: gravity produced by unit gravitational potential energy ρ_0/U
- β_3: gravity produced by unit internal energy $\rho_0\Pi$
- β_4: gravity produced by unit pressure p
- ζ: difference between radial and transverse kinetic energy on gravity
- η: difference between radial and transverse stresses on gravity
- Δ_1: dragging of inertial frames g_{0j} produced by unit momentum $\rho_0 v$
- Δ_2: difference between radial and transverse momentum on dragging of inertial frames

Here, $g_{\mu\nu}$ is the symmetrical 4x4 metric tensor with indices μ and ν taking values between 0 and 3. An index 0 will indicate the time direction and the indices i and j with values from 1 to 3 will indicate the spatial directions. In general relativity, the values of these parameters are chosen so that within the limits of velocity and small mass they coincide with Newton's law of gravity, to ensure the conservation of energy, mass, momentum and angular momentum; and to ensure the independence of the equations from the frame of reference.

For general relativity, $\gamma = \beta = \beta1 = \beta2 = \beta3 = \beta4 = \Delta1 = \Delta2 = 1$ and $\zeta = \eta = 0$.

In the most recent *alpha-zeta notation* of Will & Nordtvedt[267] and Will[268], a different set of ten PPN parameters is used:

- $\gamma = \gamma$
- $\beta = \beta$

[265] C. M. Will, "Theoretical Frameworks For Testing Relativistic Gravity. Ii. Parametrized Post-Newtonian Hydrodynamics, And The Nordtvedt Effect.," *Astrophys. J. 163: 611-28(1 Feb 1971).*, January 1, 1971, 163, 611–28, https://doi.org/10.1086/150804.

[266] Misner, Thorne, and Wheeler, *Gravitation*.

[267] Kenneth Nordtvedt Jr. and Clifford M. Will, "Conservation Laws and Preferred Frames in Relativistic Gravity. II. Experimental Evidence to Rule Out Preferred-Frame Theories of Gravity," *The Astrophysical Journal* 177 (November 1, 1972): 177, 757, https://doi.org/10.1086/151755.

[268] Clifford M. Will, "The Confrontation between General Relativity and Experiment," *Living Reviews in Relativity* 17, no. 1 (December 2014): 4, https://doi.org/10.12942/lrr-2014-4.

- $\alpha_1 = 7\Delta_1 + \Delta_2 - 4\gamma - 4$
- $\alpha_2 = \Delta_2 + \zeta - 1$
- $\alpha_3 = 4\beta_1 - 2\gamma - 2 - \zeta$
- $\zeta_1 = \zeta$
- $\zeta_2 = 2\beta + 2\beta 2 - 3\gamma - 1$
- $\zeta_3 = \beta 3 - 1$
- $\zeta_4 = \beta_4 - \gamma$
- ξ is calculated from $3\eta = 12\beta - 3\gamma - 9 + 10\xi - 3\alpha_1 + 2\alpha_2 - 2\zeta_1 - \zeta_2$

Parameters γ and β are used to describe "classical" GR tests and are the most important, the only non-zero parameters in GR and scalar-tensor gravity. Parameter ξ is non-zero in any theory of gravity that predicts the effects of preferred location; α_1, α_2, α_3 measures whether or not the theory predicts effects of the preferred post-Newtonian framework; α_3, ζ_1, ζ_2, ζ_3, ζ_4 measure whether or not the theory predicts violation of global conservation laws for total momentum.

In this notation, general relativity has the parameters PPN $\gamma = \beta = 1$ and $\alpha_1 = \alpha_2 = \alpha_3 = \zeta_1 = \zeta_2 = \zeta_3 = \zeta_4 = \xi = 0$

There is a mathematical relationship between the metric, the metric potential, and the PPN parameters for this notation, with ten metric potentials (one for each PPN parameter) to ensure a unique solution. The methodology of applying the PPN formalism to the alternative theories of gravity is a nine-step process[269]. The limits of PPN parameters[270] are determined from experimental tests.

The only gravitational field entering the equations of motion is the metric *g*. Other fields will only contribute to the generation of spacetime curvature associated with the metric. Matter can create these fields, and they together with matter can generate metrics, but they cannot act directly on matter. Matter responds only to the metric[271]. It turns out that the metric and the equations of motion for matter are primary entities for calculating observable effects, and the only distinction between two metric theories is the particular way in which matter and possibly other gravitational fields generate the metric.

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[269] Will, *Theory and Experiment in Gravitational Physics, Revised Edition*.

[270] Will, "The Confrontation between General Relativity and Experiment."

[271] Will.

At the post-Newtonian limit (slow motion, weak field), comparing a theory with gravitational experiments and theories between them is accurate enough for most tests, especially those involving the solar system. The differences appear in the numerical values of the coefficients in front of the metric potential (parameters in the PPN formalism).

Carlton Morris Caves concluded that laboratory experiments for investigating nonlinear characteristics of the gravitational field, as well as laboratory measurements of gravity produced by internal energy, are difficult and inconclusive[272]. The most accessible laboratory experiments from the point of view of post-Newtonian effects are the effects of preferred frame and preferred orientation (they can be modulated by rotating the entire laboratory apparatus relative to the inertial space) and the magnetic gravity effects (the effects associated with components of metric *g*: dragging inertial frames through rotating bodies, Lens-Thirring gyroscopic precession, gravitational accelerations produced by spin-spin interactions of rotating bodies, and gravitational accelerations due to spin-orbit coupling). Magnetic effects are much more sensitive to the direction of rotation or to the movement of a source or laboratory detector than other laboratory experiments. As a source, a rapidly rotating, symmetrical axial body can be used, and its angular velocity can be slowly modulated. [273]

2.4 Tests of general relativity and post-Einsteinian theories

Clifford M. Will describes, in *Theory and Experiment in Gravitational Physics*, [274] the emergence of a new era for general relativity, testing and checking at very high levels of accuracy.

In 1959, scientists at Lincoln Laboratories in Massachusetts bombarded the planet Venus with radio waves from Earth, hoping to detect the echo of reflected waves. They did not detect any echoes. On further analysis, they detected an echo on September 14, this being the first radar echo recorded on a planet.

In 1960, astronomers Thomas Matthews and Allan Sandage and colleagues at Mount Palomar used a telescope to record the star field around the 3C48 radio source on a photo plate. They were expecting to find a group of galaxies, but at the exact location of the radio source an object was

[272] Caves, "Theoretical Investigations of Experimental Gravitation."

[273] Caves.

[274] Will, *Theory and Experiment in Gravitational Physics, Revised Edition*.

observed as a star but with an unusual spectrum and variable brightness with the frequency of 15 minutes[275]. This was the first observed quasar. [276]

The Pound-Rebka experiment (1960) verified the principle of equivalence and gravity redshift and demonstrated the utility of quantum technology (atomic clocks, laser measurements, superconducting gravimeters, gravitational wave detectors) in high precision gravitational experiments. [277]

Radiations recorded from Venus made the solar system a laboratory for testing relativistic gravity[278]. The interplanetary space program developed in the early 1960s, and the discovery in 1964 of the relativistic effect of delay[279], offered new and accurate tests of general relativity. Until 1974, the solar system was the only way for high accuracy tests of general relativity.

In developing general relativity, Einstein was led by theoretical criteria of elegance and simplicity. His theory initially encountered "three classic tests": perihelion precession of Mercury's orbit, deflection of light by the Sun, and gravitational redshift of light.

At the end of the 1950s it was suggested that the gravitational redshift of light is not, however, a real test of general relativity. It is a pure consequence of the principle of equivalence and does not test the field equations of gravitational theory. Schiff suggested that the Eotvos experiment is more accurate than the gravitational redshift of light, which it replaced as importance, the Eotvos experiment verifying to what extent the bodies of different composition have the same acceleration. [280]

Subsequently, other tests for general relativity were proposed, such as the Lense-Thirring effect, the orbital disturbance due to the rotation of a body, and the Sitter effect, a secular movement of

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[275] Thomas A. Matthews and Allan R. Sandage, "Optical Identification of 3C 48, 3C 196, and 3C 286 with Stellar Objects.," *The Astrophysical Journal* 138 (July 1, 1963): 30–56, https://doi.org/10.1086/147615.

[276] Will, *Theory and Experiment in Gravitational Physics, Revised Edition*.

[277] R. V. Pound and G. A. Rebka, "Apparent Weight of Photons," *Physical Review Letters* 4, no. 7 (April 1, 1960): 337–41, https://doi.org/10.1103/PhysRevLett.4.337.

[278] W. B. Smith, "Radar Observations of Venus, 1961 and 1959," *The Astronomical Journal* 68 (February 1, 1963): 15–21, https://doi.org/10.1086/108904.

[279] Irwin I. Shapiro, "Fourth Test of General Relativity," *Physical Review Letters* 13, no. 26 (December 28, 1964): 789–91, https://doi.org/10.1103/PhysRevLett.13.789.

[280] L. I. Schiff, "On Experimental Tests of the General Theory of Relativity," *American Journal of Physics* 28, no. 4 (April 1, 1960): 340–43, https://doi.org/10.1119/1.1935800.

the perigee and the node of the orbit of the moon, [281] [282] but the perspectives for detecting them were still weak. [283]

Another test area for observing general relativity was cosmology, foretelling the primordial explosion called the "Big Bang" and the subsequent expansion of the Unive, but by the end of the 1950s cosmological observations could not distinguish between different theories of gravity. [284]

Meanwhile, a "proliferation" of competing alternative gravity theories of general relativity has appeared. By 1960 there were at least 25 such alternative theories. [285]

According to Will, by 1960 general relativity was empirically supported by a moderate accuracy test (change of perihelion, about 1%), a low accuracy test (light distortion, about 50%), an inconclusive test (gravitational redshift) and cosmological observations that could not distinguish between different theories. This was what Lakatos called the "stationary period". Due to its limited experimental confirmations, general relativity was even removed from basic physics. [286]

The period from 1960 to 1980 was the period of maturity of general relativity: new high-precision test methods were developed that included new tests, such as gyroscopic precession, light delay and the "Nordtvedt effect" in the moon motion, including astrophysical observations and artificial satellites.

Due to the proliferation of alternative theories, the best theoretical framework was needed to compare the checks of the different experiments, to classify the theories and to compare their predictions with the results of the experiments in a systematic way.

Year	**Experimental or observational results**	**Theoretical results**
1960	Hughes-Drever mass anisotropy	Penrose's work on spinors

[281] Josef Lense and Hans Thirring, "Über Den Einfluß Der Eigenrotation Der Zentralkörper Auf Die Bewegung Der Planeten Und Monde Nach Der Einsteinschen Gravitationstheorie," *Physikalische Zeitschrift* 19 (1918): 156–63, http://adsabs.harvard.edu/abs/1918PhyZ...19..156L.

[282] W. de Sitter, "On Einstein's Theory of Gravitation and Its Astronomical Consequences. Second Paper," *Monthly Notices of the Royal Astronomical Society* 77 (December 1, 1916): 77, 155–84, https://doi.org/10.1093/mnras/77.2.155.

[283] Will, *Theory and Experiment in Gravitational Physics, Revised Edition*.

[284] Whitrow and Morduch, "Relativistic Theories of Gravitation," chap. 14.

[285] C. DeWitt, *Experimental Relativity, in Relativity Groups and Topology. Lectures Delivered at Les Houches During the 1963 Session of the Summer School of Theoretical Physics*, Second Printing edition (Gordon & Breach, 1965), 165–313.

[286] Will, *Theory and Experiment in Gravitational Physics, Revised Edition*.

	Pound-Rebka experiment of gravitational redshift	Gyroscopic precision (Schiff) Brans-Dicke theory
1962	Discovery of non-solar X-ray sources	Bondi formula for mass loss
	Discovery of the quasar redshift	Discovery of the Kerr metric
1964	Eotvos Experiment, Princeton	Delay in time of light (Shapiro)
	Pound-Snider experiment of gravitational redshift Discovery of the 3K microwave background	Singularity theorems in general relativity
1966	Detection of solar flattening Pulsar discovery	Production of elements in the Big Bang
1968	Planetary radar measurements for time delay Launch of *Mariners* 6 and 7 Acquisition of lunar laser echo First radio deflection measurements	Nordtvedt effect and early PPN framework
1970	CygXl: a black hole candidate *Mariners 6* and 7 time-delay measurements	Preferred frame effects Refined PPN framework Increasing the domain of black holes in general relativity
1972	Eotvos Experiment, Moscow	
1974	Discovery of binary pulsars	Quantum evaporation of black holes Dipolar gravitational radiation in alternative theories
1976	Experiments of gravitational ewsahift with rockets Moon test of the Nordtvedt effect Time delay results obtained with *Mariner 9* and *Viking*	
1978	Measurements of decreasing orbital period of binary pulsar SS 433	
1980	Discovery of gravitational lenses	

Table 2.2 A chronology of the tests for verifying the theory of general relativity between 1960-80. Source: Clifford M. Will, *Theory and Experiment in Gravitational Physics*[287]

Robert Dicke performed several high-precision nullity experiments to confirm gravity theories. [288] Dicke concludes that gravitational experiments can be divided into two classes:

1. one that tests the *basis of gravity theory* (eg, the principle of equivalence): the Eotvos experiment, the Hughes-Drever experiment, the gravitational redshift experiment, etc.), verifying that gravity is a curved spacetime phenomenon (described by a "metric theory" of gravity). General relativity and Brans-Dick's theory are examples of metric theories of gravity.
2. a second class that tests the *metric theories of gravity*: the parameterized post-Newtonian formalism, or PPN, initiated by Kenneth Nordtvedt, Jr., [289] and expanded and improved by Will. [290] PPN takes into account low velocities and weak fields (post-Newtonian limit) of metric theories, based on a set of 10 real parameters. PPN was used to analyze the gravitational experiments of the solar system, to discover and analyze new tests of gravity theory, such as the Nordtvedt effect, the preferred frame effects and the preferred location effects, and to analyze and classify alternative metric theories of gravity becoming the standard theoretical tool for these experiments, searches and studies.

By the mid-1970s, many alternative theories of gravity were upheld by experiments at the solar system level, but not at the cosmological level. In 1974, Joseph Taylor and Russell Hulse discovered the binary pulsar, [291] whose extremely stable pulses were monitored radiotelescopically, allowing accurate measurement of astrophysical parameters. In 1978 the rate of change of the orbital period of the system was measured, which was confirmed by general relativity but not by most alternative theories.

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[287] Will.

[288] DeWitt, *Experimental Relativity, in Relativity Groups and Topology. Lectures Delivered at Les Houches During the 1963 Session of the Summer School of Theoretical Physics*, 165–313.

[289] Kenneth Nordtvedt, "Equivalence Principle for Massive Bodies. II. Theory," *Physical Review* 169, no. 5 (May 25, 1968): 1017–25, https://doi.org/10.1103/PhysRev.169.1017.

[290] Will, "Theoretical Frameworks For Testing Relativistic Gravity. Ii. Parametrized Post-Newtonian Hydrodynamics, And The Nordtvedt Effect.," 163, 611–28.

[291] R. A. Hulse and J. H. Taylor, "Discovery of a Pulsar in a Binary System," *The Astrophysical Journal Letters* 195 (January 1, 1975): L51-53, https://doi.org/10.1086/181708.

In the **Michelson-Morley experiment**, Michelson started from an experiment to test Fresnel and Stokes's contradictory theories about the influence of ether. [292] [293] Stokes initially believed that the two theories are observationally equivalent, both theories explaining the aberration of light. Michelson argued that his 1881 experiment was a crucial experiment that demonstrated Stokes' theory. Lorentz pointed out that Michelson "misinterpreted" the facts, and Michelson's calculations were wrong. Michelson, along with Morley, decided to repeat the experiment "at intervals of three months and thus avoid all uncertainty," [294] their conclusion rejecting Fresnel's explanation. Lorentz also questioned the new experiment: "the significance of the Michelson-Morley experiment lies rather in the fact that it can teach us something about the changes in the dimensions." In 1897 Michelson made a new experiment, concluding that the result of the experiment was an "improbable" one and decided that in 1887 he was wrong: Stokes' theory had to be rejected, and Fresnel's had to be accepted.

Fitzgerald, independent of Lorentz, produced a testable version that was rejected by Trouton, Rayleigh and Brace's experiments as it was theoretically progressive, but not empirical, Fitzgerald's theory being considered *ad-hoc* (that there is no independent (positive) evidence for it). [295] Einstein, ignoring these experiments, but stimulated by Mach's criticisms of Newtonian mechanics, arrived at a new progressive search program,[296] which "predicted" and explained the result of the Michelson-Morley experiment, but also predicted a huge range of undiscovered facts previously, that have obtained dramatic corroborations. Thus, only twenty-five years later, the Michelson-Morley experiment came to be seen as a crucial experiment, considered to be "the largest negative experiment in the history of science," [297] [298] demonstrating Lakatos's methodological tolerance.

In this context, a typical signal of the degeneration of a program is the proliferation of contradictory "facts". Using a false theory as an interpretive theory, one can obtain - without committing an

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[292] A Fresnel, "Lettre a Francois Arago Sur L'Influence Du Mouvement Terrestre Dans Quelques Phenomenes Optiques, in Annales de Chimie et de Physique - 98 Years Available - Gallica," 1818, https://gallica.bnf.fr/ark:/12148/cb343780820/date.r=Annales+de+chimie+et+de+physique.langEN.

[293] George Gabriel Stokes, *On Fresnel's Theory of the Aberration of Light* (London, 1846), 76–81.

[294] Lorentz, "Considerations on Gravitation."

[295] Joseph Larmor, *On the Ascertained Absence of Effects of Motion through the Aether, in Relation to the Constitution of Matter, and on the FitzGerald-Lorentz Hypothesis*, 1904, 624.

[296] Karl Raimund Popper, *The Logic of Scientific Discovery* (Psychology Press, 2002).

[297] J. D. Bernal, *Science in History J. D. Bernal*, 3rd edition (M.I.T Press, 1965).

[298] Lakatos, *The Methodology of Scientific Research Programmes*.

"experimental error" - contradictory factual proposals, inconsistent experimental results. [299] Michelson himself was frustrated by the inconsistency of "facts" resulting from his measurements.

Carlton Morris Caves proposes six possible laboratory experiments for non-Newtonian gravity: three use a torsion balance as a detector, and three use a high-sensitivity dielectric crystal. [300] Caves' idea is to demonstrate that technology will soon make possible a new class of experiments, exclusively laboratory tests. Caves' conclusion is that none of these experiments would be easy to do, because of the limitations of current technology. But most are feasible in the near future.

The strong effects of gravity are observed astrophysically (white dwarfs, neutron stars, black holes), in which case there are used, as experimental tests, the stability of the white dwarfs, the spin-down rate of the pulsars, the orbits of the binary pulsars, the existence of a black hole horizon, and so on.

Recently, a series of cosmological tests have been developed for theories of dark matter, using for constraints the rotation of the galaxy, the Tully-Fisher relation, the speed of rotation of dwarf galaxies, and gravitational lenses.

For the theories related to cosmic inflation, the most rigorous test is by measuring the size of the waves in the spectrum of cosmic microwave background radiation. [301]

For dark energy theories, the results of supernova brightness and age of the universe can be used as tests.

There are large differences in predictions between general relativity and classical physics, such as gravitational time dilation, gravitational lensing, gravitational redshift of light, and so on. And there are many relativistic theories of gravity, bifurcated or independent, but Einstein's general theory of relativity has upheld all predictions and is the simplest of such theories.

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[299] Lakatos.

[300] Caves, "Theoretical Investigations of Experimental Gravitation."

[301] The potential function, which is crucial for determining the dynamics of inflation, is simply postulated, and not derived from an underlying physical theory.

2.4.1 Tests proposed by Einstein

Einstein states, in *Relativity Theory - Special Relativity and General Relativity*, [302] that theories evolve through observation-based decalations, in the form of empirical laws, from which general laws are obtained. Intuition and deductive thinking play an important role in this process. After the initial stage, the investigator develops a thinking system guided by empirical data, logically constructed from fundamental assumptions (axioms). The "truth" of a theory results from its correlation with a large number of unique observations. For the same empirical data there may be several theories that differ.

Einstein speaks, in *Relativity Theory - Special Relativity and General Relativity*, of the confirmed prediction of general relativity for the motion of Mercury's perihelion, with a precision far greater than that predicted by Newton's law of universal gravity. [303]

Another confirmed prediction discussed by Einstein is the deflection of light by a gravitational field, which admits an experimental test by photographic recording of stars during a total solar eclipse, thus: stars in the vicinity of the Sun are photographed during a solar eclipse. The second photo of the same stars is taken when the sun is in a different position on the sky, a few months earlier or later. By comparing the positions of the stars, there should appear radially outward. The British Royal Society and the Royal Astronomical Society performed these tests on two expeditions, on Sobral (Brazil) and Principe Island (West Africa), confirming the prediction.

The *redshift of the spectral lines* was also predicted by the general relativity and discussed by Einstein in the same book, but when this book was written it had not yet been confirmed. Experiments were carried out on cyanogen bands, but the results were not conclusive during that period. Einstein proposed a verification of the average displacement of the lines towards the less refractory edge of the spectrum, through statistical investigations of the fixed stars.

In the second edition of the book *Relativity Theory - Special Relativity and General Relativity*, [304] Einstein states that in developing his theory for the "cosmological problem" he relied on two hypotheses:

1. There is an average density of matter throughout the space, which is everywhere the same and different from zero.

[302] Albert Einstein, *Teoria relativității: Relativitatea specială și relativitatea generală* (Nicolae Sfetcu, 2017), https://books.google.ro/books?id=aMtNDwAAQBAJ.

[303] Einstein.

[304] Einstein.

2. The size ("radius") of the space is independent of time.

The hypotheses proved to be in line with the general theory of relativity after the introduction of a hypothetical term in the field equations ("the cosmological term of the field equations"). Subsequently, Einstein came to the conclusion that one can keep the hypothesis (1) without appealing to that term, if one can renounce the hypothesis (2), respectively the initial equations of the field admit a solution in which the "radius of the world" depends on time (space expansion), thus allowing space expansion.

Hubble, through an investigation of extra-galactic nebulae, confirmed that the emitted spectral lines showed a redshift proportional to the distance between the nebulae.

For Einstein, the epistemological approach of thought experiments was of particular importance. These experiments, by the way they were developed, offered a new understanding of the discussed phenomena.

At sixteen, Einstein imagined what would happen if a *light beam is followed with the speed of light*. [305] The experiment is more difficult than it seems at first sight. Einstein was, at that time, searching for a "universal principle" that could lead to true knowledge. The experiment starts with the hypothetical situation of tracking a light wave at speed c. In this case of equal magnitude of speeds, the "surfer" will observe a "frozen" light wave, with light radiation as a static spatially oscillating electromagnetic field, and the properties of the wave would disappear. But this time-independent field does not exist, because it is not in line with Maxwell's theory. His conclusion would be that an observer can never reach the speed of light, the hypothesis being false by modus tollens in classical logic. Einstein said that this experiment contains a paradox in that the two assumptions included (the constancy of the speed of light and the independence of the laws (so also the constancy of the speed of light) of the choice of the inertial system (the principle of special relativity) are "mutually incompatible (despite the fact that both, taken separately, are based on experience)".

In September 1905, Einstein attempted to extend the principle of relativity to accelerated reference systems by introducing a new and powerful physical principle in 1907, the "principle of equivalence" (the laws of physics take the same form in a uniform system of accelerating coordinates as in a system which is at rest relative to a homogeneous gravitational field), with a very high heuristic value. [306] He argued this principle through the "*elevator thought experiment*",

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[305] Einstein, "Autobiographische Skizze," 9–17.

[306] Abraham Pais, *Subtle Is the Lord: The Science and the Life of Albert Einstein* (Oxford ; New York: Oxford University Press, 2005), 179–80.

sometimes considered Einstein's most important thought experiment. Einstein assumes an accelerated frame of reference with a constant acceleration in the x-direction, and a second frame at rest in a homogeneous gravitational field that gives all objects an acceleration in the same x-direction. Observationally, there is no distinction between the two frames. All bodies are accelerated in the same gravitational field. Thus, the principle of equivalence allows a homogeneous gravitational field to be replaced by a uniformly accelerated reference system. This hypothesis of the exact physical equivalence of the two frameworks has two important theoretical consequences: we cannot speak of an absolute acceleration of the reference system, and the equal fall of all bodies in a gravitational field.

2.4.2 Tests of post-Einsteinian theories

With the help of PPN formalism, gravity theories are confronted with the results of experiments in the solar system. The γ parameter in this formalism highlights the light deflection and the light delay. By calculations according to PPN, light deflection is obtained with respect to local straight lines, compared to rigid rods; due to the curvature of space around the Sun, determined by the parameter γ, the straight local lines are bent relative to the asymptotic straight lines away from the Sun. The development of very-long-baseline radio interferometry (VLBI) has improved the measurement of light deformation, allowing transcontinental and intercontinental VLBI observations of quasars and radio galaxies to monitor the rotation of the Earth[307]. Hipparcos optical astrometry satellite has led to improved performance. [308]

The *light delay* tests are based on a radar signal sent over the solar system along the Sun to a planet or satellite, and upon returning to Earth it suffers an additional non-Newtonian delay. Irwin Shapiro discovered this effect in 1964. Targets used include planets like Mercury or Venus, as passive radar signals (passive radar), and artificial satellites, such as Mariner 6 and 7, Voyager 2, Viking Mars, and the spacecraft. Cassini to Saturn, used as active transmitters of radar signals (active radar) [309]. Kopeikin suggested, in 2001, to measure the delay of light coming from a quasar when passing through the planet Jupiter[310], thus measuring the speed of gravitational interaction. In 2002, precise

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[307] S. S. Shapiro et al., "Measurement of the Solar Gravitational Deflection of Radio Waves Using Geodetic Very-Long-Baseline Interferometry Data, 1979--1999," *Physical Review Letters* 92, no. 12 (March 26, 2004): 121101, https://doi.org/10.1103/PhysRevLett.92.121101.

[308] François Mignard and F. Arenou, "Determination of the Ppn Parameter with the Hipparcos Data," 1997.

[309] Will, "The Confrontation between General Relativity and Experiment."

[310] Sergei M. Kopeikin, "Testing the Relativistic Effect of the Propagation of Gravity by Very Long Baseline Interferometry," *The Astrophysical Journal* 556, no. 1 (2001): L1–5,

measurements of the Shapiro delay[311] were made. But several authors have pointed out that this effect does not depend on the speed of gravity propagation, but only on the speed of light. [312]

Explaining the *anomalies of Mercury's orbit* has long been an unresolved issue half a century since Le Verrier's announcement in 1859. Several *ad-hoc* hypotheses have been tested to explain this inconsistency with the theory, including the existence of a new planet Vulcan near the Sun, a planetoid ring, a quadrupolar solar moment, and a deviation from the inverse square in the law of gravity, but all these assumptions failed. General relativity has naturally solved this problem.

Another class of experiments in the solar system for gravity verifies the *strong equivalence principle* (SEP). The SEP violation can be tested by violating the principle of low equivalence for gravitational bodies leading to disturbances in Earth-Moon orbit, preferred location and the preferred frame effects in locally measured gravitational constancy that could produce observable geophysical effects, and possible variations in gravity constant at cosmological level. [313]

Nordtvedt[314] also stated that many metric theories about gravity predict that massive bodies violate the *weak equivalence principle* (falling with different accelerations, depending on their gravitational energy). Dicke[315] notes that this effect (the "Nordtvedt effect") occurs in theories with a spatially variable gravitational constant, such as scalar-tensor gravity. The Nordtvedt effect is not noticed in the results of the laboratory experiments, for objects of laboratory dimensions. The data

https://www.academia.edu/18481905/TESTING_THE_RELATIVISTIC_EFFECT_OF_THE_PROPAGATION_OF_GRAVITY_BY_VERY_LONG_BASELINE_INTERFEROMETRY.

311 E. B. Fomalont and S. M. Kopeikin, "The Measurement of the Light Deflection from Jupiter: Experimental Results," *The Astrophysical Journal* 598, no. 1 (November 20, 2003): 704–11, https://doi.org/10.1086/378785.

312 Fintan D. Ryan, "Gravitational Waves from the Inspiral of a Compact Object into a Massive, Axisymmetric Body with Arbitrary Multipole Moments," *Physical Review D* 52, no. 10 (November 15, 1995): 5707–5718, https://doi.org/10.1103/PhysRevD.52.5707.

313 Will, "The Confrontation between General Relativity and Experiment."

314 Kenneth Nordtvedt, "Equivalence Principle for Massive Bodies. I. Phenomenology," ResearchGate, 1968, 1014–16, https://www.researchgate.net/publication/243706608_Equivalence_Principle_for_Massive_Bodies_I_Phenomenology.

315 P. G. Roll, R. Krotkov, and R. H. Dicke, "The Equivalence of Inertial and Passive Gravitational Mass," *Annals of Physics* 26 (February 1, 1964): 26, 442–517, https://doi.org/10.1016/0003-4916(64)90259-3.

analyzes did not find evidence, within the experimental uncertainty, for the Nordtvedt effect[316]. In the general relativity (GR), the Nordtvedt effect disappears[317].

Some theories violate strong equivalence principle by predicting that the results of local gravitational experiments may depend on the speed of the laboratory in relation to the average resting frame of the universe (the *effects of the preferred frame*, corresponding to PPN parameters α_1, α_2 and α_3) or to the location of the laboratory in relation to a gravitational body nearby (*preferred location effects*, some being governed by the PPN parameter ξ) [318]. The effects consist of variations and anisotropies in the locally measured value of the gravitational constant leading to the occurrence of abnormal values of the Earth and variations of the rate of rotation of the Earth, abnormal contributions to the orbital dynamics of the planets and the Moon, self-accelerations of the pulsars, and anomalous torques on the Sun which would determine the random orientation of its axis of rotation towards the ecliptic. [319]

Most theories that violate the strong equivalence principle predict a variation of the Newtonian gravitational constant measured locally, as a function of time.

Other tests to verify gravitational theories are based on *gravitomagnetism* (moving or rotating matter produces an additional gravitational field analogous to the magnetic field of a moving charge or magnetic dipole). The relativistic effects that can be measured involve the Earth-Moon system and the binary pulsar systems. [320]

Gyroscope experiments attempt to detect this frame dragging or Lense-Thirring precession effect. Another way to test the frame dragging is to measure the precession of the orbital planes of the

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[316] James G. Williams, Slava G. Turyshev, and Dale H. Boggs, "Progress in Lunar Laser Ranging Tests of Relativistic Gravity," *Physical Review Letters* 93, no. 26 (December 29, 2004): 261101, https://doi.org/10.1103/PhysRevLett.93.261101.

[317] Kenneth Nordtvedt, "The Relativistic Orbit Observables in Lunar Laser Ranging," ResearchGate, 1995, 51–62, 114, https://www.researchgate.net/publication/223758280_The_Relativistic_Orbit_Observables_in_Lunar_Laser_Ranging.

[318] Will, "The Confrontation between General Relativity and Experiment."

[319] Will, *Theory and Experiment in Gravitational Physics, Revised Edition*.

[320] K. Nordtvedt, "Gravitomagnetic Interaction and Laser Ranging to Earth Satellites," *Physical Review Letters* 61, no. 23 (December 5, 1988): 61, 2647–2649, https://doi.org/10.1103/PhysRevLett.61.2647.

bodies that rotate on a rotating body, measuring the relative precession[321]. The Earth-Moon system can be considered a "gyroscope", with the axis perpendicular to the orbital plane.

A non-zero value for any of the PPN parameters ζ_1, ζ_2, ζ_3, ζ_4 and α_3 would result in a violation of *conservation* of momentum or Newton's third law conservation in gravitational systems. A test for Newton's third law for gravitational systems was conducted in 1968 by Kreuzer, in which the gravitational attraction of fluorine and bromine was compared with accuracy. A planetary test was reported by Bartlett and van Buren[322]. Another consequence of the violation of conservation of momentum is a self-acceleration of the mass center of a stellar binary system.

The PPN formalism is no longer valid for strong gravitational fields (neutron stars, black holes), but in some cases post-Newtonian approximations can be made. Systems in strong gravitational fields are affected by the emission of gravitational radiation. For example, relativistic orbital motion (fusion or collapse of binary systems of neutron stars or black holes in the final phase) can be detected by a network of observers with gravitational interference waves with a laser interferometer, but the analysis is done using different techniques.

Only two parameters can be used in observing the generation of gravitational waves: the mass momentum and the angular momentum. Both quantities can be measured, in principle, by examining the external gravitational field of the bodies without any reference to their internal structure. Damour[323] calls this an "effacement" of the internal structure of the body.

Another way to verify the agreement with GR is by comparing the observed phase of the orbit with the theoretical phase of the model as a function of time.

The observation of gravitational waves can provide the means to test GR forecasts for polarization and wave velocity, for damping of gravitational radiation and for gravity of strong field, using gravity wave detectors with interferometer or resonant band. Broadband laser interferometers are particularly sensitive to the evolution of gravitational wave phases, which carry information about the evolution of the orbital phase.

[321] John C Ries et al., "Prospects for an Improved Lense-Thirring Test with SLR and the GRACE Gravity Mission," n.d., 7.

[322] D. F. Bartlett and Dave Van Buren, "Equivalence of Active and Passive Gravitational Mass Using the Moon," *Physical Review Letters* 57, no. 1 (July 7, 1986): 21–24, 57, https://doi.org/10.1103/PhysRevLett.57.21.

[323] T. Damour, "The Problem of Motion in Newtonian and Einsteinian Gravity.," in *Three Hundred Years of Gravitation*, 1987, 128–98, http://adsabs.harvard.edu/abs/1987thyg.book..128D.

Another possibility involves gravitational waves from a small mass orbiting and inspiralling into a spinning black hole. [324]

One of the problems considered by physicists in testing GR in the strong field is the possibility of contamination with an uncertain or complex physics. For example, a few seconds after the Big Bang, physics is relatively clear, but some theories of gravity fail to produce cosmologies that meet even the minimum requirements for big-bang nucleosynthesis or the properties of the cosmic microwave background[325]. But, within modest uncertainties, one can evaluate the quantitative difference between predictions and other theories under strong field conditions by comparing with observations. [326]

2.4.3 Classic tests

Albert Einstein proposed[327] three tests of general relativity, later named the **classic tests of general relativity**, in 1916:

1. the precession of the perihelion of Mercury's orbit
2. Sun light deflection
3. the gravitational redshift of the light.

For gravitational testing, the indirect effects of gravity are always used, usually particles that are influenced by gravity. In the presence of gravity, the particles move along curved geodesic lines. The sources of gravity that cause the curvature of spacetime are material bodies, depending on their mass. But in relativity the mass relates to the energy through the formula $E = mc^2$, and the energy with the momentum, according to the special relativity.

Einstein's equations give the relation between the spatial geometry and the properties of matter, using Riemannian geometry, the geometrical properties being described by a function called metric. In general relativity, the Riemann curvature metric and tensor take values defined at each point in spacetime. The content of matter defines a size called the energy-momentum tensor **T**. These quantities are related to each other by Einstein's equations, in which the Riemann curvature

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324 Ryan, "Gravitational Waves from the Inspiral of a Compact Object into a Massive, Axisymmetric Body with Arbitrary Multipole Moments," 52, 5707–5718.

325 Will, *Theory and Experiment in Gravitational Physics, Revised Edition*, chap. 13.2.

326 Clifford M. Will, *Was Einstein Right?: Putting General Relativity To The Test*, 2 edition (New York, NY: Basic Books, 1993).

327 Einstein, "The Foundation of the General Theory of Relativity," 769–822.

tensor and the metric define another geometric magnitude **G**, called the Einstein tensor, which describes some aspects of how spacetime is curved. Einstein's equation thus states that

$$\mathbf{G} = (8\pi G/c^4)\mathbf{T},$$

where **G** measures curvature and **T** measures the amount of matter. *G* is the gravitational constant of Newtonian gravity, and *c* is the speed of light in special relativity. Each of the quantities **G** and **T** are determined by several functions of the spacetime coordinates, thus resulting in more equations, in fact. Each solution of these equations describes a certain geometry of spacetime.

2.4.3.1 Precision of Mercury's perihelion

Urbain Le Verrier discovered, in 1859, that the orbital precession of the planet Mercury does not correspond to the theory: the ellipse of its orbit rotated (precessing) slightly faster, the difference being about 38 (subsequently corrected to 43) arcseconds of rotation per century[328]. Several *ad-hoc* hypotheses have been proposed, such as interplanetary dust, the Sun's unobserved oblation, a month undetected of Mercury, or a new planet called Vulcan. As no hypothesis has been confirmed, it was assumed that Newton's law of gravity is incorrect, trying to change the law, but new theories conflicted with other laws. In general relativity, this precession is explained by gravity mediated by the curvature of spacetime, in agreement with the observation.

2.4.3.2 Light deflection

The prediction of the light deflection was initially confirmed by observing the light of the stars (quasars) deviated while passing through the Sun[329]. In the PPN formalism, the light deflection is highlighted by the parameter γ, which encodes the influence of gravity on the geometry of spacetime. [330]

The deflection of light by a massive object has been predicted since 1784 by Henry Cavendish, and Johann Georg von Soldner in 1801, based on calculations from Newtonian gravity. This prediction was confirmed by Einstein in 1911, correcting the value of curvature in 1915 based on general

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[328] U. Le Verrier, *Lettre de M. Le Verrier à M. Faye sur la théorie de Mercure et sur le mouvement du périhélie de cette planète, in Comptes rendus hebdomadaires des séances de l'Académie des sciences* (Paris : Gauthier-Villars, 1859), 379–383, http://archive.org/details/comptesrendusheb49acad.

[329] Daniel Kennefick and Jürgen Renn, *Astronomers Test General Relativity: Light-Bending and the Solar Redshift, in Albert Einstein - Chief Engineer of the Universe: 100 Authors for Einstein Essays*, 2005, http://adsabs.harvard.edu/abs/2005alei.book.....R.

[330] Will, *Theory and Experiment in Gravitational Physics, Revised Edition*.

relativity[331]. The first observation of light deflection was made by Arthur Eddington during the total sun eclipse of May 29, 1919, simultaneously in Sobral, Brazil and São Tomé and Príncipe on the west coast of Africa[332].

The light deflection in the general relativistic case is observed only for a stationary observer who sees the path of light in relation to a gravitational body. Einstein understood, using EEP, that mass or even energy in Eisntein's formula would follow geodesic paths in spacetime, in relation to an observer at rest with the gravitational body. This result highlights the essence of EEP, showing that gravity and acceleration cannot be differentiated from one another, in a small region. Shapiro et al. [333] reported the sun's curvature of radio waves emitted by extragalactic radio sources, between 1979 and 1999.

2.4.3.3 Gravitational redshift

The gravitational redshift appears when the electromagnetic radiation from a source in a gravitational field is observed from a region with a higher gravitational potential. It is a direct result of the gravitational time dilation. In a test to confirm this effect, the reception of light must be located at a higher gravitational potential. If the observer has a gravitational potential lower than the source, he will notice a gravitational shift towards blue.

Einstein predicted the effect from the equivalence principle in 1907, stating that it can be measured in the spectral lines of a white dwarf star that has a very large gravitational field. The first accurate measurement of a white dwarf was made by Popper in 1954. [334]

Global Positioning System (GPS) must take into account the gravitational redshift in synchronization[335]. Physicians analyzed GPS data to confirm other tests[336]. Other precision tests

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[331] Will, "The Confrontation between General Relativity and Experiment."

[332] Matthew Stanley, "'An Expedition to Heal the Wounds of War' The 1919 Eclipse and Eddington as Quaker Adventurer," *Isis* 94, no. 1 (March 1, 2003): 57–89, https://doi.org/10.1086/376099.

[333] Shapiro et al., "Measurement of the Solar Gravitational Deflection of Radio Waves Using Geodetic Very-Long-Baseline Interferometry Data, 1979--1999."

[334] N. S. Hetherington, "Sirius B and the Gravitational Redshift: An Historical Review," ResearchGate, 1980, 246–52, https://www.researchgate.net/publication/234478409_Sirius_B_and_the_gravitational_redshift_An_historical_review.

[335] GPS is continuously tested by comparing atomic clocks on the ground and on orbiting satellites, for correlation with relativistic effects, cf. Neil Ashby, "Relativity in the Global Positioning System," *Living Reviews in Relativity* 6, no. 1 (January 28, 2003): 1, https://doi.org/10.12942/lrr-2003-1.

[336] Ashby.

are the Gravity Probe A satellite, launched in 1976, and the Hafele-Keating experiment that used atomic clocks in navigation aircraft. [337]

2.4.4 Modern tests

Dicke and Schiff established a framework for testing general relativity, [338] including through null experiments and using the physics of space exploration, electronics and condensed matter, such as the Pound-Rebka experiment and laser interferometry. The gravitational lens tests and the temporal delay of light are highlighted by parameter γ of the PPN formalism, equal to 1 for general relativity and with different values in other theories. The BepiColombo mission aims to test the general theory of relativity by measuring the gamma and beta parameters of the PPN formalism. [339]

2.4.4.1 Shapiro Delay

The gravitational delay (Shapiro delay), according to which the light signals require more time to pass through a gravitational field than in the absence of that field, has been successfully tested. [340] In the PPN formalism, the gravitational delay is highlighted by the parameter γ, which encodes the influence of gravity on the geometry of space. [341]

Irwin I. Shapiro proposed this test becoming "classic", predicting a relativistic delay in the return of radar signals reflected on other planets. The use of the planets Mercury and Venus as targets before and after they were eclipsed by the Sun confirmed the theory of general relativity. [342] Later the Cassini probe was used for a similar experiment. [343] The measurement of the PPN gamma parameter is affected by the gravitomagnetic effect caused by the orbital motion of the Sun around

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[337] S Schiller, "Gravitational Physics with Optical Clocks in Space," 2015, 31.

[338] Schiff, "On Experimental Tests of the General Theory of Relativity," 340–343.

[339] Brans and Dicke, "Mach's Principle and a Relativistic Theory of Gravitation," 925–935.

[340] Shapiro, "Fourth Test of General Relativity," 789–791.

[341] Irwin I. Shapiro et al., "Fourth Test of General Relativity: New Radar Result," *Physical Review Letters* 26, no. 18 (May 3, 1971): 1132–1135, https://doi.org/10.1103/PhysRevLett.26.1132.

[342] Shapiro et al., 1132–1135.

[343] Sergei M. Kopeikin and Edward B. Fomalont, "Gravimagnetism, Causality, and Aberration of Gravity in the Gravitational Light-Ray Deflection Experiments," *General Relativity and Gravitation* 39, no. 10 (October 1, 2007): 1583–1624, https://doi.org/10.1007/s10714-007-0483-6.

the barycentre of the solar system. The very long basic interferometry allowed the corrections of this effect in the field of movement of Jupiter[344] and Saturn. [345]

2.4.4.2 Gravitational dilation of time

Gravity influences the passage of time. Processes close to a massive body are slower. [346] The gravitational redshift was measured in the laboratory[347] and using astronomical observations. [348] The gravitational dilation of the time in the gravitational field of the Earth was measured using atomic clocks, [349] being verified as a side effect of the functioning of the Global Positioning System (GPS). [350] Tests in stronger gravitational fields need binary pulsars. [351] All the results are in accordance with general relativity, but also with other theories where the principle of equivalence is valid. [352]

The gravitational dilation of time coexists with the existence of an accelerated frame of reference, except for the center of a concentric distribution of matter in which there is no accelerated frame of reference, although it is assumed that here time is dilated. [353] All physical phenomena undergo in this case the same time dilation, in accordance with the principle of equivalence. The time dilation can be measured for photons that are emitted on Earth, curved near the Sun, reflected on Venus, and returned to Earth along a similar path. It is observed that the speed of light in the vicinity of the Sun is lower than *c*. The phenomenon was measured experimentally using atomic clocks on the plane, where time dilations occur also due to the differences of height less than 1 meter and

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344 Kopeikin and Fomalont, 1583–1624.

345 Ed Fomalont et al., "Recent VLBA/VERA/IVS Tests of General Relativity," *Proceedings of the International Astronomical Union* 5, no. S261 (April 2009): 291–295, https://doi.org/10.1017/S1743921309990536.

346 Misner, Thorne, and Wheeler, *Gravitation*.

347 Pound and Rebka, "Apparent Weight of Photons," 186.

348 M. A. Barstow et al., "Hubble Space Telescope Spectroscopy of the Balmer Lines in Sirius B," *Monthly Notices of the Royal Astronomical Society* 362, no. 4 (October 1, 2005): 1134–1142, https://doi.org/10.1111/j.1365-2966.2005.09359.x.

349 Hans C. Ohanian and Remo Ruffini, *Gravitation and Spacetime* (Norton, 1994).

350 Ashby, "Relativity in the Global Positioning System."

351 Michael Kramer, "Millisecond Pulsarsas Tools of Fundamental Physics," in *Astrophysics, Clocks and Fundamental Constants*, ed. Savely G. Karshenboim and Ekkehard Peik, Lecture Notes in Physics (Berlin, Heidelberg: Springer Berlin Heidelberg, 2004), 33–54, https://doi.org/10.1007/978-3-540-40991-5_3.

352 Ohanian and Ruffini, *Gravitation and Spacetime*.

353 Einstein derived these effects using the principle of equivalence as early as 1907, cf. Albert Einstein, "Über Das Relativitätsprinzip Und Die Aus Demselben Gezogene Folgerungen, in Volume 2: The Swiss Years: Writings, 1900-1909 Page 432 (468 of 692)," 1907, https://einsteinpapers.press.princeton.edu/vol2-doc/468.

were tested experimentally in the laboratory. [354] Other test modes are through the Pound-Rebka experiment, observations of the white dwarf Sirius B spectra, and experiments with time signals sent to and from Mars soil with the Viking 1.

2.4.4.3 Frame dragging and geodetic effect

In general relativity, the apsides of the orbits (the point on the orbit of the body closest to the center of mass of the system) will have a precession, forming an orbit different from an ellipse, the shape of the rose. Einstein predicted this move. Relativistic precessions have been observed for all planets that allow accurate measurements of precession (Mercury, Venus and Earth), [355] and in binary pulsar systems where it is larger by five orders of magnitude.

A binary system that emits gravitational waves loses energy. Thus, the distance between the two orbital bodies decreases, as does their orbital period. At the level of the solar system, the effect is difficult to observe. It is observable for a near binary pulsar, from which very precise frequency radio pulses are received, allowing measurements of the orbital period. Neutron stars emit large amounts of energy in the form of gravitational radiation. The first observation of this effect is due to Hulse and Taylor, using a binary pulsar PSR1913+16 discovered in 1974. This was the first, indirect, detection of gravitational waves. [356]

The relativity of the direction has several relativistic effects, [357] such as the geodetic precession: the direction of the axis of a gyroscope in free fall in curved space will change compared to the direction of light received from distant stars. [358] For the Moon-Earth system, this effect was measured using the laser reflected on the Moon, [359] and more recently with the help of the test masses on board the Gravity Probe B. [360]

Near a rotary table, there are gravitometric or frame dragging effects. In the case of rotating black holes, any object that enters the ergosphere rotates. The effect can be tested by its influence on the

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[354] Pound and Rebka, "Apparent Weight of Photons," 186.

[355] Ohanian and Ruffini, *Gravitation and Spacetime*, 406–7.

[356] Hulse and Taylor, "Discovery of a Pulsar in a Binary System," L51–L55.

[357] Roger Penrose, *The Road to Reality: A Complete Guide to the Laws of the Universe*, Reprint edition (New York: Vintage, 2007).

[358] Ohanian and Ruffini, *Gravitation and Spacetime*, sec. 7.8.

[359] Kenneth Nordtvedt, "Lunar Laser Ranging - a Comprehensive Probe of Post-Newtonian Gravity," *ArXiv:Gr-Qc/0301024*, January 7, 2003, http://arxiv.org/abs/gr-qc/0301024.

[360] C. W. F. Everitt et al., "Gravity Probe B: Final Results of a Space Experiment to Test General Relativity," *Physical Review Letters* 106, no. 22 (May 31, 2011): 221101, https://doi.org/10.1103/PhysRevLett.106.221101.

orientation of free fall gyros. [361] Tests were performed using the LAGEOS satellites, [362] with the Mars Global Surveyor probe around Mars, [363] confirming the relativistic prediction.

The first frame dragging effect was derived in 1918 by Josef Lense and Hans Thirring and is known as the *Lense-Thirring effect*. They predicted that the rotation of a massive body would distort the spacetime metric, causing the orbit of a nearby test particle to precede. In order to detect it, it is necessary to examine a very massive body or to construct a very sensitive instrument. The *linear dragging of the frames* appears by applying the RG principle to the linear momentum. It is very difficult to verify. [364] *Increasing of the static mass* is another effect, an increase in the inertia of a body when other masses are placed nearby. Einstein states that it derives from the same equation of general relativity. It is a small effect, difficult to confirm experimentally.

Several costly proposals were made, including in 1976 by Van Patten and Everitt, [365] for a special space mission to measure the Lense-Thirring precession of a pair of spacecrafts to be placed in Earth's polar orbits with non-dragging devices. In 1986 Ciufolini proposed the launch of a passive geodesic satellite in an orbit identical to that of the LAGEOS satellite. The tests were started using the LAGEOS and LAGEOS II satellites in 1996. [366] The accuracy of the tests is controversial. Neither did the Gravity Probe B experiment achieve the desired accuracy. [367]

In the case of stars orbiting near a supermassive black hole, the frame dragging should cause the orbital plane of the star to precess around the axis of rotation of the black hole, an effect that could

[361] Ohanian and Ruffini, *Gravitation and Spacetime*, sec. 4.7.

[362] Lorenzo Iorio, "An Assessment of the Systematic Uncertainty in Present and Future Tests of the Lense-Thirring Effect with Satellite Laser Ranging," *Space Science Reviews* 148, no. 1–4 (December 2009): 363–381, https://doi.org/10.1007/s11214-008-9478-1.

[363] Lorenzo Iorio, "On the Lense-Thirring Test with the Mars Global Surveyor in the Gravitational Field of Mars," *Open Physics* 8, no. 3 (January 1, 2010): 509–513, https://doi.org/10.2478/s11534-009-0117-6.

[364] Albert Einstein, "The Meaning of Relativity," Princeton University Press, 1921, https://press.princeton.edu/titles/484.html.

[365] R. A. Van Patten and C. W. F. Everitt, "Possible Experiment with Two Counter-Orbiting Drag-Free Satellites to Obtain a New Test of Einstein's General Theory of Relativity and Improved Measurements in Geodesy," *Physical Review Letters* 36, no. 12 (March 22, 1976): 629–632, https://doi.org/10.1103/PhysRevLett.36.629.

[366] Iorio, "An Assessment of the Systematic Uncertainty in Present and Future Tests of the Lense-Thirring Effect with Satellite Laser Ranging," 363–381.

[367] Everitt et al., "Gravity Probe B."

be detected in the following years by astrometric monitoring of the stars in the center of the Milky Way galaxy. [368]

Relativistic jets can provide evidence for frame dragging. [369] The gravitomagnetic model developed by Reva Kay Williams predicts the high energy particles emitted by quasars and active galactic nuclei, the extraction of X and γ rays and e- e+ relativistic pairs, jets collimated around the polar axis, and asymmetric jets formation.

2.4.4.4 Testing of the principle of equivalence

At the beginning of the 17th century Galileo developed a principle similar to that of equivalence when he showed experimentally that the acceleration of a body due to gravity is independent of its mass quantity. Kepler emphasized the principle of equivalence through a thought experiment, what would happen if the Moon were stopped in orbit and dropped to Earth.

The principle of equivalence has historically played an important role in the law of gravity. Newton considered it from the opening paragraph of the *Principia*. Einstein also relied on this principle in general relativity. Newton's principle of equivalence states that the "mass" of a body is proportional to its "weight" (the **weak equivalence principle**, WEP). An alternative definition of WEP is that the trajectory of a body in the absence of forces is independent of its internal structure and composition. A simple WEP test is the comparison of the acceleration of two bodies of different composition in an external gravitational field. Other high-precision experiments include from Newton, Bessel and Potter's pendulum experiments to the classical torsion measurements of Eotvos, [370] Dicke, [371] and Braginsky. [372] There are several projects to improve the values measured with the help of satellites.

The **Einstein Equivalence Principle** (EEP) is stronger and more comprehensive, stating that the WEP is valid, and the results of local non-gravitational experiments are independent of the speeds of the appropriate reference frames and the place and time they are performed. The independence

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[368] Ohanian and Ruffini, *Gravitation and Spacetime*, sec. 7.8.

[369] For a distant observer, jets sometimes seem to move faster than light, but this is an optical illusion that does not violate the principles of relativity.

[370] Roland V. Eötvös, Desiderius Pekár, and Eugen Fekete, "Beiträge Zum Gesetze Der Proportionalität von Trägheit Und Gravität," *Annalen Der Physik* 373 (1922): 11–66, 68, https://doi.org/10.1002/andp.19223730903.

[371] R. H. Dicke, *Gravitation and the Universe.*, 1969, http://adsabs.harvard.edu/abs/1969grun.book.....D.

[372] V. B. Braginsky and V. I. Panov, "Verification of the equivalence of inertial and gravitational mass," *Soviet Journal of Experimental and Theoretical Physics* 34 (1972): 34, 463–466, https://istina.msu.ru/publications/article/4687588/.

of the frame of reference is called local Lorentz invariance, and independence of its internal structure and composition is called local position invariance.

The special relativity benefited from a series of experiments that subsequently contributed to the acceptance of the GR:

- Michelson-Morley experiment and subsequent equivalent experiments, [373]
- Ives-Stillwell, Rossi-Hall, other tests of time dilation, [374]
- independence of the speed of light from the source speed, using X-ray binary stellar sources, and high energy pions, [375]
- isotropy of light speed. [376]

In recent years, scientists have begun to look for apparent violations of the Lorentz invariance resulting from certain quantum gravity models. A simple modality, embodied in the c2 formalism, assumes that the electromagnetic interactions suffer a slight violation of the Lorentz invariance by changing the velocity of the electromagnetic radiation *c* relative to the limiting speed of the testing particle of particles, [377] trying to select a prefered universal resting frame, possible of cosmic background radiation. [378] Through the Michelson-Morley experiments the speed of light is verified; the Brillet-Hall experiment[379] used a Fabry-Perot laser interferometer; in other experiments, the frequencies of the oscillators of the electromagnetic cavity in different orientations were compared with each other or with the atomic clocks, depending on the orientation of the laboratory. [380]

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[373] A. Brillet and J. L. Hall, "Improved Laser Test of the Isotropy of Space," *Physical Review Letters* 42 (February 1, 1979): 42, 549–552, https://doi.org/10.1103/PhysRevLett.42.549.

[374] F. J. M. Farley et al., "The Anomalous Magnetic Moment of the Negative Muon," *Il Nuovo Cimento A (1965-1970)* 45, no. 1 (September 1, 1966): 45, 281–286, https://doi.org/10.1007/BF02738104.

[375] T. Alväger et al., "Test of the Second Postulate of Special Relativity in the GeV Region," *Physics Letters* 12, no. 3 (October 1, 1964): 12, 260–262, https://doi.org/10.1016/0031-9163(64)91095-9.

[376] null Krisher et al., "Test of the Isotropy of the One-Way Speed of Light Using Hydrogen-Maser Frequency Standards," *Physical Review. D, Particles and Fields* 42, no. 2 (July 15, 1990): 42, 731–734.

[377] Will, "The Confrontation between General Relativity and Experiment."

[378] C. H. Lineweaver et al., "The Dipole Observed in the COBE DMR 4 Year Data," *The Astrophysical Journal* 470 (October 1, 1996): 470, 38–42, https://doi.org/10.1086/177846.

[379] Brillet and Hall, "Improved Laser Test of the Isotropy of Space," 42, 549–552.

[380] Paul L. Stanwix et al., "Test of Lorentz Invariance in Electrodynamics Using Rotating Cryogenic Sapphire Microwave Oscillators," *Physical Review Letters* 95, no. 4 (July 21, 2005): 040404, https://doi.org/10.1103/PhysRevLett.95.040404.

The principle of local position invariance can be tested by the gravitational redshift experiments. The first such experiments were the Pound-Rebka-Snider series from 1960 to 1965, which measured the frequency change of the gamma radiation photons. The most accurate standard redshift test was the Vessot-Levine rocket experiment in June 1976. [381] A "null" redshift experiment conducted in 1978 tested whether the relative rate of two different clocks depends on position. The most recent experiments have used laser cooling and trapping techniques to obtain extreme clock stability and compared the hyperfine transition Rubidium-87, [382] the ionic quadrupole transition Mercury-199, [383] the atomic transition with Hydrogen 1S- 2S, [384] or an optical transition in Ytterbium-171, [385] against hyperfine ground-state transition in Cesium-133. [386]

The Einstein equivalence principle is part of the hard core of Einstein's research program, since the existence of EEP implies gravity as a phenomenon in "curved spacetime". It turns out that the only theories of gravity that can fully incorporate EEP are those that satisfy the postulates of "metric theories of gravity", respectively: [387]

1. Spacetime has a symmetrical value.
2. The trajectories of free-falling bodies are geodesic of this metric.
3. In the free-falling local reference frames, the non-gravitational laws of physics are those written in the language of special relativity.

In 1960, Schiff developed the hypothesis that any complete, self-consistent theory of gravity that embodies strong equivalence principle (SEP) necessarily embodies EEP (the validity of SEP itself guarantees the validity of local Lorentz and position invariance). In this case, it follows, based on the energy conservation hypothesis, that Eotvos experiments are direct empirical bases for EEP. The first successful attempt to prove Schiff's conjecture more formally was made by Lightman and

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[381] R. F. C. Vessot et al., "Test of Relativistic Gravitation with a Space-Borne Hydrogen Maser," *Physical Review Letters* 45, no. 26 (December 29, 1980): 45, 2081–2084, https://doi.org/10.1103/PhysRevLett.45.2081.

[382] H. Marion et al., "A Search for Variations of Fundamental Constants Using Atomic Fountain Clocks," *Physical Review Letters* 90, no. 15 (April 18, 2003): 90, 150801–1–4, https://doi.org/10.1103/PhysRevLett.90.150801.

[383] S. Bize et al., "Testing the Stability of Fundamental Constants with the 199Hg+ Single-Ion Optical Clock," *Physical Review Letters* 90, no. 15 (April 18, 2003): 90, 150802–1–4, https://doi.org/10.1103/PhysRevLett.90.150802.

[384] M. Fischer et al., "New Limits to the Drift of Fundamental Constants from Laboratory Measurements," *Physical Review Letters* 92, no. 23 (June 10, 2004): 92, 230802–1–4, https://doi.org/10.1103/PhysRevLett.92.230802.

[385] E. Peik et al., "New Limit on the Present Temporal Variation of the Fine Structure Constant," *Physical Review Letters* 93, no. 17 (October 18, 2004): 93, 170801–1–4, https://doi.org/10.1103/PhysRevLett.93.170801.

[386] Will, "The Confrontation between General Relativity and Experiment."

[387] Will.

Lee, [388] using a framework called "THεμ formalism" which includes all metric theories of gravity and many non-metric theories, which uses the rate of falling of a "tested" body consisting of interacting charged particles.

Empirical evidence supporting the Einstein principle of equivalence states that the only theories of gravity that hope to be viable are metric theories, or possibly theories that are metric outside of very weak or short-lived non-metric couplings (as in string theory). [389]

There may be other gravitational fields besides metric ones, such as scalar or vector fields, which mediate how matter and non-gravitational fields generate gravitational fields and produce the metric; but once the metric is determined, it only acts backwards in the manner prescribed by the EEP. Thus, all metric theories of gravity can be divided into two fundamental classes: "purely dynamic" and "previously geometric." [390] In a "purely dynamic metric theory" the gravitational fields have the structure and evolution determined by the partially coupled differential field equations. A "previously geometric" theory contains "absolute elements", fields or equations whose structure and evolution are given *a priori* and are independent of the structure and evolution of the other fields of theory. General relativity is a purely dynamic theory.

The **strong equivalence principle** states that: WEP is valid for all bodies, and the result of any local testing experiment is independent of the speed of the apparatus and the place and time of the experiment.

Compared to WEP, SEP includes gravitational sources (planets, stars) and experiments involving gravitational forces (Cavendish experiments, gravimetric measurements). Note that WEP includes EEP as a special case where local gravitational forces are ignored. If the WEP is strictly valid, there must be only one gravitational field in the universe, the metric *g*, but there is no rigorous evidence of this statement so far.

The Einstein equivalence principle can be tested, in addition to WEP tests, by looking for the variation of dimensionless constants and mass ratios.

The strong equivalence principle implies that gravity is geometric by nature and does not contain additional associated fields. Thus, SEP says that a measurement of a flat space surface is absolutely

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[388] A. P. Lightman and D. L. Lee, "Restricted Proof That the Weak Equivalence Principle Implies the Einstein Equivalence Principle," *Physical Review. D, Particles Fields* 8, no. 2 (1973): 8, 364–376, http://inis.iaea.org/Search/search.aspx?orig_q=RN:5098997.

[389] Will, "The Confrontation between General Relativity and Experiment."

[390] Will.

equivalent to any other flat space surface in any other part of the universe. Einstein's theory of general relativity is the only theory of gravity that satisfies the strong equivalence principle.

The SEP can be tested by searching for a variation of Newton's gravitational constant *G*, or a variation of the mass of the fundamental particles. These would result from deviations from the law of gravitational force from general relativity, especially deviations from inverse-quadratic proportionality, which can be explained by the existence of the fifth force. Other sought effects are the Nordtvedt effect, a "polarization" of the orbits of the solar system due to the gravitational acceleration of self-generation at a rate different from the normal matter, sought by the Lunar Laser Ranging experiment. Other tests include studying the deflection of radiation from radio sources far from the sun measured with very long basic interferometry or measuring the change in frequency of signals to and from the Cassini spacecraft.

Quantum gravity theories, such as string theory and loop quantum gravity, predict violations of the weak equivalence principle. Currently, the tests of the weak equivalence principle have a degree of sensitivity so that the non-detection of an infringement is as profound as the discovery of an infringement. Discovering the violation of the principle of equivalence would provide an important guide to unification. [391]

A formalism of non-gravitational laws of physics in the presence of gravity that incorporates the possibility of nonmetric (nonuniversal) and metric coupling is the TH formalism elaborated by Lightman and Lee. [392] It allows quantitative forecasting for experiment results.

2.4.4.5 Solar system tests

The dynamic environment of spacetime around Earth allows testing of gravitational theories, with geodetic satellites as test masses. An example is the LAGEOS satellites, launched for geodetic and geodynamic purposes, and for fundamental physical studies. LAGEOS satellites are used as a target for laser pulses sent from ground stations to calculate the instantaneous distance ("Satellite Laser Ranging" (SLR) technique). The determination of the orbit of the satellites requires models for the dynamics of the satellites, for the measurement procedures and for the transformations of the reference frames. [393] The models take into account geopotential, lunar and planetary disturbances,

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[391] James Overduin et al., "The Science Case for STEP," *Advances in Space Research* 43, no. 10 (May 15, 2009): 1532–1537, https://doi.org/10.1016/j.asr.2009.02.012.

[392] Lightman and Lee, "Restricted Proof That the Weak Equivalence Principle Implies the Einstein Equivalence Principle," 8, 364–76.

[393] Friedrich W. Hehl et al., "General Relativity with Spin and Torsion: Foundations and Prospects," *Reviews of Modern Physics* 48, no. 3 (July 1, 1976): 393– 416, https://doi.org/10.1103/RevModPhys.48.393.

pressure of solar radiation and Earth's albedo, Rubin-cam and Yarkovsky-Schach effects, SLR station coordinates, ocean loading, earth orientation parameters and measurement procedure. [394] The models also include general relativistic corrections in the post-Newtonian parametric formalism (PPN). [395] The tests performed confirm the general relativity predictions (Schwarzschild precession, Lense-Thirring effect) and exclude an alternative theory (NLRI/Yukawa potential).

2.4.5 Strong field gravitational tests

When the density of the body becomes large enough, general relativity predicts the formation of a black hole. The neutron stars of about 1.4 solar masses and the black holes are the final stage for the evolution of the massive stars. [396] Usually a black hole in a galaxy has played an important role in its formation and related cosmic structures. Such bodies provide an efficient mechanism for the emission of electromagnetic radiation[397] and the formation of microquasars. [398] Accretion can lead to relativistic jets. General relativity allows the modeling of these phenomena, [399] confirmed by observations.

Black holes are the areas where gravitational waves are searched, sometimes formed by combining binary stars with black holes, detected on Earth; the pre-fusion phase ("chirp") can be used as a "standard illumination" to deduce the distance to the fusion events, serving as a proof of cosmic

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[394] Emil T. Akhmedov et al., "Experimental Tests of Quantum Gravity and Exotic Quantum Field Theory Effects," ResearchGate, 2014, https://www.researchgate.net/publication/274948108_Experimental_Tests_of_Quantum_Gravity_and_Exotic_Quantum_Field_Theory_Effects.

[395] Nordtvedt and Will, "Conservation Laws and Preferred Frames in Relativistic Gravity. II. Experimental Evidence to Rule Out Preferred-Frame Theories of Gravity," 775–792.

[396] Cole Miller, "Stellar Structure and Evolution (Lecture Notes for Astronomy 606)," 2002, http://www.astro.umd.edu/~miller/teaching/astr606/.

[397] R. D. Blandford, "Astrophysical Black Holes.," in *Three Hundred Years of Gravitation*, 1987, 277–329, http://adsabs.harvard.edu/abs/1987thyg.book..277B.

[398] Annalisa Celotti, John C. Miller, and Dennis W. Sciama, "Astrophysical Evidence for the Existence of Black Holes," *Classical and Quantum Gravity* 16, no. 12A (December 1, 1999): A3–A21, https://doi.org/10.1088/0264-9381/16/12A/301.

[399] José A. Font, "Numerical Hydrodynamics in General Relativity," *Living Reviews in Relativity* 6, no. 1 (August 19, 2003): 2, https://doi.org/10.12942/lrr-2003-4.

expansion over long distances. [400] When a black hole joins another supermassive black hole, it can provide direct information about the geometry of the supermassive black hole. [401]

In February 2016 and later in June 2016, June 2017 and August 2017, Advanced LIGO announced that it had directly detected gravitational waves from a black hole stellar fusion. [402] Gravitational waves can be detected directly, and many aspects of the Universe can be found in their study. The astronomy of gravitational waves is concerned with the testing of general relativity and of alternative theories, verifying the predicted shape of the waves and their conformity with solutions of the field equations of the theories. [403]

Other tests for strong gravity allow the gravitational redshift of the light from the star S2 orbiting the supermassive black hole Sagittarius A* in the center of the Milky Way, with the help of the Very Large Telescope using GRAVITY, NACO and SIFONI. [404]

The strong equivalence principle of general relativity for bodies with strong self-gravity was tested using a triple star system called PSR J0337+1715, consisting of a neutron star with a white dwarf star located approximately 4,200 light-years from Earth. which orbit along with another distant white dwarf star. The observations, with high accuracy, compare the way in which the gravitational pull of the outer white dwarf affects the pulsar which has a strong autogravity and the inner white dwarf. The results confirmed the general theory of relativity. [405]

2.4.5.1 Gravitational lenses

When a massive astronomical body lies between the observer and a distant body with an appropriate mass and distance, several distorted images of the distant body can be seen, forming

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[400] Neal Dalal et al., "Short GRB and Binary Black Hole Standard Sirens as a Probe of Dark Energy," *Physical Review D* 74, no. 6 (September 18, 2006): 063006, https://doi.org/10.1103/PhysRevD.74.063006.

[401] Leor Barack and Curt Cutler, "LISA Capture Sources: Approximate Waveforms, Signal-to-Noise Ratios, and Parameter Estimation Accuracy," *Physical Review D* 69, no. 8 (April 30, 2004): 082005, https://doi.org/10.1103/PhysRevD.69.082005.

[402] Charles Q. Choi, "Gravitational Waves Detected from Neutron-Star Crashes: The Discovery Explained," Space.com, 2017, https://www.space.com/38471-gravitational-waves-neutron-star-crashes-discovery-explained.html.

[403] B. P. Abbott et al., "Tests of General Relativity with GW150914," *Physical Review Letters* 116, no. 22 (May 31, 2016): 221101, https://doi.org/10.1103/PhysRevLett.116.221101.

[404] R. Abuter et al., "Detection of the Gravitational Redshift in the Orbit of the Star S2 near the Galactic Centre Massive Black Hole," *Astronomy & Astrophysics* 615 (July 1, 2018): L15, https://doi.org/10.1051/0004-6361/201833718.

[405] Anne M. Archibald et al., "Universality of Free Fall from the Orbital Motion of a Pulsar in a Stellar Triple System," *Nature* 559, no. 7712 (July 2018): 73–76, https://doi.org/10.1038/s41586-018-0265-1.

the effect known as gravitational lenses, [406] two or more images are the shape of a light ring. known as the Einstein ring or partial rings (arches). [407] The first such observation was in 1979. [408] The effect can be measured according to the brightness of the distant body. Gravitational lenses allow the presence and distribution of dark matter to be detected, being a kind of "natural telescope" for observing distant galaxies and obtaining an independent estimate of the Hubble constant. Their statistical assessments provide information about the structural evolution of galaxies. [409] The observation of gravitational lenses is expected to complement observations in the electromagnetic spectrum, [410] to provide information on black holes, neutron stars and white dwarfs, and on processes in supernovae and the very early universe, and to check the alternative theories including string theory in quantum gravitation. [411]

Gravitational lenses also form at the level of the solar system, with the Sun interposed between the observer and the light source, but the convergence point of such lenses would be approximately 542 AU from the Sun. However, this distance exceeds the capabilities of the probe equipment and goes far beyond the solar system.

Sources for gravitational lenses are radio sources far away, especially some quasars. For detection are used long-distance radio telescopes combined with very long basic interferometry technique. For accuracy, we consider the systematic effects on the Earth level, where the telescopes are located. The observations confirmed the value of the deformation predicted by the general relativity. [412]

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[406] Joachim Wambsganss, "Gravitational Lensing in Astronomy," *Living Reviews in Relativity* 1, no. 1 (November 2, 1998): 12, https://doi.org/10.12942/lrr-1998-12.

[407] Bernard Schutz, "Gravity from the Ground Up by Bernard Schutz," Cambridge Core, December 2003, https://doi.org/10.1017/CBO9780511807800.

[408] D. Walsh, R. F. Carswell, and R. J. Weymann, "0957 + 561 A, B: Twin Quasistellar Objects or Gravitational Lens?," *Nature* 279, no. 5712 (May 1979): 381–384, https://doi.org/10.1038/279381a0.

[409] Ramesh Narayan and Matthias Bartelmann, "Lectures on Gravitational Lensing," *ArXiv:Astro-Ph/9606001*, June 3, 1996, sec. 3.7, http://arxiv.org/abs/astro-ph/9606001.

[410] Kip S. Thorne, "Gravitational Waves," *ArXiv:Gr-Qc/9506086*, June 30, 1995, 160, http://arxiv.org/abs/gr-qc/9506086.

[411] Curt Cutler and Kip S. Thorne, "An Overview of Gravitational-Wave Sources," *ArXiv:Gr-Qc/0204090*, April 30, 2002, 4090, http://arxiv.org/abs/gr-qc/0204090.

[412] E. Fomalont et al., "Progress in Measurements of the Gravitational Bending of Radio Waves Using the VLBA," *The Astrophysical Journal* 699, no. 2 (July 10, 2009): 1395–1402, https://doi.org/10.1088/0004-637X/699/2/1395.

With the help of the astronomical satellite Hipparcos of the European Space Agency it was found that the whole sky is slightly distorted due to the gravitational deviation of the light caused by the Sun (except the direction opposite to the Sun). This requires some minor corrections for virtually all stars.

2.4.5.2 Gravitational waves

Gravitational waves were predicted in 1916 by Albert Einstein. [413] They are disturbances in the curved spacetime geometry, generated by the accelerated masses and propagating with the speed of light. They were confirmed on February 11, 2016 by the Advanced LIGO team. [414] For the weak fields a linear approximation can be made for these waves. Data analysis methods are based on the Fourier decomposition of these waves. [415] Exact solutions can be obtained without approximation, but for gravitational waves produced by the fusion of two black holes, numerical methods are the only way to build suitable models. [416]

Gravitational waves were initially suggested by Henri Poincaré in 1905, and then predicted in 1916 by Albert Einstein based on the general theory of relativity. The laws of classical mechanics do not guarantee their existence, this being one of the classical limitations. Binary neutron star systems are a powerful source of gravitational waves during fusion. Gravitational waves were detected by the LIGO and VIRGO observatories. They allow the observation of the fusion of black holes and the study of the distant universe, opaque to electromagnetic radiation.

Einstein and Rosen published the first correct version of gravitational waves in 1937. [417] Gravitational waves are created by accelerating mass in space, but if the acceleration is spherically

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[413] Albert Einstein, "Näherungsweise Integration Der Feldgleichungen Der Gravitation," *Sitzungsberichte Der Königlich Preußischen Akademie Der Wissenschaften (Berlin), Seite 688-696.*, 1916, 1: 688–696, http://adsabs.harvard.edu/abs/1916SPAW.......688E.

[414] B. P. Abbott, The LIGO Scientific Collaboration, and the Virgo Collaboration, "Observation of Gravitational Waves from a Binary Black Hole Merger," *Physical Review Letters* 116, no. 6 (February 11, 2016): 116(6): 061102, https://doi.org/10.1103/PhysRevLett.116.061102.

[415] Piotr Jaranowski and Andrzej Królak, "Gravitational-Wave Data Analysis. Formalism and Sample Applications: The Gaussian Case," *Living Reviews in Relativity* 8, no. 1 (March 21, 2005): 8 (1): 3, https://doi.org/10.12942/lrr-2005-3.

[416] Edward Seidel, "Numerical Relativity: Towards Simulations of 3D Black Hole Coalescence," *ArXiv:Gr-Qc/9806088*, June 23, 1998, 6088, http://arxiv.org/abs/gr-qc/9806088.

[417] A. Einstein and N. Rosen, "On Gravitational Waves," *Journal of The Franklin Institute* 223 (January 1, 1937): 43–54, https://doi.org/10.1016/S0016-0032(37)90583-0.

symmetrical, no gravitational waves are radiated. Binary systems always radiate gravitational waves, because their acceleration is asymmetrical.

The first indirect detection of gravitational waves was in 1974 by Hulse and Taylor, from a binary pulsar PSR 1913+16, using delayed radio wave detection. [418] They found that the gravitational time dilation was in line with the GR prediction and contradicted most alternative theories. [419] The first direct detection of gravitational waves occurred in 2015, with two Advanced LIGO detectors, from source GW150914, a binary black hole. [420] These observations confirmed the spacetime curvature as described by GR.

Joseph Weber designed and built the first gravitational wave detectors, in 1969 reporting that he detected the first gravitational waves, then reporting signals regularly from the Galactic Center. But the frequency of detection raised doubts about the validity of his observations. [421]

Some scientists disagree with the fact that experimental results are accepted on the basis of epistemological arguments. Based on gravitational wave detection experiments, Harry Collins developed an argument he calls the "experimenters' regress":[422] a correct result is obtained with a good experimental apparatus, respectively one that gives correct results. Collins argues that there are no formal criteria for checking the device, not even by calibrating a device by using a "surrogate" signal. [423] The problem is finally solved by negotiation within the scientific community, depending on factors such as the career, social and cognitive interests of the scientists, and the perceived usefulness for future work, but without using epistemological criteria or rational judgment. Thus, Collins asserts that there is serious doubt about experimental evidence and their use in evaluating scientific hypotheses and theories. The example given by Collins is early experiments to detect gravitational radiation or gravitational waves. [424]

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418 Hulse and Taylor, "Discovery of a Pulsar in a Binary System," L51–L53.

419 Will, "The Confrontation between General Relativity and Experiment," 17.

420 Abbott, The LIGO Scientific Collaboration, and the Virgo Collaboration, "Observation of Gravitational Waves from a Binary Black Hole Merger," 116(061102).

421 Jorge L. Cervantes-Cota, Salvador Galindo-Uribarri, and George F. Smoot, "A Brief History of Gravitational Waves," *Universe* 2, no. 3 (September 2016): 2 (3): 22, https://doi.org/10.3390/universe2030022.

422 Collins, *Changing Order*, 4:79-111.

423 Franklin and Perovic, "Experiment in Physics."

424 Allan Franklin, "Calibration," in *Can That Be Right? Essays on Experiment, Evidence, and Science*, ed. Allan Franklin, Boston Studies in the Philosophy of Science (Dordrecht: Springer Netherlands, 1999), 5: 31–80, https://doi.org/10.1007/978-94-011-5334-8_9.

The physical community was forced to compare Weber's assumptions with reports of six other experiments that did not detect gravitational waves. Collins argues that the decision between these contradictory experimental results could not be made on epistemological or methodological grounds - the six negative experiments could not legitimately be considered as replications, and thus were considered less important. In his experiments Weber used a new type of device to detect a hitherto unobserved phenomenon, which could not be subjected to standard calibration techniques. [425]

The results of other scientists who contradicted Weber's were more numerous, and have been carefully verified, and have been confirmed by other groups of researchers. They investigated whether their analysis procedure, a linear algorithm, could explain the failure in observing Weber's results. They changed the procedure to the one used by Weber, a nonlinear algorithm, to analyze their own data, but again found no trace of gravitational waves. They recalibrated their experimental devices by introducing known acoustic energy impulses and thus detecting a signal. [426]

There were other doubts about Weber's analysis procedures. An admitted programming error generated false coincidences between the two detectors that could be interpreted during the experiments as real.

The results of the critics were much more credible from the point of view of the procedures that had to be followed: they verified the results by independent confirmation that included the sharing of data and analysis programs, eliminated a plausible source of error, and they calibrated the devices by injecting known energy pulses and observing the output. Allan Franklin and Slobodan Perovic believe that the scientific community made a motivated judgment by initially rejecting Weber's results by accepting those of his critics. Although no strict formal rules were applied, the procedure was reasonable. [427]

Another way of detecting gravitational waves is through the interaction of the waves with the walls of a microwave cavity, with a formalism developed by Caves, for measuring inertial frame dragging[428] and detecting high frequency gravitational waves. [429]

[425] Franklin and Perovic, "Experiment in Physics."

[426] Franklin and Perovic.

[427] Franklin and Perovic.

[428] C. M. Will, "The Theoretical Tools of Experimental Gravitation," 1974, 1, http://adsabs.harvard.edu/abs/1974exgr.conf....1W.

[429] Caves, "Theoretical Investigations of Experimental Gravitation."

2.4.5.3 Synchronization binary pulsars

Pulsars are rotating neutron stars that emit radio waves in pulses as they rotate, thus functioning as watches that allow a very precise measurement of their orbital movements. Their observations showed that their precessions that cannot be explained by classical mechanics can be explained by general relativity. [430]

Measurements on binary pulsars can test the combined relativistic effects, including the Shapiro delay. [431] And, since the gravitational field near the pulsars is strong, the weak equivalence principle can also be tested due to the invariant position of the objects with strong self-gravity properties. [432]

2.4.5.4 Extreme environments

Extreme gravity environments are close to very massive compact bodies, where the curvature of spacetime is very pronounced and the general relativistic effects are profound. These are usually neutron stars and black holes (especially supermassive ones), the active galactic nucleus and quasars. Deviations from the GR are most likely to occur here, under strong gravity regime. Such a test, for 16 years, was performed by Gillessen et al., [433] for Sagitarius A* [Sgr A*], a light radio source in the center of the Milky Way where there is a supermassive black hole. The observations made by Hambaryan et al. [434] were in full agreement with the GR, an essential confirmation for this theory.

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[430] Joel M. Weisberg, David J. Nice, and Joseph H. Taylor, "Timing Measurements of the Relativistic Binary Pulsar PSR B1913+16," *The Astrophysical Journal* 722, no. 2 (October 20, 2010): 722 (2): 1030–1034, https://doi.org/10.1088/0004-637X/722/2/1030.

[431] Lijing Shao and Norbert Wex, "Tests of Gravitational Symmetries with Radio Pulsars," *Science China Physics, Mechanics & Astronomy* 59, no. 9 (September 2016): 59(699501), https://doi.org/10.1007/s11433-016-0087-6.

[432] Will, *Theory and Experiment in Gravitational Physics, Revised Edition*.

[433] S. Gillessen et al., "Monitoring Stellar Orbits around the Massive Black Hole in the Galactic Center," *The Astrophysical Journal* 692, no. 2 (February 20, 2009): 692(2), pp.1075–1109, https://doi.org/10.1088/0004-637X/692/2/1075.

[434] V. Hambaryan et al., "On the Compactness of the Isolated Neutron Star RX J0720.4-3125," *Astronomy & Astrophysics* 601 (May 2017): A108, https://doi.org/10.1051/0004-6361/201630368.

2.4.6 Cosmological tests

The current cosmological models are built based on general relativity. The solutions of the specific equations, Friedmann-Lemaître-Robertson-Walker, [435] allow to model the evolution of the universe starting from the Big Bang.[436] Some of the parameters of the universe have been established by observations. Based on these, and other observational data, the models can be tested. [437] Predictions include the initial abundance of chemical elements formed in a period of nucleosynthesis during the Big Bang period, the subsequent structure of the universe, [438] cosmic background radiation, [439] and so on.

Observations on the expansion velocity of the universe allow estimation of the total amount of matter, some of which theories predict that 90% is dark matter, with mass but without electromagnetic interactions, and cannot be directly observed. The gravitational redshift of the supernovae and the measurements of the cosmic background radiation show a dependence of the universe evolution on a cosmological constant with an acceleration of the cosmic expansion or, alternatively, a form of energy called "dark energy".[440]

From the measurements of the cosmic background radiation, [441] in 1980 the initial existence of an inflationary phase was deduced, followed by a strongly accelerated expansion phase after about 10^{-33} seconds, thus explaining the almost perfect homogeneity of the cosmic background radiation.

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[435] Sean M. Carroll, "The Cosmological Constant," *Living Reviews in Relativity* 4, no. 1 (February 7, 2001): 4 (1): 1, https://doi.org/10.12942/lrr-2001-1.

[436] At large scales of about one hundred million light-years and more, the universe really looks isotropic and homogeneous, so simplified models are justified.

[437] Sarah L. Bridle et al., "Precision Cosmology? Not Just Yet . . .," *Science* 299, no. 5612 (March 7, 2003): 299 (5612): 1532–1533, https://doi.org/10.1126/science.1082158.

[438] Volker Springel et al., "Simulations of the Formation, Evolution and Clustering of Galaxies and Quasars," *Nature* 435, no. 7042 (June 2005): 435 (7042): 629–636, https://doi.org/10.1038/nature03597.

[439] Uroš Seljak and Matias Zaldarriaga, "Signature of Gravity Waves in the Polarization of the Microwave Background," *Physical Review Letters* 78, no. 11 (March 17, 1997): 78 (11): 2054–2057, https://doi.org/10.1103/PhysRevLett.78.2054.

[440] Thomas Buchert, "Dark Energy from Structure: A Status Report," *General Relativity and Gravitation* 40, no. 2 (February 1, 2008): 40 (2–3): 467–527, https://doi.org/10.1007/s10714-007-0554-8.

[441] D. N. Spergel et al., "Wilkinson Microwave Anisotropy Probe (WMAP) Three Year Results: Implications for Cosmology," *The Astrophysical Journal Supplement Series* 170, no. 2 (June 2007): 170 (2): 377–408, https://doi.org/10.1086/513700.

The phenomena in the area of the black holes question our fundamental concepts about space, time, determinism, irreversibility, information and causality. Normally, we can consider the current state of the Universe as the effect of its past and the cause of its future. Each state of the Universe is determined by a set of initial conditions and the laws of physics. Theorems apply only to mathematical objects, not to reality. The existence of solutions to some equations of physical laws does not imply physical existence, this being independent of our conceptions. The solutions of dynamic equations cannot predict all future events. General relativity implies the existence of all events represented by a manifold, so it is an ontological deterministic theory. But the impossibility of determining the horizons of black holes shows that general relativity is an example of a theory that can be determinist ontologically, but nonetheless epistemologically undetermined. [442]

2.4.6.1 The expanding universe

The Big Bang theory is the main cosmological model[443] for the early history of the universe and its subsequent evolution. It provides an explanation for a wide range of phenomena, including the abundance of light elements, the cosmic microwave background, the structure of the universe, and Hubble's law. [444] The physicists did not agree that the universe started from a singularity or our present knowledge is insufficient to deduce the initial state. Measures of the expansion rate of the universe show that the universe was born 13.8 billion years ago. After the initial expansion, the universe cooled down into subatomic particles and then atoms. The coagulation of these primordial elements by gravity has led to the formation of stars and current galaxies.

From several alternative theories, the scientific community has preferred the Big Bang theory due to its much greater heuristic power, coupled with a wide range of empirical evidence, such as the redshift analyzed by Edwin Hubble in 1929, and the discovery of cosmic background radiation in 1964. [445] The evolution of the universe is deduced starting from the present situation, towards an initial state of huge density and temperature.

Particle accelerators can replicate conditions after the first moments of the universe, confirming and refining the details of the Big Bang model. The Big Bang theory explains many observed

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[442] Gustavo E. Romero, "Philosophical Issues of Black Holes," *ArXiv:1409.3318 [Astro-Ph, Physics:Gr-Qc, Physics:Physics]*, September 10, 2014, http://arxiv.org/abs/1409.3318.

[443] Dennis Overbye, "Cosmos Controversy: The Universe Is Expanding, but How Fast?," *The New York Times*, February 20, 2017, sec. Science, https://www.nytimes.com/2017/02/20/science/hubble-constant-universe-expanding-speed.html.

[444] E. L Wright, "What Is the Evidence for the Big Bang?, In Frequently Asked Questions in Cosmology," 2009, http://www.astro.ucla.edu/~wright/cosmology_faq.html#BBevidence.

[445] R. B. Partridge, *3K: The Cosmic Microwave Background Radiation* (Cambridge University Press, 2007), xvii.

phenomena. The Big Bang model is based on general relativity theory and simplifying assumptions, such as homogeneity and isotropy of space. The model equations were formulated by Alexander Friedmann, and similar solutions were found by Willem de Sitter. The parameterization of the Big Bang model as a standard model, called the Lambda-CDM model, allows current investigations of theoretical cosmology.

The theoretical deductions from the observed phenomena lead us to an initial singularity (at time $t = 0$), with infinite density and temperature. [446] General relativity is not able to describe this regime, nor any other physical laws, nor can these laws be extrapolated beyond the end of the Planck period (10^{-37} seconds from the beginning of the expansion). Expansion measurements by observing supernovae and measuring temperature fluctuations in the cosmic microwave environment show that the "age of the universe" is 13.799 ± 0.021 billion years, [447] this result favoring the ΛCDM cosmological model.

Measurements from Wilkinson Microwave Anisotropy Probe (WMAP) show conformity with the Lambda-CDM model where dark matter is assumed to be cold[448] and account for about 23% of the matter / energy of the universe, while baryon matter represents about 4.6%. An "extended model" includes dark hot neutrino matter.

Evidence from supernova observation and cosmic background radiation shows a universe dominated by a form of energy known as dark energy, that permeates all space, accounting for 73% of the total energy density in today's universe. Its composition and mechanism are unknown. [449]

The core of the Big Bang research program includes two major hypotheses: the universality of physical laws and the cosmological principle (according to which the universe is largely homogeneous and isotropic). Currently is testing these hypotheses from the outside of the Big Bang research program. The first hypothesis was tested taking into account the largest possible deviation

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[446] Tai L. Chow, *Gravity, Black Holes, and the Very Early Universe: An Introduction to General Relativity and Cosmology* (Springer Science & Business Media, 2007), 211.

[447] P. a. R. Ade et al., "Planck 2015 Results - XIII. Cosmological Parameters," *Astronomy & Astrophysics* 594 (October 1, 2016): 594: A13, https://doi.org/10.1051/0004-6361/201525830.

[448] D. N. Spergel et al., "First-YearWilkinson Microwave Anisotropy Probe(WMAP) Observations: Determination of Cosmological Parameters," *The Astrophysical Journal Supplement Series* 148, no. 1 (September 2003): 148 (1): 175–194, https://doi.org/10.1086/377226.

[449] P. J. E. Peebles and Bharat Ratra, "The Cosmological Constant and Dark Energy," *Reviews of Modern Physics* 75, no. 2 (April 22, 2003): 75 (2): 559–606, https://doi.org/10.1103/RevModPhys.75.559.

of the constant fine structure for the age of the universe of the order of 10^{-5}. [450] The cosmological principle was confirmed at a level of 10^{-5} by the observations of the background cosmic radiation. [451]

The oldest and most direct observational evidence of the Big Bang is the expansion of the universe according to Hubble's law (deduced from the redshift of galaxies), the discovery and measurement of cosmic background radiation, and the relative quantities of light elements produced by Big Bang nucleosynthesis. Recent observations on galaxy formation and the evolution and distribution of cosmic structures on a large scale also confirm this theory. [452]

The current Big Bang models introduce various *ad-hoc* hypotheses for exotic physical phenomena that have not been observed in experiments or incorporated into the standard particle physics model. Of these, the dark matter hypothesis is currently being investigated at the laboratory level. [453] For the dark energy, no direct or indirect detection method has yet been found. [454]

Hubble's law and space expansion are verified by observations of redshifts of galaxies and quasars. The expansion of the universe was predicted from general relativity by Alexander Friedmann in 1922[455] and Georges Lemaître in 1927,[456] confirming the Big Bang theory developed by Friedmann, Lemaître, Robertson and Walker.

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[450] A. V. Ivanchik, A. Y. Potekhin, and D. A. Varshalovich, "The Fine-Structure Constant: A New Observational Limit on Its Cosmological Variation and Some Theoretical Consequences," *ArXiv:Astro-Ph/9810166*, October 10, 1998, 343: 459, http://arxiv.org/abs/astro-ph/9810166.

[451] Jeremy Goodman, "Geocentrism Reexamined," *Physical Review D* 52, no. 4 (August 15, 1995): 52 (4): 1821–1827, https://doi.org/10.1103/PhysRevD.52.1821.

[452] Michael D. Gladders et al., "Cosmological Constraints from the Red-Sequence Cluster Survey," *The Astrophysical Journal* 655, no. 1 (January 2007): 655 (1): 128–134, https://doi.org/10.1086/509909.

[453] Bernard Sadoulet, "The Direct Detection of Dark Matter," ResearchGate, 1998, https://www.researchgate.net/publication/260854303_The_Direct_Detection_of_Dark_Matter.

[454] Partridge, *3K*, xvii.

[455] A. Friedman, "On the Curvature of Space," *General Relativity and Gravitation* 31, no. 12 (December 1, 1999): 10 (1): 377–386, https://doi.org/10.1023/A:1026751225741.

[456] Abbé G. Lemaître, "A Homogeneous Universe of Constant Mass and Increasing Radius Accounting for the Radial Velocity of Extra-Galactic Nebulæ," *Monthly Notices of the Royal Astronomical Society* 91, no. 5 (March 13, 1931): 47A: 41, https://doi.org/10.1093/mnras/91.5.483.

Radiation of the cosmic microwave background was discovered in 1964 by Arno Penzias and Robert Wilson, as an omnidirectional signal in the microwave band. This confirmed the Big Bang theory of Alpher, Herman and Gamow in 1950.

In 1989, NASA launched the Cosmic Background Explorer (COBE) satellite which, in 1990, by high-precision spectrum measurements, showed that the cosmic microwave background (CMB) frequency spectrum is an almost perfect black body; then in 1992, others found tiny fluctuations (anisotropies) at cosmic microwave background temperature throughout the sky. In the years 2000-2001, several experiments, such as BOOMERanG, concluded that the shape of the universe is almost a spatial plane, by measuring the typical angular dimension of anisotropies. [457] In 2003, the Wilkinson Microwave Anisotropy Probe (WMAP) results rejected some specific models of cosmic inflation but were in line with inflation theory in general. [458]

The *relative abundances of the elements* depend on the ratio between photons and baryons. The measurements are in agreement with those predicted from a single value of the baryon-photon ratio, fully confirming the deuterium, approximately 4He, and a larger difference for 7Li. But the general identity with the abundances predicted by Big Bang nucleosynthesis confirms this model. [459]

The *evolution and distribution of galaxies and quasars* are in agreement with the Big Bang. Observations and theory suggest that the first quasars and galaxies formed about one billion years after the Big Bang, after which galaxy clusters and superclusters formed. Differences between relatively recently formed galaxies and those formed shortly after the Big Bang confirm this model and disprove the stationary model. [460]

The *primordial gas clouds* were confirmed in 2011, by analyzing absorption lines in the spectra of distant quasars. They do not contain heavier elements, just hydrogen and deuterium. [461]

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[457] A. Melchiorri et al., "A Measurement of Omega from the North American Test Flight of BOOMERANG," *The Astrophysical Journal* 536, no. 2 (June 20, 2000): 536(2): L63–L66, https://doi.org/10.1086/312744.

[458] Spergel et al., "Wilkinson Microwave Anisotropy Probe (WMAP) Three Year Results," 170 (2): 377–408.

[459] Barbara Ryden, *Introduction to Cosmology*, 2003, http://adsabs.harvard.edu/abs/2003itc..book.....R.

[460] Edmund Bertschinger, "Cosmological Perturbation Theory and Structure Formation," *ArXiv:Astro-Ph/0101009*, December 31, 2000, http://arxiv.org/abs/astro-ph/0101009.

[461] Michele Fumagalli, John M. O'Meara, and J. Xavier Prochaska, "Detection of Pristine Gas Two Billion Years After the Big Bang," *Science* 334, no. 6060 (December 2, 2011): 334 (6060): 1245–9, https://doi.org/10.1126/science.1213581.

The *age of the universe* estimated from the Hubble expansion and CMB is in agreement with the measurements of the stellar evolution in the globular groups and the radiometric dating of the individual stars.

The prediction that the *CMB temperature* was higher in the past was experimentally proved by the observations of the very low temperature absorption lines in the gas clouds due to the redshift. [462]

2.4.6.2 Cosmological observations

Stephen Hawking introduced the concept of Hawking radiation according to which black holes have entropy. This concept states that black holes can radiate energy, conserving entropy and solving the problems of incompatibility with the second law of thermodynamics. The loss of energy suggests that black holes "evaporate" over time.

A black hole acts as an ideal black body because it does not reflect light. The theory of the quantum field in curved spacetime predicts that the horizons of the event emit Hawking radiation with the same spectrum as a black body, [463] with a temperature inversely proportional to its mass, the order of billions of kelvins, making them essentially impossible to observe.

The presence of a black hole can be deduced indirectly through its interaction with other materials and electromagnetic radiation. Matter falling on a black hole can form an external accretion disk, one of the brightest objects in the universe. If there are other stars orbiting a black hole, their orbits may be used to determine the mass and location of the black hole, after excluding alternatives such as neutron stars. In this way, it was established that the radio source Sagittarius A*, from the center of the Milky Way galaxy, contains a supermassive black hole of approximately 4.3 million solar masses. On February 11, 2016, LIGO announced the first observation of gravitational waves that are supposed to have been generated by a black hole fusion, [464] and in December 2018, another detection of an event from gravitational waves was announced, resulted from joining a black hole with a neutron star. [465] On April 10, 2019, the first image of a black hole was captured with the

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[462] A. Avgoustidis et al., "Constraints on the CMB Temperature-Redshift Dependence from SZ and Distance Measurements," *Journal of Cosmology and Astroparticle Physics* 2012, no. 02 (February 2012): 2012 (2): 013, https://doi.org/10.1088/1475-7516/2012/02/013.

[463] P. C. W. Davies, "Thermodynamics of Black Holes," *Reports on Progress in Physics* 41, no. 8 (August 1978): 41 (8): 1313–1355, https://doi.org/10.1088/0034-4885/41/8/004.

[464] Abbott, The LIGO Scientific Collaboration, and the Virgo Collaboration, "Observation of Gravitational Waves from a Binary Black Hole Merger," 116 (6): 061102.

[465] LIGO Scientific Collaboration, "Detection of Gravitational Waves," 2019, https://www.ligo.org/detections.php.

help of the Event Horizon Telescope observations in 2017 of the supermassive black holes in the galactic center of Messier 87. [466]

The "no-hair" theorem states that a stable black hole has only three independent physical properties: mass, charge and angular momentum. [467] Any two black holes that have the same values for these properties cannot be distinguished according to classical (non-quantum) mechanics. These properties are visible from outside a black hole and can be measured.

The horizon of events is similar to a dissipative system that is almost analogous to that of an elastic conductive membrane with electric friction and resistance - the membrane paradigm. [468] There is no way to avoid losing information about the initial conditions, including quantum parameters.[469] This behavior was called the *paradox of black hole information loss*. [470]

The existence of the black holes is deduced by indirect observations, based on the gravitational interactions with its vicinity. [471]

Observing the *orbits of the stars around Sagittarius A** in the center of the Milky Way, provided strong evidence of the existence of a supermassive black hole. [472] In addition, there is some

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[466] K. L. Bouman et al., "Computational Imaging for VLBI Image Reconstruction," in *2016 IEEE Conference on Computer Vision and Pattern Recognition (CVPR)*, 2016, 913–922, https://doi.org/10.1109/CVPR.2016.105.

[467] Markus Heusler, Piotr T. Chruściel, and João Lopes Costa, "Stationary Black Holes: Uniqueness and Beyond," *Living Reviews in Relativity* 15, no. 1 (December 2012): 15 (7): 7, https://doi.org/10.12942/lrr-2012-7.

[468] Kip S. Thorne, Richard H. Price, and Douglas A. MacDonald, *Black Holes: The Membrane Paradigm*, 1986, http://adsabs.harvard.edu/abs/1986bhmp.book.....T.

[469] The components of a quantum field inside and outside the black hole will generally be separated, but the micro-causality implies that the inseparably degrees of freedom from the black hole cannot recombine coherently with those from the outer universe. Thus, when the black hole has completely evaporated, these separations will disappear, and the entropy of the universe will increase.

[470] Warren G. Anderson, "Black Hole Information Loss," 1996, http://math.ucr.edu/home/baez/physics/Relativity/BlackHoles/info_loss.html.

[471] NASA, "Black Holes | Science Mission Directorate," 2019, https://science.nasa.gov/astrophysics/focus-areas/black-holes.

[472] Gillessen et al., "Monitoring Stellar Orbits around the Massive Black Hole in the Galactic Center," 692 (2): 1075–1109.

observational evidence that this cosmic body could have an event horizon, a clear feature of black holes.[473]

By preserving the angular momentum, the gas in the gravitational well of a black hole forms a disk-like structure around the object (*accretion disk*),[474] emitting electromagnetic radiation (mainly X-rays) that can be detected by telescopes. In some cases, the accretion discs may be accompanied by relativistic jets emitted along the poles, by which there is removed much of the energy. Many of the energetic phenomena of the universe are the accumulation of matter by the black holes, especially the active galactic nuclei and the quasars, considered to be the discs of accumulation of supermassive black holes. In November 2011, the first direct observation of an accretion disk for a quasar around a supermassive black hole was reported.[475]

Binary X-ray systems emit a large part of their radiation when one of the stars picks up mass from another star, thus being able to study the existence of a black hole.[476] For this purpose, Cygnus X-1, discovered by Charles Thomas Bolton, Louise Webster and Paul Murdin in 1972, was studied, the results not being certain as the accompanying star is much heavier than the candidate black hole. Subsequently, other better candidates were found. The lack of the accretion disk of such a system is due to an accumulation mass flow dominated by advection which, if confirmed by observation, is a strong evidence for the presence of an event horizon.[477] X-ray emissions from the accretion discs sometimes behave as quasi-periodic oscillations, with frequency dependent on the mass of the compact object. This phenomenon can be used to determine the mass of the black holes.

Astronomers have observed certain galaxies, called "active", with unusual characteristics, such as unusual emission of spectral lines and very strong radio emissions.[478] They can be explained by the presence of supermassive black holes. The observational correlation between the mass of this

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[473] Avery E. Broderick, Abraham Loeb, and Ramesh Narayan, "The Event Horizon of Sagittarius A*," *The Astrophysical Journal* 701, no. 2 (August 20, 2009): 701(2): 1357–1366, https://doi.org/10.1088/0004-637X/701/2/1357.

[474] J. A. Marck, "Shortcut Method of Solution of Geodesic Equations for Schwarzschild Black Hole," *Classical and Quantum Gravity* 13, no. 3 (March 1, 1996): 13 (3): 393–402, https://doi.org/10.1088/0264-9381/13/3/007.

[475] José A. Muñoz et al., "A Study of Gravitational Lens Chromaticity with the Hubble Space Telescope," *The Astrophysical Journal* 742, no. 2 (December 1, 2011): 742 (2): 67, https://doi.org/10.1088/0004-637X/742/2/67.

[476] Celotti, Miller, and Sciama, "Astrophysical Evidence for the Existence of Black Holes," 16 (12A): A3–A21.

[477] Ramesh Narayan and Jeffrey E. McClintock, "Advection-Dominated Accretion and the Black Hole Event Horizon," *New Astronomy Reviews*, Jean-Pierre Lasota, X-ray Binaries, Accretion Disks and Compact Stars, 51, no. 10 (May 1, 2008): 51 (10–12): 733–751, https://doi.org/10.1016/j.newar.2008.03.002.

[478] Julian Henry Krolik, *Active Galactic Nuclei: From the Central Black Hole to the Galactic Environment* (Princeton University Press, 1999).

black hole and the dispersion velocity of the host galaxy, known as the M-sigma relationship, suggests a link between the formation of the black hole and the galaxy itself. [479]

Scientists hope that in the future they will be able to test black holes by observing the effects caused by a strong gravitational field in their vicinity, such as the gravitational lens. There are already observations about weak gravitational lenses, in which the light rays are deflected with only a few seconds, but never directly for a black hole. There are several candidates for this purpose, orbiting around Sagittarius A*.[480]

There are several *ad-hoc* conjectures that have been introduced to better explain the observations of identical astronomical black hole candidates, but with different operating mechanisms: gravastar, black star (semi-classical gravity), [481] dark energy star, etc. [482]

Cosmology, as the study of the physical universe, began as a branch of theoretical physics through the static model of Einstein's 1917 universe, later developed by Lemaître. [483] Since 1960, cosmology has been considered a branch of philosophy. The standard model of cosmology is based on extrapolations of existing theories, especially general relativity. It is based on a set of Friedman-Lemaître-Robertson-Walker (FLRW) solutions with uniform and three-dimensional symmetrical geometry with three possible curves: positive (spherical space), zero (Euclidean space), and negative (hyperbolic space).

The basic characteristics of the models that are based on the FLRW solutions, which can be considered as the hard core for the related cosmological research program, are: the models are dynamic (universe constantly changing), the rate of expansion of the universe varies according to the different types of dominant material, and FLRW models have a uniqueness in a finite time in the past (Big Bang).

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[479] Laura Ferrarese and David Merritt, "A Fundamental Relation Between Supermassive Black Holes and Their Host Galaxies," *The Astrophysical Journal* 539, no. 1 (August 10, 2000): 539 (1): 9–12, https://doi.org/10.1086/312838.

[480] Valerio Bozza, "Gravitational Lensing by Black Holes," *General Relativity and Gravitation* 42, no. 9 (September 1, 2010): 42 (9): 2269–2300, https://doi.org/10.1007/s10714-010-0988-2.

[481] Charles Q. Choi, "Black Hole Pretenders Could Really Be Bizarre Quantum Stars," Scientific American, 2018, https://www.scientificamerican.com/article/black-hole-pretenders-could-really-be-bizarre-quantum-stars/.

[482] Philip Ball, "Black Holes 'Do Not Exist,'" *Nature*, March 31, 2005, news050328-8, https://doi.org/10.1038/news050328-8.

[483] Lemaître, "A Homogeneous Universe of Constant Mass and Increasing Radius Accounting for the Radial Velocity of Extra-Galactic Nebulæ."

In the case of FKRW models, there are two types of observational tests for their verification: the geometry of the background space and its evolution is studied using the matter and radiation in the universe, or the mode of formation of the model structure that describes the evolution of small disturbances is studied.

The observational study of the geometry of the universe shows that it is isotropic at sufficiently large scales, according to the data resulting from the cosmic radiation of the microwave background (CMB) and from discrete sources (galaxies, etc.). The study of the model's structure formation uses a small number of parameters for observations from different periods, using temperature anisotropies in CMB and the power spectrum of matter by observing galaxies as independent constraints of these parameters, and of the background parameters. [484]

The standard cosmological model includes several periods in the evolution of the universe treated separately in experimental and observational verifications: [485]

- *Quantum gravity*: the beginning period, when quantum effects were essential in describing phenomena
- *Inflation*: a period of exponential expansion of the universe, during which pre-existing substances and radiation are rapidly diluted, and then the universe is repopulated with matter and energy by degrading the field in other areas at the end of inflation ("reheating").
- *Big Bang nucleosynthesis*: the period in which the constituents of the universe include neutrons, protons, electrons, photons and neutrinos, closely coupled in the local thermal equilibrium, and light elements appear.
- *Decoupling*: electrons become bound in stable atoms and photons decouple with matter; as the univers expand, the photons cool adiabically but retain a spectrum of the black body - background cosmic radiation that contains much information about the state of the universe at decoupling. [486]
- *Dark period*: after decoupling, the baryon matter formed from neutral hydrogen and helium coagulates into stars; Dark Age ends with the emergence of light from the stars.
- *Structure formation*: the first generation of stars is aggregated into galaxies, and galaxies into clusters; The massive stars end up in supernova explosions and spread in space heavy elements created inside them, forming the second generation of stars surrounded by planets.

[484] Christopher Smeenk and George Ellis, "Philosophy of Cosmology," in *The Stanford Encyclopedia of Philosophy*, ed. Edward N. Zalta, Winter 2017 (Metaphysics Research Lab, Stanford University, 2017), https://plato.stanford.edu/archives/win2017/entries/cosmology/.

[485] Smeenk and Ellis.

[486] P. a. R. Ade et al., "Planck 2015 Results - XX. Constraints on Inflation," *Astronomy & Astrophysics* 594 (October 1, 2016): 594: A20, https://doi.org/10.1051/0004-6361/201525898.

- *Dark energy domination*: dark energy (or a non-zero cosmological constant) gets to dominate the expansion of the universe, leading to accelerated expansion; the expansion will continue indefinitely if the dark energy is in fact a cosmological constant.[487]

The standard cosmological model includes several free parameters, such as the abundance density of different types of matter, which can be measured in several ways with distinct theoretical hypotheses and sources of error. At present, there are large differences between the different measurement methods, and the significance and implications of these differences are still unclear.

The standard model of nucleosynthesis is confirmed by several independent evidence to eliminate isolated theoretical errors or sources of systematic errors.

Although it is the most complete, the standard cosmological model encounters three problems that imply the need for a new physics: [488] there is no complete description of the nature or dynamics of dark matter, [489] dark energy[490] and the inflationary field; [491] the formation of galaxies, [492] and the possible refutation of the model if objects in the universe with an age greater than the determined one of the universe would be discovered, by approx. 13.7 billion years. [493]

There is a view that current cosmological evidence is not sufficient to determine which scientific theory to choose, and each theory according to a certain number of data offers quite different descriptions of the world. Duhem[494] characterized the difficulty of choosing physical theories, and Quine[495] pleaded for sub-determination. The difficulty lies in the characterization of the empirical

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487 An alternative explanation, according to string theory, is that the universe has multiple dimensions and gravity is losing gravitons moving from one dimension to another.

488 Smeenk and Ellis, "Philosophy of Cosmology."

489 Gianfranco Bertone, Dan Hooper, and Joseph Silk, "Particle Dark Matter: Evidence, Candidates and Constraints," *Physics Reports* 405, no. 5 (January 1, 2005): 405(5–6): 279–390, https://doi.org/10.1016/j.physrep.2004.08.031.

490 Peebles and Ratra, "The Cosmological Constant and Dark Energy," 75(2): 559–606.

491 David H. Lyth and Antonio Riotto, "Particle Physics Models of Inflation and the Cosmological Density Perturbation," *Physics Reports* 314, no. 1 (June 1, 1999): 314(1–2): 1–146, https://doi.org/10.1016/S0370-1573(98)00128-8.

492 Joseph Silk, "Formation of Galaxies," The Philosophy of Cosmology, April 2017, 161–178, https://doi.org/10.1017/9781316535783.009.

493 G. F. R. Ellis and J. E. Baldwin, "On the Expected Anisotropy of Radio Source Counts," *Monthly Notices of the Royal Astronomical Society* 206, no. 2 (January 1, 1984): 206(2): 377–381, https://doi.org/10.1093/mnras/206.2.377.

494 Duhem, Vuillemin, and Broglie, *The Aim and Structure of Physical Theory*.

495 W. V. Quine, "On the Reasons for Indeterminacy of Translation," The Journal of Philosophy, January 1, 1970, 67(6): 178–183, https://doi.org/10.2307/2023887.

content of the theories. Van Fraassen (1980) defines a theory as "empirically appropriate" if what is said about observable phenomena is true. In cosmology the basic characteristics of the standard model impose two fundamental limits: the finiteness of the speed of light, and the fact that the theories that can be tested by their implications for cosmology imply too much energy to be tested on Earth. (Ellis (2007))

The observational cosmology research program[496] [497] shows to what extent an ideal set of observations can determine the spacetime geometry based on a minimum of cosmological hypotheses. The ideal data set involves astrophysical objects that can be used as standards for determining the properties and evolution of some sources. In practice, observers do not have access to the ideal data set, so they face challenges in understanding the nature of the sources and their evolution.

According to Christopher Smeenk and George Ellis, the problem in cosmology is the discrimination between models of a given theory, rather than a choice between competing theories. They give as an example the global symmetry assumed in the derivation of FLRW models. All the existing evidence is equally compatible with the models where this symmetry is not valid. One possibility would be that it be considered *a priori*, or as a precondition for cosmological theorizing. [498] Recently the justification of the FLRW models has been tried by using another weaker general principle, in conjunction with theorems related to homogeneity and isotropy. The Ehlers-Geren-Sachs theorem[499] shows that if all geodesic observers in a model where expansion is accepted determine the free-propagating background radiation is exactly isotropic, then the FLRW model is confirmed. If the causal past is "typical", the observations along our universe line will constrain what other observers can see (the Copernican principle). This principle can be tested indirectly, by verifying isotropy through the Sunyaev-Zel'dovich effect. Other tests are direct with a sufficiently good set of standards, and an indirect test based on the elapsed time of cosmological redirection. This way of working offers an empirical argument that the observed universe is well approximated

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[496] J. Kristian and R. K. Sachs, "Observations in Cosmology," *The Astrophysical Journal* 143 (February 1, 1966): 143: 379-399, https://doi.org/10.1086/148522.

[497] G. F. R. Ellis et al., "Ideal Observational Cosmology," *Physics Reports* 124, no. 5 (July 1, 1985): 124(5–6): 315–417, https://doi.org/10.1016/0370-1573(85)90030-4.

[498] Claus Beisbart, "Can We Justifiably Assume the Cosmological Principle in Order to Break Model Underdetermination in Cosmology?," *Journal for General Philosophy of Science* 40, no. 2 (December 1, 2009): 40(2): 175–205, https://doi.org/10.1007/s10838-009-9098-9.

[499] J. Ehlers, P. Geren, and R. K. Sachs, "Isotropic Solutions of the Einstein-Liouville Equations," *Journal of Mathematical Physics* 9, no. 9 (September 1, 1968): 9(9): 1344–1349, https://doi.org/10.1063/1.1664720.

by a FLRW model, thus transforming the initial philosophical hypothesis into an observationally tested basis. [500]

Soviet physicist Yakov Zeldovici called the early universe the "poor man's accelerator", because by observing the early universe phenomena from high energy physics can be studied. For quantum gravity, cosmology offers the only practical way to evaluate competing ideas.

Currently, there are debates about the legitimacy of different research programs in cosmology. One answer is to resort to hypothetical-deductivist (HD) models: a hypothesis becomes more reliable as one of its consequences is verified, and vice versa. But the HD model has several contested aspects (it is often called "naive HD", similar to Popper's naive falsifiability). The naive view does not allow the distinction between the sub-determined rival theories that make the same predictions. [501] Scientists distinguish between theories that simply "fit in with the data," as opposed to those that accurately capture laws and evaluate some successful predictions as more revealing than others.

A more sophisticated methodology can explicitly recognize the criteria that scientists use to evaluate scientific theories, [502] which include explanatory power, and coherence with other theories, in addition to compatibility with evidence. These factors should be clear and discriminatory. Alternatively, some of the desirable characteristics may be considered as part of what constitutes an empirical success.

2.4.6.3 Monitoring of weak gravitational lenses

With the help of the Hubble Space Telescope and the Very Large Telescope, general relativity tests were performed on a galactic scale. The ESO 325-G004 galaxy acts as a strong gravitational lens, distorting light from a farther galaxy and creating an Einstein ring around its center. Comparing ESO 325-G004 mass, by measurements of the motion of the stars inside this galaxy, with the curvature of the space around it, gravity behaved according to general relativity. [503]

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[500] Smeenk and Ellis, “Philosophy of Cosmology.”

[501] Vincenzo Crupi, “Confirmation,” May 30, 2013, https://plato.stanford.edu/archives/win2016/entries/confirmation/.

[502] George F R Ellis, “Issues in the Philosophy of Cosmology,” in *Philosophy of Physics*, ed. Jeremy Butterfield and John Earman, Handbook of the Philosophy of Science (Amsterdam: North-Holland, 2007), 1183–1286, https://doi.org/10.1016/B978-044451560-5/50014-2.

[503] Thomas E. Collett et al., “A Precise Extragalactic Test of General Relativity,” *Science* 360, no. 6395 (June 22, 2018): 360 (6395): 1342–1346, https://doi.org/10.1126/science.aao2469.

Weak gravitational lens studies are in its infancy. The weak lenses produce distortions in the apparent image of the size, shape and fluxes of the astrophysical object used as a cosmic lens. The study of weak gravitational lenses is a good method for GR testing, and a strong proof of the existence of dark energy and dark matter. [504]

Reyes and others measured "gravitational slip" as the difference between two different gravitational potentials that define matter disturbances. In the GR this value is zero or very small, but in other theories it is different from zero and leads to substantial differences in the power of gravitational lenses. [505]

More recently, Blake et al., [506] performed similar GR tests on cosmological distances, using spectroscopic data and imaging. They found that the results validate the GR.

2.5 Anomalies of general relativity

Over time, the general theory of relativity has accumulated several anomalies and discrepancies, indicating the need for a better theory about gravity or other approaches:

- Stars in galaxies have a distribution of increasing speeds from the center to the periphery, with a greater variation than predicted. The same is true of galaxies in galaxy clusters. The hypothesis of dark matter, which would interact by gravity but not electromagnetically, could explain the discrepancy. There are also various changes in Newtonian dynamics that can explain this anomaly, such as the MOND theory.
- Spacecrafts experienced greater acceleration than predicted during gravitational maneuvers.
- The metric expansion of space seems to be accelerating. Dark energy was introduced as a hypothesis to explain this. A recent explanation is that space geometry is not homogeneous due to galaxy clusters, but this hypothesis is challenged. [507]

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[504] Yong-Seon Song and Olivier Doré, "A Step towards Testing General Relativity Using Weak Gravitational Lensing and Redshift Surveys," *Journal of Cosmology and Astroparticle Physics* 2009, no. 03 (March 23, 2009): 025, https://doi.org/10.1088/1475-7516/2009/03/025.

[505] Reinabelle Reyes et al., "Confirmation of General Relativity on Large Scales from Weak Lensing and Galaxy Velocities," *Nature* 464, no. 7286 (March 2010): 464(7286: 256–258, https://doi.org/10.1038/nature08857.

[506] Chris Blake et al., "RCSLenS: Testing Gravitational Physics through the Cross-Correlation of Weak Lensing and Large-Scale Structure," *Monthly Notices of the Royal Astronomical Society* 456, no. 3 (March 1, 2016): 456(3): 2806–2828, https://doi.org/10.1093/mnras/stv2875.

[507] Anil Ananthaswamy, "Swiss-Cheese Model of the Cosmos Is Full of Holes," New Scientist, 2008, https://www.newscientist.com/article/mg20026783-800-swiss-cheese-model-of-the-cosmos-is-full-of-holes/.

- Recent measurements show that planetary orbits grow faster than predicted by the loss of the Sun's mass by radiative energy.
- Photons from cosmic radiation should gain energy and then lose it on the way, but in reality, they gain twice as much energy as predicted by theory. One hypothesis would be that gravity decreases faster than the inverse square at certain distances.
- Extra massive hydrogen clouds: Lyman-alpha spectral lines suggest that hydrogen clouds are more crowded at certain scales than expected and, like dark flux, may indicate that gravity is slower than inverse squares at certain distances. [508]

The ad-hoc hypotheses introduced in general relativity to explain gravitational singularities based on energy conditions are not very efficient. More detailed assumptions on the content of the subject are needed. [509] Many scientists and philosophers have come to the conclusion that singularities must be associated with reaching the limits of the physical validity of general relativity, and a new theory of quantum gravity needs to be developed.

A singularity that can causally influence certain parts of the space is called *naked singularity*. Penrose proposed the elimination of naked singularities using the cosmic censorship hypothesis. [510] Demonstrating the cosmic censorship hypothesis is one of the central mathematical problems of general relativity.

According to some scientists, general relativity contains the germs of its own destruction, since the theory is incapable of predicting physics on the Planck scale, and problems such as non-renormalizability and singularities are "known unknown." [511]

2.6 The saturation point of general relativity

According to the methodology of Lakatos research programs, general relativity can be divided into several periods: the initial period, the stagnation period, the maturity period, and the saturation point. The initial period ("Genesis", 1887-1919) includes the two great experiments of relativistic physics, the Michelson-Morley experiment and the Eotvos experiment, and the two confirmations, the deformation of light and the perihelion advance of Mercury. There followed a period of

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[508] Marcus Chown, "Gravity May Venture Where Matter Fears to Tread," New Scientist, accessed May 3, 2019, https://www.newscientist.com/article/mg20126990-400-gravity-may-venture-where-matter-fears-to-tread/.

[509] Alan D. Rendall, "The Nature of Spacetime Singularities," *ArXiv:Gr-Qc/0503112*, November 2005, 76–92, https://doi.org/10.1142/9789812700988_0003.

[510] R. Penrose, "Singularities and Time-Asymmetry.," 1979, 581–638, http://adsabs.harvard.edu/abs/1979grec.conf..581P.

[511] David Tong, *String Theory* (University of Cambridge, 2009), http://www.damtp.cam.ac.uk/user/tong/string/string.pdf.

stagnation ("Hibernation", 1920-1960) during which the theory took it before technological and experimental possibilities, the theory being even removed from the textbooks of physics and astronomy.

The maturity of the theory begins in 1960, when the astronomical discoveries and new experiments drew attention to the GR. This period (1960 - 1980) was named by Will as a "Golden Era",[512] in which observable predictions of GR were systematized, compared to other alternative theories, and new experiments were proposed for testing. The first experiment of this period was developed to confirm the change in gravitational frequency of light (1960) and ended with the confirmation of the GR prediction of the energy loss of gravitational waves (1979) by observing the Hulse-Taylor binary pulsar.

From 1980 the saturation zone of the GR began, called by Will as "Quest for Strong Gravity". Some of the new predictions of the theory are now insignificant and difficult to verify, in some cases requiring still undeveloped technologies. The theory began to be attacked by new experimental theories or techniques, such as using laser-cooled ion atoms and traps to perform ultra-precise tests, proposing a "fifth" force, or additional dimensions to test the inverse square law of gravity. Increased attention has begun to be paid to the effects of strong gravitational fields, near the horizon of the event of a non-rotating black hole, in neutron stars or, for the extended universe, associated gravitational fields on the Planck scale.

In Einstein's equations of classical general relativity, there remains a fundamental asymmetry between gravitational and non-gravitational fields: on the left, a geometrical object ($g_{\mu\nu}$, the Einstein tensor), representing the curvature of spacetime, is identical with the phenomenological but non -geometrical representation of tensor of the matter on the right side.

$$(1)\ G_{\mu\nu} = kT_{\mu\nu},\ \text{where}\ G_{\mu\nu} \equiv R_{\mu\nu} - (1/2)g_{\mu\nu}R$$

Thus, in his lecture for the Nobel Prize in July 1923, Einstein stated:

> "The mind striving after unification of the theory cannot be satisfied that two fields should exist which, by their nature, are quite independent. A mathematically unified field theory is sought in which the gravitational field and the electromagnetic field are interpreted as only different components or manifestations of the same uniform field, … The gravitational theory, considered in

512 Will, "The Confrontation between General Relativity and Experiment."

> terms of mathematical formalism, i.e., Riemannian geometry, should be generalized so that it includes the laws of the electromagnetic field." [513]

There is theoretical evidence that disregards Einstein equivalence principle (EEP) in certain cases, through quantum gravitational effects, effects derived from string theory, or through other undetected interactions so far. In string theory there are such fields that violate EEP, but the theory is not yet mature enough to materialize such a refutation. Clifford M. Will states that observing effects that appear to violate the EEP is, to some extent, semantic. The fields involved in string theory can be long distances and can mimic gravitational fields, but no way has been found to do so. [514] The idea of using EEP tests in this way appeared in the 1980s, in search of a "fifth" force[515] as a force of about a percentage of gravity but with a range of several hundred meters, implying a deviation from the inverse-square law of Newtonian gravity. The idea came about when using gravity profile measurements from deep mines in Australia and from new ideas in particle physics, suggesting the possible presence of very small gravity particles. Numerous experiments have sought evidence of this force by measuring acceleration differences by composition, but the results have not been conclusive, the consensus being that there is no credible experimental evidence for a fifth force. [516]

The possibility that the inverse square law would be violated at very short intervals in laboratory tests[517] provided that some of the extra spatial dimensions in string theory could extend beyond macroscopic scales. On a small scale, gravity deviates from the known law. Many methods of high precision and low noise have been developed, adapted for laboratory tests. No deviations from the inverse square law were found. [518]

Gravitational singularities are considered to be a spacetime limit. General relativity allows for the existence of singularities, but it cannot say anything about what is happening inside them, and scientists have not yet agreed on a definition of them, also considering that without a geometry in accordance with the laws of physics cannot exist a spacetime location. In conclusion, they say, one

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513 Albert Einstein, *Fundamental Ideas and Problems of the Theory of Relativity: Lecture Delivered to the Nordic Assembly of Naturalists at Göteborg on July 11, 1923* (Nobel Museum, 2009), 489.

514 Will, "The Confrontation between General Relativity and Experiment."

515 Fischbach et al., "Reanalysis of the Eotvos Experiment," 56, 3–6.

516 C. M. Will, "Twilight Time for the Fifth Force?," 1990, 80, 472–479, http://connection.ebscohost.com/c/articles/9011192203/twilight-time-fifth-force.

517 Lisa Randall and Raman Sundrum, "An Alternative to Compactification," *Physical Review Letters* 83, no. 23 (December 6, 1999): 83, 4690–4693, https://doi.org/10.1103/PhysRevLett.83.4690.

518 Joshua C. Long et al., "Upper Limits to Submillimetre-Range Forces from Extra Space-Time Dimensions," *Nature* 421, no. 6926 (February 2003): 421, 922–925, https://doi.org/10.1038/nature01432.

cannot speak of singularities, but rather of singular spacetimes, although in principle these terms are equivalent. [519] Clarke[520] and Earman, [521] as well as Geroch, Can-bin and Wald[522] and Curiel,[523] argue that a precise, rigorous and univocal definition of singularity is needed for a better approach to them and for a more accurate modeling of spacetime aspects. [524] It is common assertion that general relativity, considering spacetime as singular, predicts its own inability to limit the singularities of black holes and the Big Bang, negating their reality. It is hoped that a more fundamental theory, possibly quantum gravity, will solve this problem. [525]

The black holes appear, according to general relativity, when the cosmic body collapsed under the so-called Schwarzschild ray, proportional to the body mass. The "event horizon" of a black hole is the point where there is no turning back, within which the gravitational attraction is greater than any attempt to exit this area, including for light.[526] (1) For a standard black hole (uncharged, non-rotating), the horizon of the event is within the Schwarzschild radius. From the point of view of a person outside the event horizon, the time near a black hole is delayed due to the strong gravity, until the time intervals reach infinitely large within the horizons of events. From the perspective of the person entering the horizon of events, nothing unusual happens. Time is running the same way and he does not realize that he has entered the horizon of events.

Relativistic black holes are purely gravitational entities. They are solutions to the "vacuum" of Einstein's field equations. In the context of general relativity, Erik Curiel states that gravity is given up and a curved geometry of spacetime is postulated that produces all the effects of gravity, the

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[519] Erik Curiel, "Singularities and Black Holes," in *The Stanford Encyclopedia of Philosophy*, ed. Edward N. Zalta, Spring 2019 (Metaphysics Research Lab, Stanford University, 2019), https://plato.stanford.edu/archives/spr2019/entries/spacetime-singularities/.

[520] C. J. S. Clarke, "The Analysis of Space-Time Singularities by C. J. S. Clarke," Cambridge Core, May 1994, https://doi.org/10.1017/CBO9780511608155.

[521] John Earman, "Bangs, Crunches, Whimpers and Shrieks: Singularities and Acausalities in Relativistic Spacetimes," *British Journal for the Philosophy of Science* 49, no. 2 (1998): 338–347.

[522] Robert Geroch, Liang Can-bin, and Robert M. Wald, "Singular Boundaries of Space–Times," *Journal of Mathematical Physics* 23, no. 3 (March 1, 1982): 23(3): 432–435, https://doi.org/10.1063/1.525365.

[523] Erik Curiel, "The Analysis of Singular Spacetimes," *Philosophy of Science* 66, no. 3 (1999): 66(S1): S119–S145.

[524] Nicolae Sfetcu, *Singularitățile ca limite ontologice ale relativității generale* (MultiMedia Publishing, 2018), http://doi.org/10.13140/RG.2.2.17470.18242.

[525] Abhay Ashtekar and Martin Bojowald, "Quantum Geometry and the Schwarzschild Singularity," *Classical and Quantum Gravity* 23, no. 2 (January 21, 2006): 23(2): 391–411, https://doi.org/10.1088/0264-9381/23/2/008.

[526] A more accurate description distinguishes other types of horizon, such as apparent horizons, cf. HawkingHawking et al., *The Large Scale Structure of Space-Time*, 312–20.

black hole being no more a "thing" in space, but a feature of spacetime itself. [527] The matter of the collapsing star disappears in the singularity of the black hole, leaving only the geometrical properties of the black hole (mass, charge and angular momentum), according to theorems called "no-hair", regardless of the previous physical properties of objects that collapse into a black hole.

A "naked" singularity does not have a horizon of events. This implies a fundamental break in the structure of spacetime. [528] [529] A version of a naked singularity is the "white hole", a black hole reversed in time, from which matter and objects from nothing could appear. Since the equations of the field of general relativity do not select a preferred direction of time, and the formation of a black hole is allowed, then white holes will be allowed by these laws. [530] Roger Penrose asserts that naked singularities will never be formed, introducing an ad-hoc hypothesis called the "cosmic censorship hypothesis": a singularity will always be in a black hole that is surrounded by the horizon of events. The former was abandoned in time. Several alternative hypotheses have been proposed to eliminate the possibility of naked singularities that violate the principle of causality, [531] [532] but none is considered satisfactory to date.

Black holes provide an essential testing ground for the conceptual problems underlying quantum gravity and general relativity, regarding the violation of energy conservation and micro-causality, and the paradox of information loss. Quantum gravity seems to be the best candidate for modeling these phenomena.

In 1971, Hawking introduced the conjecture that the total surface of event horizons in any group of black holes does not decrease, even if they unite (the second law of black hole mechanics, by similarity to entropy in thermodynamics). [533] To prevent the black holes from having zero entropy, Bekenstein proposed that a black hole would have an entropy proportional to the area of its horizon. [534] Hawking discovered that quantum field theory predicts that a black hole behaves like a black body radiating at a constant temperature, thus violating the second law of black hole mechanics

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[527] Curiel, "Singularities and Black Holes."

[528] Sfetcu, *Singularitățile ca limite ontologice ale relativității generale*.

[529] Earman, "Bangs, Crunches, Whimpers and Shrieks," 65–66.

[530] Curiel, "Singularities and Black Holes."

[531] Pankaj S. Joshi, "Cosmic Censorship: A Current Perspective," *ArXiv:Gr-Qc/0206087*, June 28, 2002, 17(15): 1067–1079, http://arxiv.org/abs/gr-qc/0206087.

[532] Earman, "Bangs, Crunches, Whimpers and Shrieks," chap. 3.

[533] S. W. Hawking, "Gravitational Radiation from Colliding Black Holes," *Physical Review Letters* 26, no. 21 (May 24, 1971): 26 (21): 1344–1346, https://doi.org/10.1103/PhysRevLett.26.1344.

[534] Robert M. Wald, "The Thermodynamics of Black Holes," *Living Reviews in Relativity* 4, no. 1 (July 9, 2001): 4 (1): 6, https://doi.org/10.12942/lrr-2001-6.

due to energy loss and hence shrinkage. But radiation removes also entropy, and so the amount of entropy of matter is increasing. This allows the formulation of the first law of black hole mechanics similar to the first law of thermodynamics, with the mass acting as energy, the gravity of the surface as temperature, and the area as entropy. [535] In this interpretation of the black hole, general relativity is unsatisfactory, and a better theory of quantum gravity is needed. [536]

A black hole only holds information about the total mass, charge and angular momentum. The theory of stable black holes states that this loss is not a problem, because the information can be considered as being present in the black hole, inaccessible from the outside but represented on the horizon of the event in accordance with the holographic principle. But in the theory that black holes slowly evaporate through Hawking radiation, information about the matter that formed the black hole is irretrievably lost. In quantum mechanics, the loss of information corresponds to the violation of unity, related to the conservation of probability, resulting in the violation of energy conservation. [537] The latest studies show that information and unity are nevertheless preserved in a quantum treatment of the problem. [538]

In the case of a body falling into a black hole, the theory of the quantum field in curved space involves quantities of Hawking radiation, including only a finite amount of information encoded in Hawking radiation. But the inseparability of the particle at the exit of all the Hawking radiation that the black hole has previously emitted creates a paradox called "the monogamy of inseparability." [539] To solve the paradox, one of the three theories tested over time should be discarded: the principle of Einstein's equivalence, unitarity, or the existing theory of the quantum field. The renunciation of the principle of equivalence implies a "firewall" that destroys the particles that enter in the horizon of the event. [540] The 2016 LIGO data shows possible echo signals

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[535] Wald, 4 (1): 6.

[536] S. Carlip, "Black Hole Thermodynamics and Statistical Mechanics," in *Physics of Black Holes: A Guided Tour*, ed. Eleftherios Papantonopoulos, Lecture Notes in Physics (Berlin, Heidelberg: Springer Berlin Heidelberg, 2009), 769: 89–123, https://doi.org/10.1007/978-3-540-88460-6_3.

[537] Steven B. Giddings, "The Black Hole Information Paradox," *ArXiv:Hep-Th/9508151*, August 28, 1995, http://arxiv.org/abs/hep-th/9508151.

[538] Samir D. Mathur, "The Information Paradox: Conflicts and Resolutions," *Pramana* 79, no. 5 (November 1, 2012): 1059–73, https://doi.org/10.1007/s12043-012-0417-z.

[539] Zeeya Merali, "Astrophysics: Fire in the Hole!," *Nature News* 496, no. 7443 (April 4, 2013): 20–23, https://doi.org/10.1038/496020a.

[540] Jennifer Ouellette, "Black Hole Firewalls Confound Theoretical Physicists," Scientific American, 2012, https://www.scientificamerican.com/article/black-hole-firewalls-confound-theoretical-physicists/.

due to a fuzzy horizon of events, possible in fuzzball theories, but impossible in general classical relativity. [541]

The need for consistency between quantum theory and general relativity, [542] and the existence of singularities, require the emergence of a complete theory of quantum gravity. [543] So far, such a complete and consistent theory has failed to develop, although there are several candidates. [544]

The generalization of quantum field theory from the elementary particle physics to include gravity has failed. [545] At low energies the theory is acceptable, but at very high energies, the results are very divergent and lead to models without predictive power. [546]

An attempt to eliminate these limitations is string theory, a quantum theory. The theory promises a unification of gravity with the other forces, supplementing the three spatial dimensions with another six. [547] A newer version of the theory, the superstring theory, is trying to unify general relativity and supersymmetry, under the name of supergravity, [548] and a hypothetical unifying model with eleven dimensions known as M-theory. [549]

Another approach uses the canonical quantization of quantum theory in which, starting from general relativity, one reaches the Wheeler-deWitt equation, an analogue of the Schrödinger

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[541] Zeeya Merali, "LIGO Black Hole Echoes Hint at General-Relativity Breakdown," *Nature News*, 2016, 540, https://doi.org/10.1038/nature.2016.21135.

[542] S. Carlip, "Quantum Gravity: A Progress Report," *Reports on Progress in Physics* 64, no. 8 (August 1, 2001): sec. 2, https://doi.org/10.1088/0034-4885/64/8/301.

[543] Schutz, "Gravity from the Ground Up by Bernard Schutz," 407.

[544] Herbert W. Hamber, *Quantum Gravitation: The Feynman Path Integral Approach* (Berlin Heidelberg: Springer-Verlag, 2009), https://www.springer.com/gp/book/9783540852926.

[545] G. 't Hooft and M. Veltman, "One-Loop Divergencies in the Theory of Gravitation," *Annales de L'Institut Henri Poincare Section (A) Physique Theorique* 20 (1974): 20 (1): 69, http://adsabs.harvard.edu/abs/1974AIHPA..20...69T.

[546] Steven Weinberg, *The Quantum Theory of Fields, Volume 2: Modern Applications*, 1 edition (Cambridge: Cambridge University Press, 2005).

[547] M. B. Green, J. H. Schwarz, and E. Witten, "Superstring Theory. Vol. 1: Introduction," *ZAMM - Journal of Applied Mathematics and Mechanics / Zeitschrift Für Angewandte Mathematik Und Mechanik* 68, no. 6 (1988): 258–258, https://doi.org/10.1002/zamm.19880680630.

[548] Steven Weinberg, *The Quantum Theory of Fields, Volume 3: Supersymmetry*, 1st Edition edition (Cambridge: Cambridge University Press, 2005).

[549] P. K. Townsend, "Four Lectures on M-Theory," *ArXiv:Hep-Th/9612121*, December 11, 1996, 13: 385, http://arxiv.org/abs/hep-th/9612121.

equation, but which has been wrongly defined. [550] By introducing Ashtekar *ad-hoc* (variable) hypotheses, it was developed the theory of loop quantum gravity. [551]

There are numerous other attempts to arrive at a viable theory of quantum gravity, based on the Feynman approach and the Regge calculation, dynamic triangulations, causality sets, twistor models[552] or the models based on integrals of paths of the quantum cosmology. [553] All candidate theories still have major formal and conceptual problems that are difficult to overcome so far, including the impossibility of verifying predictions through experimental tests. [554]

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[550] Karel Kuchař, "Canonical Quantization of Gravity," *Relativity, Astrophysics and Cosmology*, 1973, 237–288, https://doi.org/10.1007/978-94-010-2639-0_5.

[551] Abhay Ashtekar and Jerzy Lewandowski, "Background Independent Quantum Gravity: A Status Report," *Classical and Quantum Gravity* 21, no. 15 (August 7, 2004): 21 (15): R53–R152, https://doi.org/10.1088/0264-9381/21/15/R01.

[552] Penrose, *The Road to Reality*.

[553] S. W. Hawking and W. Israel, *Quantum Cosmology, in Three Hundred Years of Gravitation* (Cambridge University Press, 1989), 631–651.

[554] John H. Schwarz, "String Theory: Progress and Problems," *Progress of Theoretical Physics Supplement* 170 (May 1, 2007): 170: 214–226, https://doi.org/10.1143/PTPS.170.214.

3. Quantum gravity

Recent decades indicate "a blurring of distinction between physical science and mathematical abstraction ... [reflecting] a growing tendency to accept, and in some cases ignore, serious testability problems." [555] Oldershaw lists dozens of major non-testing issues in the pre-instrumentalist era.

From a methodological point of view, both Newton and Einstein, and later Dirac, unreservedly supported the principle of mathematical simplicity in discovering the new physical laws of nature. They were joined by Poincaré and Weyl. "For Dirac the principle of mathematical beauty was partly a method-ological moral and partly a postulate about nature's qualities. It was clearly inspired by the theory of relativity, the general theory in particular, and also by the development of quantum mechanics... mathematical-aesthetic considerations should (sometimes) have priority over experimental facts and in this way act as criteria of truth." [556]

Eduard Prugovecki states that quantum gravity has required the consideration of fundamental epistemological questions, which can be identified in philosophy with the mind-body problem and the problem of free will. [557] These questions influenced the epistemology of quantum mechanics in the form of von Neumann's "psycho-physical parallelism"[558] and the subsequent analysis of the thesis by Wigner[559] that "the collapse of the wave packet" occurs in the mind of the "observer". Quantum gravity in cosmology involves the problem of the experimenter's freedom to change local physical conditions, a passive "observer". In any theory that describes a single universe, questions arise about the nature of causality in the traditional philosophical sense. [560]

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[555] Robert L. Oldershaw, "The New Physics—Physical or Mathematical Science?," *American Journal of Physics* 56, no. 12 (December 1, 1988): 1076, https://doi.org/10.1119/1.15749.

[556] Helge Kragh, *Dirac: A Scientific Biography*, 1 edition (Cambridge England ; New York: Cambridge University Press, 1990), 277, 284.

[557] Hermann Weyl and Frank Wilczek, *Philosophy of Mathematics and Natural Science*, Revised ed. edition (Princeton, N.J: Princeton University Press, 2009).

[558] John Von Neumann, *Mathematische grundlagen der quantenmechanik,* (Berlin: J. Springer, 1932).

[559] E. P. Wigner et al., "The Scientist Speculates: An Anthology of Partly-Baked Ideas," *American Journal of Physics* 32, no. 4 (April 1, 1964): 168–81, https://doi.org/10.1119/1.1970298.

[560] Mario Bunge, "The Revival of Causality," in *La Philosophie Contemporaine / Contemporary Philosophy: Chroniques Nouvelles / A New Survey*, ed. Guttorm Fløistad, International Institute of Philosophy / Institut International de Philosophie (Dordrecht: Springer Netherlands, 1982), 133–55, https://doi.org/10.1007/978-94-010-9940-0_6.

A quantum theory of gravity may be useful in unifying general relativity with the principles of quantum mechanics, but difficulties arise in this attempt. [561] The resulting theory is not renormalizable,[562] and cannot make significant physical predictions. Later developments led to string theory and loop quantum gravity. [563] The structure of general relativity would result from the quantum mechanics of the interaction of theoretical particles without mass of spin-2, called gravitons, [564] although there is no concrete evidence of them.

The dilaton appeared in Kaluza-Klein theory, a five-dimensional theory that combines gravity and electromagnetism, and later in string theory. The equation of the field that governs the dilaton, derived from the differential geometry, could be subject to quantization. [565] Because this theory can combine gravitational, electromagnetic and quantum effects, their coupling could lead to a means of justifying the theory through cosmology and experiments.

However, gravity is perturbatively nonrenormalizable. [566] The theory must be characterized by a choice of *finitely many* parameters which, in principle, can be established by experiment. But, in quantifying gravity, in the theory of perturbation, there are *infinitely many independent parameters* needed to define the theory.

It is possible that, in a correct quantum gravity theory, the infinite unknown parameters are reduced to a finite number which can then be measured. One of the possibilities is to have new, undiscovered principles of symmetry that constrain the parameters and reduce them to a finite set, a path followed by string theory.

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561 A. Zee, *Quantum Field Theory in a Nutshell, 2nd Edition*, 2 edition (Princeton, N.J: Princeton University Press, 2010), 172, 434–435.

562 Renormalization is an "absorption" of infinities by redefining a finite number of physical parameters. The physical parameters (mass, charge, etc.) have perfectly finite values when observed in real experiments. In the case of gravity, the perturbative theory is not renormalizable. In order to renormalize the theory, we should introduce infinitely many "absorption parameters", each having to be determined by experiment.

563 Penrose, *The Road to Reality*, 1017.

564 S. Deser, "Self-Interaction and Gauge Invariance," *General Relativity and Gravitation* 1, no. 1 (March 1, 1970): 1: 9–18, https://doi.org/10.1007/BF00759198.

565 T. Ohta and R. B. Mann, "Canonical Reduction of Two-Dimensional Gravity for Particle Dynamics," *Classical and Quantum Gravity* 13, no. 9 (September 1, 1996): 13 (9): 2585–2602, https://doi.org/10.1088/0264-9381/13/9/022.

566 Richard P Feynman et al., *Feynman Lectures on Gravitation* (Reading, Mass.: Addison-Wesley, 1995), xxxvi–xxxviii; 211–12.

There are several theories that address quantum gravity, but none are complete and consistent. The models must overcome major formal and conceptual problems, including the formulation of predictions that can be verified by experimental tests. [567]

String theory involves objects similar to strings propagating in a fixed spacetime background, and interactions between closed strings give rise to spacetime in a dynamic way. This promises to be a unified description of all particles and interactions. [568] One way in string theory will always correspond to a graviton, but to this theory unusual features appear, such as six additional dimensions of space. In an evolution of this program, the superstring theory, it is trying to unify the string theory, general relativity and supersymmetry, known as supergravity in an eleven-dimensional hypothetical model known as M-theory. [569]

Quantum gravitational effects are extremely weak, and therefore difficult to test. In recent years physicists have concentrated on studying the possibilities of experimental tests, [570] the most targeted being the violations of Lorentz invariance, the quantum gravitational effects in the cosmic microwave background, and the decoherence induced by the spacetime fluctuations.

Quantum gravity theories are affected by a lot of technical and conceptual problems. Tian Cao argues that quantum gravity offers a unique opportunity for philosophers, allowing them "a good chance to make some positive contributions, rather than just analysing philosophically what physicists have already established." [571] Carlo Rovelli (the architect of loop quantum gravity) urges philosophers not to limit themselves to "commenting and polishing the present fragmentary physical theories, but would take the risk of trying to look ahead." [572]

Conceptual difficulties arise mainly from the nature of gravitational interaction, in particular the equivalence of gravitational and inertial masses, which allows the representation of gravity as a

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[567] Abhay Ashtekar, "Loop Quantum Gravity: Four Recent Advances and a Dozen Frequently Asked Questions," in *The Eleventh Marcel Grossmann Meeting* (World Scientific Publishing Company, 2008), 126, https://doi.org/10.1142/9789812834300_0008.

[568] L. E. Ibanez, "The Second String (Phenomenology) Revolution," *Classical and Quantum Gravity* 17, no. 5 (March 7, 2000): 17 (5): 1117–1128, https://doi.org/10.1088/0264-9381/17/5/321.

[569] Townsend, "Four Lectures on M-Theory," 13: 385.

[570] Sabine Hossenfelder, "Experimental Search for Quantum Gravity," *ArXiv:1010.3420 [Gr-Qc, Physics:Hep-Ph, Physics:Hep-Th]*, October 17, 2010, chap. 5, http://arxiv.org/abs/1010.3420.

[571] Tian Yu Cao, "Prerequisites for a Consistent Framework of Quantum Gravity," *Studies in History and Philosophy of Science Part B: Studies in History and Philosophy of Modern Physics* 32, no. 2 (2001): 138.

[572] Carlo Rovelli, "Halfway Through the Woods: Contemporary Research on Space and Time," in *The Cosmos of Science*, ed. John Earman and John Norton (University of Pittsburgh Press, 1997), 182.

property of space itself, rather than as a field propagated in spacetime. When quantizing gravity some of the properties of spacetime are subjected to quantum fluctuations. But quantum theory implies a well-defined classical background for these fluctuations. [573]

Yoichiro Nambu[574] has researched the "postmodern physics" of quantum gravity, of its spacing from experiments. There are certain methods of evaluating the theory, and constraints. Their investigation is a current research problem. [575] Audretsch[576] argues that quantum gravity research runs counter to Kuhn's paradigms, in quantum gravity co-existing several paradigms, both well-confirmed and universal. Given that both general relativity and quantum theory claim to be universal theories, any conceptual or formal tension between them would indicate that the universality of one or both theories is wrong. Peter Galison[577] argues that mathematical constraints take the place, in quantum gravity, of empirical constraints.

Most physicists focus their attention on string theory, but loop quantum gravity (LQG) is an active program, as are other programs. It is extremely difficult to make concrete predictions in these theories. String theory is affected by the lack of testable experimental predictions due to the extremely large number of distinct states, and the absence of guiding principles for highlighting the physically significant ones. [578] The LQG seems to be less affected by the lack of predictions, the discreteness of the area and volume operators represent concrete forecasts of the theory, with potentially verifiable consequences, making the theory more susceptible to falsification and therefore more scientific than string theory. [579] But it is not clear how these quantities can actually be observed.

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[573] Steven Weinstein, "Absolute Quantum Mechanics," Preprint, 2000, 52: 67–73, http://philsci-archive.pitt.edu/836/.

[574] Y. Nambu, "Directions of Particle Physics," *Progress of Theoretical Physics Supplement* 85 (1985): 104–110, https://doi.org/10.1143/PTPS.85.104.

[575] Dean Rickles, "A Philosopher Looks at String Dualities," *Studies in the History and Philosophy of Modern Physics* 42 (2011): 42: 54–67, https://doi.org/10.1016/j.shpsb.2010.12.005.

[576] Audretsch, "Quantum Gravity and the Structure of Scientific Revolutions," 12(2): 322–339.

[577] Peter Galison, *Laws of Nature: Essays on the Philosophic, Scientific, and Historical Dimensions* (Berlin and New York: Walter de Gruyter, 1995), 369–408.

[578] Steven Weinstein and Dean Rickles, "Quantum Gravity," in *The Stanford Encyclopedia of Philosophy*, ed. Edward N. Zalta, Winter 2018 (Metaphysics Research Lab, Stanford University, 2018), https://plato.stanford.edu/archives/win2018/entries/quantum-gravity/.

[579] Lee Smolin, *The Trouble With Physics: The Rise of String Theory, The Fall of a Science, and What Comes Next*, Reprint edition (Boston u.a: Mariner Books, 2007).

Steven Weinstein and Dean Rickles state that it is difficult to develop an observational test of a theory if we do not know where to look or what to look at, [580] due to the fact that most quantum gravity theories seem to consider only very large energy scales, of the order 10^{19} GeV, needing a particle accelerator of galactic size to approach the necessary energies.

The most notable "test" of theories of quantum gravity imposed by the community to date involves a phenomenon that has never been observed, the so-called Hawking radiation from black holes. The string theory and the loop quantum gravity both passed the test, using different degrees of microscopic freedom. Erik Curiel[581] argued how this test is used as evidence in the same way that empirical evidence is used to justify a common theory. Although the result of Bekenstein-Hawking does not have the empirical factual status, it is a powerful deduction from a framework that is quite mature, namely the quantum field theory on a curved spacetime background, which may function as a constraint on possible theories.

In quantum gravity, it is particularly important to have some constraints agreed to guide the construction, and a complete theory of quantum gravity should reproduce the predictions of the semi-classical theory of gravity as one of its possible limits. [582] Curiel questions the classification of quantum gravity approaches according to scientific merit, such as elegance and coherence, which he does not consider to be scientific. He states that the explanatory potential of theories must be taken into account. So far, none of the main research programs has shown that it properly reproduces the world at low energies. There are indications that both theories will overcome this challenge. [583] [584]

Bryce DeWitt stated that the gravitational field should be quantized to be consistent with quantum mechanics, [585] based on two premises: logical arguments, and the analogy between the electromagnetic and gravitational fields. But Planck's length is so small that aspects of reality that

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[580] Brading, Castellani, and Teh, "Symmetry and Symmetry Breaking."

[581] Erik Curiel, "Against the Excesses of Quantum Gravity: A Plea for Modesty," *Proceedings of the Philosophy of Science Association* 2001, no. 3 (2001): 68(3): S424–S441.

[582] Weinstein and Rickles, "Quantum Gravity."

[583] Thomas Thiemann, "The Phoenix Project: Master Constraint Programme for Loop Quantum Gravity," *Classical and Quantum Gravity* 23, no. 7 (April 7, 2006): 23(7): 2211, https://doi.org/10.1088/0264-9381/23/7/002.

[584] Mariana Graña, "The Low Energy Limit of String Theory and Its Compactifications with Background Fluxes," *Letters in Mathematical Physics* 78, no. 3 (December 1, 2006): 78(3): 279–305, https://doi.org/10.1007/s11005-006-0125-z.

[585] Bryce S. DeWitt, "Definition of Commutators via the Uncertainty Principle," *Journal of Mathematical Physics* 3 (July 1, 1962): 619–24, https://doi.org/10.1063/1.1724265.

define a theory of quantum gravity, such as "emergence", "phenomenon" or "empirical", cannot be considered under this dimension.

The first approach to interpreting quantum theory was "instrumentalist". Jeremy Butterfield and Christopher Isham state that the Copenhagen interpretation of quantum theory is not only as a minimal statistical interpretation of quantum formalism in terms of frequency of measurement results, but as insisting on a classical domain which, if it includes space and classical time, involves the fact that, speaking of "quantum gravity", we are wrong in trying to apply quantum theory to something that belongs to the classical background of this theory. A quantum theory of gravity should be avoided, but we can try the development of a "quantum theory of space and time." [586]

The "literalist" vision implies the interpretation of quantum theory "as close as possible" to quantum formalism. This involves two versions, one by Everett and one based on quantum logic. Everett's literalism has been discussed in relation to quantum gravity (especially quantum cosmology). Its purpose is to solve the "measurement problem": when the wave function collapse occurs in relation to macroscopic objects (such as instruments).

The theories of the extra values aim to interpret the quantum theory, especially in the measurement problem, without resorting to the collapse of the state vector, by postulating extra values for a certain "preferred quantity", together with a rule for the evolution of these values. But, contrary to Everett's theory, "extra values" do not imply other real physical worlds; they are just trying to be more accurate about the preferred quantity and dynamics of its values. Such theories are deBroglie-Bohm's interpretation of the "pilot wave" of quantum theory, and the various types of modal interpretation. [587] Basically, "extra values" preserve the ordinary unit dynamics (Schrodinger equation) of quantum theory but add equations that describe the temporal evolution of its extra values. The pilot wave interpretation was applied only to the quantum gravity research program based on quantum geometrodynamics. [588]

According to Jeremy Butterfield and Christopher Isham, the new dynamic is more radical than "extra values". It replaces the usual dynamics for solving the measurement problem by dynamically suppressing overlays. In recent years, the new dynamics, especially as a result of Ghirardi, Rimini

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[586] Jeremy Butterfield and Chris Isham, "Spacetime and the Philosophical Challenge of Quantum Gravity," in *Physics Meets Philosophy at the Panck Scale* (Cambridge University Press, 2001).

[587] Jeffrey Bub, *Interpreting the Quantum World*, 1st edition (Cambridge: Cambridge University Press, 1999).

[588] Butterfield and Isham, "Spacetime and the Philosophical Challenge of Quantum Gravity."

and Weber[589] and Pearle's "spontaneous localization" theories, [590] have developed considerably. Penrose was particularly active in supporting this idea.

Motivations for a theory of quantum gravity, from the perspective of elementary particle physics and quantum field theory:

1. Matter is made of elementary particles described in terms of quantum and interacting gravitationally.
2. The relativistic quantum field theory could only make sense by including gravity.
3. Quantum gravity will help unify the three fundamental non-gravitational forces.

Motivations for a theory of quantum gravity, from the perspective of general relativity:

1. The hope of eliminating singularities by introducing quantum effects.
2. The quantum explanation of the final nature of the black holes that lose mass through Hawking radiation.
3. Quantum gravity can help explain the very early universe, deducing from here the 4-dimensionality of spacetime, and the origin of the inflationary evolution.
4. It is hoped that a theory of quantum gravity will provide a quantum cosmology.

J. Butterfield lists four types of approaches in search of a theory of gravity: [591]

1. *Quantized general relativity*: it starts with the general relativity to which a certain type of quantification algorithm is applied. Two types of techniques are used for this purpose: a 4-dimensional spacetime approach to quantum field theory, and a canonical 3-dimensional approach to physical space. It was the first type of approach.
2. *General relativity as a limit to the low energy of a quantification of a different classical theory*: quantification algorithm is applied to a certain classical theory, recovered as a classical limit of the new quantum theory. This type of approach is exemplified by the main current research program: the superstring theory. There have been also several attempts to construct quantum theories of topology, and of causal structures.
3. *General relativity as a limit to the low energy of a quantum theory which is not a quantification of a classical theory*: it is considered to construct a quantum theory from scratch without a reference to a classical theory, without a certain classical limit.
4. *Starting from scratch with a radical new theory*. it is developed a theory that differs from both general relativity and quantum theory.

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[589] G. C. Ghirardi, A. Rimini, and T. Weber, "Unified Dynamics for Microscopic and Macroscopic Systems," *Physical Review D* 34, no. 2 (July 15, 1986): D34:470–491, https://doi.org/10.1103/PhysRevD.34.470.

[590] null Pearle, "Combining Stochastic Dynamical State-Vector Reduction with Spontaneous Localization," *Physical Review. A, General Physics* 39, no. 5 (March 1, 1989): A39:2277–2289.

[591] Butterfield and Isham, "Spacetime and the Philosophical Challenge of Quantum Gravity."

The fundamental principles of general relativity and quantum theory are so incompatible that any reconciliation will require a rethinking of the categories of space, time and matter. Currently, the dominant program is that of the superstrings, of the second type. The canonical quantum gravity in the Ashtekar approach is of the first type.

The construction of a quantum gravity theory is associated with two assumptions: classical notions of space and time are only approximately valid concepts, resulting from the "real" quantum nature of space and time, [592] and quantum gravity will provide classical physics on a deeper level. [593] [594]

The measurement problem implies that quantum theory cannot, in itself, explain any classical phenomenon - such as measurement results defined with well-defined spacetime and energy properties. [595] The need for general relativity for quantum gravity is somewhat analogous to the need for classical mechanics for quantum mechanics, the role of general relativity in the first case being to specify the scope of quantum theory. But quantum gravity can circumvent the need for a classical theory by choosing a different interpretation of quantum mechanics.

A first attempt to develop a theory of quantum gravity was the coupling of GR and quantum field theory (QFT), forming the so-called semi-classical theories. [596] In these theories matter fields are fundamental quantum theoretical structures, and gravity, that is, spacetime, is fundamentally classical (non-quantum). Basically, such a theory rewrites Einstein's equation.

Currently, "quantum gravity" is a more substantial reconciliation of gravity quantization, [597] building a quantum theory whose classical limit is in agreement with classical theory. Quantization does not necessarily imply the discretion of all observables, as in the case of position and momentum operators. Therefore, quantification of GR does not imply the discreteness of space.

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[592] J. Butterfield and C. J. Isham, "On the Emergence of Time in Quantum Gravity," *ArXiv:Gr-Qc/9901024*, January 8, 1999, 111–68, http://arxiv.org/abs/gr-qc/9901024.

[593] Steven Weinberg, *Dreams Of A Final Theory: The Search for The Fundamental Laws of Nature* (Random House, 2010).

[594] Max Tegmark and John Archibald Wheeler, "100 Years of the Quantum," *ArXiv:Quant-Ph/0101077*, January 17, 2001, 68–75, http://arxiv.org/abs/quant-ph/0101077.

[595] Henrik Zinkernagel, "The Philosophy Behind Quantum Gravity," *Theoria : An International Journal for Theory, History and Fundations of Science* 21, no. 3 (2010): 295–312.

[596] S. Carlip, "Is Quantum Gravity Necessary?," *Classical and Quantum Gravity* 25, no. 15 (August 7, 2008): 154010, https://doi.org/10.1088/0264-9381/25/15/154010.

[597] Christian Wuthrich, "To Quantize or Not to Quantize: Fact and Folklore in Quantum Gravity," Published Article or Volume, Philosophy of Science, 2005, 777–788, http://www.jstor.org/stable/10.1086/508946.

According to Kiefer, [598] quantum gravity (QG) theories can be grouped into primary and secondary theories. The former use standard quantization procedures (canonical or covariant) as in the case of quantum electrodynamics. The second includes QG as a limit of a fundamental quantum theoretical framework, e.g. string theory. It should be noted that this classification is based on how the approaches are conducted. From a systemic point of view, however, these approaches can be correlated. [599]

It is hoped that the quantum gravity will resolve the incompleteness of the current physics related to the QG problem, having as motivated cosmological considerations, the evolution of black holes, theoretical problems in QFT and unification. [600] [601] But there is no empirical need to build the theory. Both theories (quantum theory and general relativity) are in perfect agreement with all available data. The typical energy scale (or length) in which quantum gravitational effects become relevant is about 16 orders of magnitude larger than the current one. [602] So, pragmatically we cannot really hope for direct experimental data. [603]

In quantum gravity, the Planck length dimension is so small that it suggests that those aspects of reality that require a quantum gravity theory to describe them should not be referred to as, for example, "aspect", "phenomenon" or "empirical". Kantians assert that "emergence" is not only what is practically accessible, but whatever is located in space is part of the empirical reality. But J. Butterfield considers it unacceptable that these scales of length, energy, etc., being so small, really exist "in principle." [604] He states that these elements or their localized aspects are not empirical, although we might still call them "physical" and "real". If this is accepted, the various Kantian claims that space and time may have certain characteristics - for example, continuity - as a matter of *a priori* to the claims of those quantum gravity programs that deny space and time have to be reconciled. "The apparent contradiction would be an artefact of an ambiguity in 'space and

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[598] C. Kiefer, "Quantum Gravity: General Introduction and Recent Developments," *Annalen Der Physik* 518 (January 1, 2006): 15(12), 129148, https://doi.org/10.1002/andp.200510175.

[599] Steven Weinberg, "What Is Quantum Field Theory, and What Did We Think It Is?," *ArXiv:Hep-Th/9702027*, February 3, 1997, 241–251, http://arxiv.org/abs/hep-th/9702027.

[600] Wuthrich, "To Quantize or Not to Quantize," 777–788.

[601] Kiefer, "Quantum Gravity," 15(12), 129148.

[602] Nima Arkani-Hamed, "The Future of Fundamental Physics," 2012, 141(3), 53–66.

[603] Kian Salimkhani, "Quantum Gravity: A Dogma of Unification?," in *Philosophy of Science. European Studies in Philosophy of Science, Vol 9.*, ed. Alexander Christian et al. (Cham: Springer, 2018), 23–41.

[604] Butterfield and Isham, "Spacetime and the Philosophical Challenge of Quantum Gravity."

time': the quantum gravity programmes would not be about space and time in the Kantian sense." [605]

The Copenhagen interpretation can be understood not only as a minimal statistical interpretation of the quantum formalism for the frequency of the measurement results, but also as emphasizing a classical domain in the quantum system, with a firm separation from it and a quantum description of the first interpretation. If the classical domain includes the classical space and time, with regard to "quantum gravity" we would be wrong in applying quantum theory to something that is related to the classical background of that theory. To build a "quantum theory of space and time", a radical change of interpretation, possibly also of mathematical formalism and of quantum theory itself, is needed. [606]

An instrumentalist view specific to quantum theory should either deny that the quantum state describes individual systems, at least between measurements (similarly, be cautious in quantum description of these systems), or postulate a "non-quantum" domain whose description can be taken literally (not instrumentalist as in the first condition), with the respective domain being postulated as "classical domain" understood as macroscopic and / or the field of "measurements" and / or described by classical physics. [607] But recent applications of quantum theory make these conditions difficult to meet. It follows that we should seek an interpretation in which no fundamental role is assigned to "measurement", understood as an operation outside the domain of formalism.

If the instrumentalist interpretation of quantum theory is "as close as possible" to quantum formalism ("literalism"), one may reject the use of ideas such as measurement, "classical domain" or "external observer" to which a quantum-theoretical description is denied, rather a search for an interpretation of formalism is sought.

The question now arises whether theoretical statements can address any topic beyond observational data. Scientific anti-realists deny this possibility, as opposed to scientific realists. The scientific realist gives the electron and quark the same ontological status as the chairs and tables. The antirealist considers the concepts of invisible objects as mere technical tools to describe and predict visible phenomena, useful but without a value of truth. The instrumentalist also denies the possibility of true statements about invisible theoretical objects. Bas van Fraassen considers a less radical way to reject scientific realism. His constructive empiricism believes that statements about theoretical objects may in principle have a truth value, but it is impossible to gather sufficient evidence for the truth of any particular statement. Richard Dawid states that by avoiding the

[605] Butterfield and Isham.

[606] Butterfield and Isham.

[607] Butterfield and Isham.

ontological quality of the instrumentalist claim, constructive empiricism remains at an epistemological level. [608]

Due to the multitude of empirical data, scientists must build theoretical structures to help manipulate and analyze such data. There may be several sets of such theoretical structures that compete with each other and replace one another over time. Even the essential elements of scientific theories are not uniquely determined by empirical data (the principle of underdetermining scientific theories by experimental data). So there are no scientific statements that need to be considered indisputable (pessimistic meta-induction). Scientific theories seem too underdetermined to fit into a realistic scheme, but they are not sufficiently underdetermined to allow empiricism, this dilemma being difficult to avoid. [609]

A generalization of the underdetermination hypothesis espoused in particular by Quine, argues that no hypothetical ideal theoretical description, consistently covering all possible experimental data, would be unique. He admits the existence of theories that have identical phenomenological consequences but are still "logically incompatible" because of their incompatible sets of ontological objects. Quine is thus forced to distinguish between different theories by purely conceptual means, and on an ontological basis.

Richard Dawid believes that instrumentalism is most plausible in the context of underdeveloped theory, because the ascension of the theory can open "new frontiers of the visible whose identification with frontiers of existence appears less plausible than in the classical cases", and because "once the balance between theoretical effort and observational consequence has become too tilted, it gets quite problematic to hold that the theoretical physicist's sound motivations for his activity exclusively lie in the visible regime." [610] His conclusion is that physicists working in string theory are not interested in experiments for predicting visible phenomena. Their theory is not yet capable of such a thing. But observation is a prerequisite for attributing the meaning of concepts and string theory. A motivation for possible future visible consequences does not seem convincing.

Steven Weinstein considers QG as a "a physical theory describing the gravitational interactions of matter and energy in which matter and energy are also described by quantum theory." [611] Many theories of quantum gravity are quantizations of gravity but, as Callender and Huggett point out,

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[608] Richard Dawid, "Scientific Realism in the Age of String Theory," *Physics and Philosophy*, 2007.

[609] Dawid.

[610] Dawid.

[611] Weinstein and Rickles, "Quantum Gravity."

this is an empirical choice, rather than a logical one. [612] Finally, a quantification of gravity by GR suggests more, especially those in the canonical quantum gravity field (CQG), that a certain quantization method is required for space.

One of the earlier attempts to reconcile quantum with gravity appeared in the 1960s and is known as semi-classical theory. Although semi-classical theory was quickly understood to be flawed, it was seen as an excellent heuristic device for feeding the problem of quantum gravity. This theory, along with other dilemmas, such as the quantification debate, has led to the need for more robust theories about quantum gravity.

Unlike other modern theories in physics, where consensus has been reached in theory, quantum gravity has a number of alternative research programs that develop a basic hypothesis through the auxiliary hypotheses. Three of the most popular quantum gravity research programs in its short history include semi-classical theory, string theory, and canonical quantum gravity. But so far, none have experimental support. Some experiments were performed, but all were negative. The experiments were developed in such a way that the theory predicts only what might happen according to a certain specific scenario, which is not the only one possible, so they are not potentially refutable.

Given the lack of empirical progress, a pluralistic strategy for theoretical development is recommended in all quantum gravity approaches. In string theory there are different theoretical formulations, or physically equivalent dualities, which is relevant to the problem of sub-determining theories by data. It is argued that a more empirical perspective on the semantics of theories should be adopted, in order to understand what the theories of space and time tell us.

In string theory, unlike other approaches, there is a true unification of different forces, not just a quantum description of gravity, but some scientists criticize this theory as using too many resources at the expense of other approaches to quantum gravity.

Thinking experiments may be important for heuristic purposes, but in the case of quantum gravity, conclusions based on thought experiments are not very reliable. The lack of empirical results has led some scientists and philosophers to assert that these theories are not truly scientific.

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[612] Craig Callender and Nick Huggett, *Physics Meets Philosophy at the Planck Scale: Contemporary Theories in Quantum Gravity* (Cambridge University Press, 2001).

Simonluca Pinna and Simone Pinna propose a "conceptual test" to evaluate whether the mathematical content of quantum gravity theory refers to a possible verifiable empirical model. [613] The best empirical observations are the astrophysical ones for the strong gravity, so there are two options: (1) the development of new appropriate experimental frameworks, [614] and (2) the possibility of replacing the standard scientific verification criteria with the least empirically regulated ones. [615] There are two opinions of scientists: those who consider that spacetime is not a fundamental physical structure, [616] and those who consider it fundamental in any physical field[617] that presuppose the epistemological conservative approach expressed by (1). Those who support the disappearance of spacetime seem to follow the perspective, (2).

Some methodologists claim that the thesis of the disappearance of spacetime at high energies requires a change of the criteria of scientific verification, in order to adapt the empirical coherence to these theses in quantum gravity. This would involve changes in the concepts of "observer" and its connection with observations and measurements.

Geometrodynamics[618] was the first attempt to quantify gravity starting from the canonical (Hamiltonian) formulation of the general theory of relativity interpreted as a background-independent theory. [619] Subsequently, the followers of loop quantum gravity, a canonical approach, assert that relativistic spacetime disappears to the limit of high energy. This could imply the absence of a spacetime framework. [620] There are suspicions about the disappearance of spacetime

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[613] S. Pinna and Simone Pinna, "A Conceptual Test for Cognitively Coherent Quantum Gravity Models," 2017, https://doi.org/10.3390/technologies5030051.

[614] Sabine Hossenfelder and Lee Smolin, "Phenomenological Quantum Gravity," *ArXiv:0911.2761 [Gr-Qc, Physics:Physics]*, November 14, 2009, 66, 99–102, http://arxiv.org/abs/0911.2761.

[615] Richard Dawid, *String Theory and the Scientific Method*, 1 edition (Cambridge: Cambridge University Press, 2013).

[616] Carlo Rovelli, "Quantum Gravity," Cambridge Core, November 2004, https://doi.org/10.1017/CBO9780511755804.

[617] Amit Hagar and Meir Hemmo, "The Primacy of Geometry," ResearchGate, 2013, 44, 357–364, https://www.researchgate.net/publication/259158226_The_primacy_of_geometry.

[618] Karel Kuchar, "Canonical Quantum Gravity," *ArXiv:Gr-Qc/9304012*, April 8, 1993, 119–150, http://arxiv.org/abs/gr-qc/9304012.

[619] C. Kiefer, "Time in Quantum Gravity," in *The Oxford Handbook of Philosophy of Time*, ed. Craig Callender (Oxford University Press, 2011), 663–678.

[620] Carlo Rovelli, "The Disappearance of Space and Time," in *The Disappearance of Space and Time*, ed. Dennis Dieks (Elsevier, 2007), 25–36.

and other approaches, [621] including string theory that is generally interpreted as background dependent.

Hagar and Hemmo declare the need for a certain type of spacetime even at QG level; physics consists not only of dynamic theories, but also of experiments and measurements by which models must be tested. So, there must be something observable with geometric features or that can be translated into geometric terms. [622] They assert that the interpretation of QG theories as spaceless theories would be in contradiction with the epistemic basis of experimental physics, respectively with the primacy of geometric observations and measurements.

Supporters of the disappearance of spacetime follow a leibnizian approach, according to Earman, even Pythagorean, of reality, according to which the sense of physical reality can be derived directly from mathematical theory using *a priori* more "reasonable" criteria. [623] The operationalist perspective defines the physical reality with respect to its measurability, respectively any concept is "nothing more than a set of operations; the concept is synonymous with the corresponding set of operations." [624] Detection of measurable quantities in quantum gravity is the main goal of the experimenters, as measurability is an essential feature for identifying physically relevant quantities.

It has not yet been possible to include gravity in the theoretical framework of the quantum field of the standard model, because gravitational interactions do not meet the principles of renormalizability.

3.1 Heuristics of quantum gravity

As for the attempt to create a gravitational quantum theory, there are several research programs, some of which became obsolete over time due to the higher heuristic power of other programs. J. Butterfield thus distinguishes three major research programs: [625]

The **program of particles** establishes as the basic entity the graviton, the quanta of the gravitational field. The graviton spreads in a Minkowski spacetime and is associated with the specific

[621] Nick Huggett, Tiziana Vistarini, and Christian Wuthrich, "Time in Quantum Gravity," *ArXiv:1207.1635 [Gr-Qc, Physics:Physics]*, July 3, 2012, 242–261, http://arxiv.org/abs/1207.1635.

[622] Hagar and Hemmo, "The Primacy of Geometry," 44, 357–364.

[623] John Earman, "Thoroughly Modern Mctaggart: Or, What Mctaggart Would Have Said If He Had Read the General Theory of Relativity," *Philosophers' Imprint* 2 (2002): 2, 1–28.

[624] Richard Feldman, "Naturalized Epistemology," July 5, 2001, 5, https://plato.stanford.edu/archives/sum2012/entries/epistemology-naturalized/.

[625] Butterfield and Isham, "Spacetime and the Philosophical Challenge of Quantum Gravity."

representation of the zero-mass Poincare group and the spin 0 or 2. But this program presents many conceptual dysfunctionalities.

The **program of superstructures**, an approach motivated by the success of the transition from the old non-renormalizable theory of weak interactions to the new renormalizable unification of the weak and electromagnetic forces found by Salam, Glashow and Weinberg. The idea was to add fields of matter from general relativity to eliminate the UV problem. Thus appeared the theory of supergravity which, after some minor successes, came to the conclusion that it does not solve the divergences, but its line of thinking is currently continued by the superstring theory, which is the dominant research program in quantum gravity. The program has not yet matured. From the point of view of the response offered to the conceptual aspects, the program of superstrings is similar in many respects with the program of particles.

The **program of canonical quantum gravity** began with the Wheeler-DeWitt theory. Later came the program of Ashtekar that uses the Wheeler-DeWitt equation, [626] with the help of a set of canonical variables that produce a simplification of the structure of the central constraint functions, and is still a very active program, with impressive developments in recent years.

All three programs are similar in that the main way they go beyond the common treatment of spacetime is by quantifying an amount that is a standard type of variable in classical physics.

There are three major problems in the conception of a theory of quantum gravity: both quantum theory and general relativity present significant conceptual problems in themselves, the disparate fundamental bases of the two theories generate major new problems when trying to combine them, and the contrast between the lack of a satisfactory theory of quantum gravity and successful ingredient theories raise questions about the nature and function of the philosophical discussion of quantum gravity.

According to Laudan, the preferred theory is the one that maximizes the empirical successes, while reducing the conceptual problems, and the research preferred tradition is the one that supports the most successful theories.

According to Péter Szegedi, the history of quantum mechanics interpretations fit very well with Lakatos' methodology of rival scientific research programmes, compared to Kuhn's methodology

[626] Bryce S. DeWitt, "Quantum Theory of Gravity. I. The Canonical Theory," *Physical Review* 160, no. 5 (August 25, 1967): 160 (5): 1113–1148, https://doi.org/10.1103/PhysRev.160.1113.

which does not allow the simultaneous existence of different rival paradigms. [627] [628] It turns out that the development of quantum mechanics itself is a development, an evolution of progressive problems, if it is progressive both theoretically and empirically. Interpretations of quantum mechanics can be arranged as a series of theories, resulting in theoretical progressivity, but empirical progressivity is difficult to evaluate. Thus, according to the criteria, the interpretive programs can be scientific, but they are degenerative, respectively they are characterized by stagnation. The evaluation may change in the future, being a long-term program: "Moreover, it occasionally happens that when a research pro gramme gets into a degenerating phase, a little revolution or a creative shift in its positive heuristic may push it forward again." [629]

There is a possibility that a degenerate program may be revived, or even considered successful if it provides useful results for other programs. [630]

Péter Szegedi distinguishes, in the case of various quantum interpretations, a hard core and a heuristic adapting to the problems that have arisen. [631] Thus, in Louis de Broglie's program, the synthesis of wave-particle images is the hard core, while the real forms of realization in order of appearance (positive heuristic) are the following: the principle of double solution, the theory of pilot waves, the hypothesis of non-linearity and the hidden thermodynamics. In the case of David Bohm, the hard core is the theory of hidden variables and the quantum potential, to which at one point he added the hypothesis of stochasticity. Vigier used the same hard core, but with an additional assumption of the hidden degrees of freedom hypothesis. There are other programs in the interpretations of quantum mechanics. In the Fényes-Nelson-de Peňa research program, stochasticity is not an additional hypothesis, but a hard core, where the positive heuristic forced the initial use of diffusion processes, then the Brownian motion and, finally, stochastic electrodynamics. The positive heuristics of these programs are different, but generally they use the relativistic approach, the principle of determinism or causality and the principle of the unity of nature. In orthodox interpretation, according to Cushing, the hard core consists of the canonical commutation relations and Hamiltonian equations of motion, and the positive heuristic applies to the classical forms of Hamiltonians for specific systems, the principle of correspondence and the

[627] Péter Szegedi, "Lakatos On Crucial Experiments And The History Of Interpretations Of Quantum Mechanics," in *Appraising Lakatos: Mathematics, Methodology and the Man*, ed. G. Kampis, L. : Kvasz, and M. Stöltzner (Kluwer Academic Publishers, 2002), 1–101.

[628] Lakatos, *The Methodology of Scientific Research Programmes*, 33–34.

[629] Lakatos, 51.

[630] H. Zandvoort, Paul Weingartner, and Methology and Philosophy of Science International Congress of Logic, *Intrinsic Success and Extrinsic Success of Research Programs, in 7th International Congress of Logic, Methodology and Philosophy of Science: Salzburg, July 11th-16th, 1983 Vol. 4, Vol. 4,* (Salzburg: Huttegger, 1983), 289–92.

[631] Szegedi, "Lakatos On Crucial Experiments And The History Of Interpretations Of Quantum Mechanics."

principle of observables; as an auxiliary hypothesis, the operator-observer report was used. Lakatos says about this program:

> "In the new, post-1925 quantum theory the 'anarchist' position became dominant and modern quantum physics, in its 'Copenhagen interpretation', became one of the main standard bearers of philosophical obscurantism. In the new theory Bohr's notorious 'complementarity principle' enthroned [weak] inconsistency as a basic ultimate feature of nature, and merged subjectivist positivism and antilogical dialectic and even ordinary language philosophy into one unholy alliance. After 1925 Bohr and his associates introduced a new and unprecedented lowering of critical standards for scientific theories. This led to a defeat of reason within modern physics and to an anarchist cult of incomprehensible chaos." [632]

Lakatos' crucial experiments in quantum mechanics begin with a Gedanken experiment, the Einstein-Podolsky-Rosen experiment. [633] Commentators distinguish (at least) five hypotheses here: the principle of realism, the validity of quantum mechanical formalism, the hypothesis of completeness, the principle of separability, and the validity of classical logic. According to the EPR argument, one of the five assumptions is false. The next step was taken by Bohm, who reformulated the Gedanken experiment with spins, [634] but without seeming yet another crucial experiment as it was not stated that different theories offer different measurement results.

The work of John Bell has given hope that experimental testing of interpretations is possible, [635] emphasizing that there must be differences between quantum mechanical and hidden predictions. He assumed that in a real experiment we could measure probabilities. Bell's inequality was even closer to the real conditions of an easy-to-manage experiment.

3.2 The tests of quantum gravity

The primordial test of any quantum theory of gravity is the reproduction of the successes of general relativity. This involves reconstructing the local geometry from the non-local observables. In

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[632] Lakatos, *The Methodology of Scientific Research Programmes*, 59–60.

[633] A. Einstein, B. Podolsky, and N. Rosen, "Can Quantum-Mechanical Description of Physical Reality Be Considered Complete?," *Physical Review* 47, no. 10 (May 15, 1935): 770–80, https://doi.org/10.1103/PhysRev.47.777.

[634] Bohm, *Quantum Theory*.

[635] J. S. Bell, "On the Einstein Podolsky Rosen Paradox," *Physics Physique Fizika* 1, no. 3 (November 1, 1964): 447, https://doi.org/10.1103/PhysicsPhysiqueFizika.1.195.

addition, quantum gravity should probabilistically predict the large-scale topology of the Universe, which may soon be measurable, [636] and phenomena at the Planck scale. [637]

There is already a prediction that relates to quantum gravity: the existence and spectrum of Hawking radiation of the black hole, a "semi-classical" prediction resulting from quantum field theory on a fixed curved background, and subsequently confirmed theoretically. [638] It is assumed that a theory of gravity that will not reproduce this prediction is wrong.

For the Planck energy scale several tests have been proposed based on two ideas: that we can detect very small deviations of the exact symmetries, and that we can integrate over long distances or times to observe very small collective effects. These proposals remain extremely speculative, but they are plausible. [639] Some of these ideas can be found in Giovanni Amelino-Camelia, *Are we at the dawn of quantum-gravity phenomenology*: [640]

- Violations of the principle of equivalence. [641] Accuracy tests of the equivalence principle could be developed by atomic and neutron interferometry.
- Violations of CPT (charge, parity, and time) invariance, [642] for example by forming virtual black holes. The current experimental limits approach the observation level of these effects. [643] Violations of other global symmetries, such as CP, can also occur, with consequences that can be observed on the Planck scale. [644]

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[636] Neil Cornish, David Spergel, and Glenn Starkman, "Circles in the Sky: Finding Topology with the Microwave Background Radiation," *Classical and Quantum Gravity* 15, no. 9 (September 1, 1998): 15, 2657, https://doi.org/10.1088/0264-9381/15/9/013.

[637] Richard Easther et al., "Inflation as a Probe of Short Distance Physics," *Physical Review D* 64, no. 10 (October 16, 2001): 103502, https://doi.org/10.1103/PhysRevD.64.103502.

[638] Fay Dowker et al., "Pair Creation of Dilaton Black Holes," *Physical Review D* 49, no. 6 (March 15, 1994): 2909, https://doi.org/10.1103/PhysRevD.49.2909.

[639] Carlip, "Quantum Gravity."

[640] Giovanni Amelino-Camelia, "Are We at the Dawn of Quantum-Gravity Phenomenology?," *ArXiv:Gr-Qc/9910089*, October 25, 1999, http://arxiv.org/abs/gr-qc/9910089.

[641] G. Z. Adunas, E. Rodriguez-Milla, and D. V. Ahluwalia, "Probing Quantum Aspects of Gravity," *Physics Letters B* 485, no. 1–3 (July 2000): 215, https://doi.org/10.1016/S0370-2693(00)00697-3.

[642] Alan Kostelecky and Rob Potting, "Expectation Values, Lorentz Invariance, and CPT in the Open Bosonic String," *Physics Letters B* 381, no. 1–3 (July 1996): 89, https://doi.org/10.1016/0370-2693(96)00589-8.

[643] R. Adler et al., "Test of CPT Symmetry and Quantum Mechanics with Experimental Data from CPLEAR," *Physics Letters B* 364, no. 4 (December 1995): 239, https://doi.org/10.1016/0370-2693(95)01416-0.

[644] Renata Kallosh et al., "Gravity and Global Symmetries," *Physical Review D* 52, no. 2 (July 15, 1995): 912, https://doi.org/10.1103/PhysRevD.52.912.

- Distortions of dispersion relationships for light and neutrinos over long distances, resulting in a frequency-dependent light speed. [645] It can be observed by observing the gamma rays, the current experimental limits are close to the observation level. If the effect depends on polarization, gravity-induced birefringence tests may be within observation limits. [646]
- Interferometers for detecting gravitational waves could observe quantum fluctuations testable in space geometry, [647] an idea still controversial.
- Quantum gravity near Planck mass affects renormalization group fluxes and low energy coupling constants in large unified theories, [648] but this effect is rather a disadvantage making other possible tests more difficult.
- Use of powerful lasers for (indirect) observation of Unruh radiation, the counterpart of Hawking radiation for an acceleration particle. [649] This may be at least a test of theoretical quantum field predictions from quantum gravity.
- An indirect test from analogues of condensed matter with black holes, which should emit phonons through "Hawking radiation" from sonic horizons. [650] Tests may be possible in the future in Bose-Einstein condensates, [651] superfluid helium 3[652] and "slow light" in dielectrics. [653]

These experiments will not differentiate between specific models of quantum gravity, as current models cannot yet make sufficiently clear predictions, but phenomena can be tested on the Planck

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[645] Jorge Alfaro, Hugo A. Morales-Tecotl, and Luis F. Urrutia, "Quantum Gravity Corrections to Neutrino Propagation," *Physical Review Letters* 84, no. 11 (March 13, 2000): 2318, https://doi.org/10.1103/PhysRevLett.84.2318.

[646] Reinaldo J. Gleiser and Carlos N. Kozameh, "Astrophysical Limits on Quantum Gravity Motivated Birefringence," *Physical Review D* 64, no. 8 (September 2001): 083007, https://doi.org/10.1103/PhysRevD.64.083007.

[647] Y. Jack Ng and H. van Dam, "Measuring the Foaminess of Space-Time with Gravity-Wave Interferometers," *Foundations of Physics* 30, no. 5 (2000): 795, https://doi.org/10.1023/A:1003745212871.

[648] L. J. Hall and U. Sarid, "Gravitational Smearing of Minimal Supersymmetric Unification Predictions," *Physical Review Letters* 70, no. 18 (May 3, 1993): 2673, https://doi.org/10.1103/PhysRevLett.70.2673.

[649] Pisin Chen and Toshi Tajima, "Testing Unruh Radiation with Ultraintense Lasers," *Physical Review Letters* 83, no. 2 (July 12, 1999): 256, https://doi.org/10.1103/PhysRevLett.83.256.

[650] Matt Visser, "Acoustic Black Holes," *ArXiv:Gr-Qc/9901047*, January 15, 1999, http://arxiv.org/abs/gr-qc/9901047.

[651] L. J. Garay et al., "Sonic Analog of Gravitational Black Holes in Bose-Einstein Condensates," *Physical Review Letters* 85, no. 22 (November 27, 2000): 4643, https://doi.org/10.1103/PhysRevLett.85.4643.

[652] G. E. Volovik, "Field Theory in Superfluid 3He: What Are the Lessons for Particle Physics, Gravity and High-Temperature Superconductivity?," *Proceedings of the National Academy of Sciences* 96, no. 11 (May 25, 1999): 6042, https://doi.org/10.1073/pnas.96.11.6042.

[653] U. Leonhardt and P. Piwnicki, "Relativistic Effects of Light in Moving Media with Extremely Low Group Velocity," *Physical Review Letters* 84, no. 5 (January 31, 2000): 822, https://doi.org/10.1103/PhysRevLett.84.822.

scale affected by quantum gravity. Lately, physicists have focused on the idea of experimental tests for a certain class of quantum gravity models, "gravity on the TeV scale" or "world of branes",[654] which postulate additional "large" dimensions, of one millimeter.

The problem of how the measurement affects the ontological state of the observed system is called the *measurement problem*. Measurement in quantum mechanics is viewed in different ways in various interpretations. In classical mechanics, a simple point system is fully described by the particle's position and momentum. In quantum mechanics, a system is described by its quantum state, by the probabilities of possible positions and momentums. The predicted values of the measurements are described by a probability distribution or an "average" (or "expectation") of the measurement operator based on the quantum state of the prepared system. The measurement process is often considered random and indeterministic in some interpretations, while in other interpretations indeterminism is fundamental and irreducible.

There are several possible ways to mathematically describe the measurement process (both the probability distribution and the collapsed wave function). The most convenient description depends on the spectrum (ie the set of eigenvalues) of the observable.

The most obvious feature in quantum gravity is the lack of data (there are no phenomena that can be identified unequivocally as a result of an interaction between general relativity and quantum theory). This is because the quantum gravity scale (Planck length) is extremely small, as is Planck energy and Planck time. It turns out that the only physical regime in which the effects of quantum gravity could be studied directly is in the immediate post-Big Bang era, in addition to the problems related to the interaction of spin-2 gravitons with a conserved energy-momentum tensor. It follows that different quantum gravity theories could be empirically verified only at very high energies.

For physics, this means that it is very difficult to build a fully satisfactory theory. From a philosophical point of view, the difficulty is due to the conceptual problems of space, time and matter, but also due to the theoretical construction, since there is no agreement on the types of data that a quantum theory of gravity would obtain. In this situation, J. Butterfield states that the theoretical construction becomes much more strongly influenced by theoretical considerations, based on the different first-hand opinions on how the theory should look, based in part on the philosophical bias of the researcher and on the mathematical techniques considered. successful. Thus, a research program tends to construct abstract theoretical schemes compatible with a preconceived conceptual framework and internally coherent in a mathematical sense, resulting in a "sub-determination of data theory". Moreover, the program tends to produce schemes based on a

[654] Lisa Randall and Raman Sundrum, "A Large Mass Hierarchy from a Small Extra Dimension," *Physical Review Letters* 83, no. 17 (October 25, 1999): 3370, https://doi.org/10.1103/PhysRevLett.83.3370.

wide range of philosophical motivations, which could be presumed to be unconscious projections of the individual researcher's psychic, and could be rejected as such.

It is important to determine if quantum gravity effects are measurable below the Planck limits, possibly resulting from a non-perturbative effect. But the very existence of such effects, and the phenomena they predict, are themselves probably strongly dependent on theory. It follows that the subject of quantum gravity presents to the philosopher a wide and varied range of approaches, provided that in quantum gravity there are not sufficiently well defined theories, not even well established.

From the dimensional analyzes it would appear that quantum gravity requires experimentally high energies, of the Planck energy level. This would require a particle accelerator larger than our galaxy, so direct quantum gravity tests seem impossible according to these calculations. It turns out that high precision laboratory tests in the weak field will be the only possibility to make quantum gravity a testable / falsifiable physical theory. This would be possible in macroscopic systems that still adhere to the laws of quantum theory - those described by macroscopic wave functions. These would allow, for example, the measurement of quantum gravitational excitation energies. [655] Johan Hansson and Stephane Francois suggest the possibility of testing quantum gravity theories using macroscopic quantum systems; superfluid helium, Bose-Einstein gas condensates and "macroscopic" molecules still subject to quantum mechanics, and neutron stars. The effects of quantum gravity, defined here as observable gravitational interactions between quantum objects, should be observed using existing technology, allowing for low energy falsifiability in the weak field regime. [656]

Roberto Balbinot and Alessandro Fabbri, in *Amplifying the Hawking Signal in BECs*, [657] propose simple models of Bose-Einstein condensates to study the analogue effects of pair creation, namely, the Hawking effect of acoustic black holes and the Casimir dynamic effect. The idea is to reproduce in a context of condensed matter some quantum effects predicted by quantum field theory in curved space, including the thermal emission of black holes predicted by Hawking in 1974. [658] The authors

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[655] Johan Hansson, "Aspects of Nonrelativistic Quantum Gravity," *ArXiv:0910.4289 [Astro-Ph, Physics:Gr-Qc, Physics:Hep-Ph, Physics:Quant-Ph]*, October 22, 2009, 707 (2009), http://arxiv.org/abs/0910.4289.

[656] Johan Hansson and Stephane Francois, "Testing Quantum Gravity," *International Journal of Modern Physics D* 26, no. 12 (October 2017): 1743003, https://doi.org/10.1142/S0218271817430039.

[657] Roberto Balbinot and Alessandro Fabbri, "Amplifying the Hawking Signal in BECs," *Advances in High Energy Physics* 2014 (2014): 1–8, https://doi.org/10.1155/2014/713574.

[658] S. W. Hawking, "Particle Creation by Black Holes," *Communications in Mathematical Physics* 43, no. 3 (August 1, 1975): 199–220, https://doi.org/10.1007/BF02345020.

of this experiment conclude that they have obtained some results that could be useful in future experimental research.

THe formalism is based on the Lagrangian form which regulates the dynamics of the point particles with mass and charge and the electromagnetic field in a static, spherically symmetrical gravitational field described by the phenomenological gravitational potentials *T*, *H*, *e*. This theory was used to interpret the results of the experimental tests of the strong equivalence principle. [659]

The *xg formalism* introduced by W.-T. Ni[660] initially offered us a framework for the analysis of electrodynamic physics in a gravitational background field, then expanded to cover other sectors of the standard model.

The *Kostelecky formalism*, developed by Colladay and Kostelecky, is used to deal with the possibility of spontaneous breakdown of Lorentz symmetry in the context of string theory. [661]

A formalism based on the forms of the equations of motion has the advantage of directly addressing some natural requirements.

3.3 Canonical quantum gravity

In the interpretation of canonical quantum gravity (CQG), gravity appears as a geometric pseudoforce, is reduced to spacetime geometry and becomes a simple effect of spacetime curvature. [662] (Maudlin[663]). Lehmkuhl[664] argues that canonical formalism does not confirm this interpretation. General relativity (GR) associates gravity with spacetime, but the type of association is not fixed. [665] Instead of the geometric interpretation, one can use the field interpretation (the spacetime geometry is reduced to a gravitational field, respectively the metric, considered as "just another

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[659] J. E. Horvath et al., "Einstein Equivalence Principle and Theories of Gravitation: A Gravitationally Modified Standard Model," *Physical Review D* 38, no. 6 (September 15, 1988): 1754, https://doi.org/10.1103/PhysRevD.38.1754.

[660] W.-T. Ni, "Equivalence Principles and Electromagnetism," *Physical Review Letters* 38 (February 1, 1977): 301, https://doi.org/10.1103/PhysRevLett.38.301.

[661] Don Colladay and Alan Kostelecky, "Lorentz-Violating Extension of the Standard Model," *Physical Review D* 58, no. 11 (October 26, 1998): 6760, https://doi.org/10.1103/PhysRevD.58.116002.

[662] Salimkhani, "Quantum Gravity."

[663] Tim Maudlin, "On the Unification of Physics," *Journal of Philosophy* 93, no. 3 (1996): 129–144.

[664] D. Lehmkuhl, D. Dieks, and M. Redei, "Is Spacetime a Gravitational Field?, In The Ontology of Spacetime II, Volume 4 - 1st Edition," 2008, 83–110, https://www.elsevier.com/books/the-ontology-of-spacetime-ii/dieks/978-0-444-53275-6.

[665] Lehmkuhl, Dieks, and Redei, 84.

field") or the egalitarian interpretation (a conceptual identification of gravity and spacetime in GR[666]). These alternative interpretations reduce the conceptual differences between GR and other field theories.

Instrumentalism allows the ignoring of quantum gravity, since it conceives scientific theories only as predictive tools. Canonical quantum gravity follows a nonperturbative quantum theory of the gravitational field. It is based on consistency between quantum mechanics and gravity, without trying to unify all fields. The main idea is to apply standard quantification procedures to the general theory of relativity. For this, it is necessary for general relativity to be expressed in canonical (Hamiltonian) form and then quantified as usual. This was (partially) successfully done by Dirac[667] and (differently) by Arnowitt, Deser and Misner. [668]

3.3.1 Tests proposed for the CQG

Carlip states, with reference to quantum gravity: "The ultimate measure of any theory is its agreement with Nature; if we do not have any such tests, how will we know whether we're right?" [669] Usually, a new theory is constructed using the available experimental data, which attempts to match the phenomenological models, then verifying through predictions. Often, the conceptual and formal consistency is bypassed in an attempt to match the reality. At quantum gravity everything happens very differently: it is almost entirely based on conceptual and formal consistency, along with the constraints imposed, and seems impossible to approach through experimental research. Dean Rickles states that the basic test of any scientific theory is an experimental test, without which the theory becomes entangled in pure mathematics or, even worse, in metaphysics. [670]

Giovanni Amelino-Camelia initiated a new research program called "quantum gravitational phenomenology", in which he tries to transform quantum gravity research into a true experimental discipline. The scale at which quantum gravitational effects occur is determined by the different physical constants of fundamental physics: *h*, *c* and *G*, which characterize quantum, relativistic and gravitational phenomena. By combining these constants, we obtain the Planck constants at which the effects of quantum gravity must manifest.

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[666] Lehmkuhl, Dieks, and Redei, 84.

[667] Paul A. M. Dirac, *Lectures on Quantum Mechanics* (Mineola, NY: Snowball Publishing, 2012).

[668] R. Arnowitt, S. Deser, and C. W. Misner, "The Dynamics of General Relativity," *General Relativity and Gravitation* 40, no. 9 (September 2008): 1997–2027, https://doi.org/10.1007/s10714-008-0661-1.

[669] Carlip, "Quantum Gravity," 64: 885.

[670] Dean Rickles, "Quantum Gravity: A Primer for Philosophers.," Preprint, October 2008, http://philsci-archive.pitt.edu/5387/.

These are many orders of magnitude beyond current experimental capabilities. But the scale argument applies to individual quantum gravitational events. The idea is to combine such events to amplify the effects that can be detected with current or near future equipment. Quantum gravity can also be studied by observing the opposite end of the scale spectrum, astronomical systems, by observing cosmic radiation, gamma ray generating explosions, Kaon explosions, particles, light and cosmic background radiation, through quantum gravitational effects that might manifest in these systems. In these systems, the Planck scale effects are naturally amplified.

Name	Formula	Value (SI)
Lungimea Planck length	$l_P = \sqrt{\hbar G/c^3}$	$1{,}616229(38)\times10^{-35}$ m
Planck mass	$m_P = \sqrt{\hbar c/G}$	$2{,}176470(51)\times10^{-8}$ kg
Planck time	$t_P = l_P/c = \hbar/m_Pc^2 = \sqrt{\hbar G/c^5}$	$5{,}39116(13)\times10^{-44}$ s
Planck charge	$q_P = \sqrt{4\pi\varepsilon_0\hbar c} = e/\sqrt{\alpha}$	$1{,}875\,545\,956(41)\times10^{-18}$ C
Planck temperature	$T_P = m_Pc^2/k_B = \sqrt{\hbar c^5/Gk_B^2}$	$1{,}416808(33)\times10^{32}$ K

- **Name >>> Formula >>> Value (SI)**
- Planck length >>> $l_P = \sqrt{\hbar G/c^3}$ >>> $1.616229\ (38) \times 10^{-35}$ m
- Planck mass >>> $m_P = \sqrt{\hbar c/G}$ >>> $2.176470\ (51) \times 10^{-8}$ kg
- Planck time >>> $t_P = l_P/c = \hbar/m_Pc^2 = \sqrt{\hbar G/c^5}$ >>> $5.39116\ (13) \times 10^{-44}$ s
- Planck charge >>> $q_P = \sqrt{4\pi\varepsilon_0\hbar c} = e/\sqrt{\alpha}$ >>> $1.875\ 545\ 956\ (41) \times 10^{-18}$ C
- Planck temperature >>> $T_P = m_Pc^2/k_B = \sqrt{\hbar c^5/Gk_B^2}$ >>> $1.416808\ (33) \times 10^{32}$ K

Tabelul 3.1 Constantele Planck

But such effects can also be studied in experimental devices on Earth, also using "natural experiments", such as particles moving over large distances at enormous speeds. [671] Bryce DeWitt argued that quantum gravitational effects will not be measurable on individual elementary particles, since the gravitational field itself does not make sense at these scales. The static field of such a particle would not exceed the quantum fluctuations. [672]

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[671] Rickles.

[672] B. S. DeWitt and Louis Witten, *The Quantization of Geometry, in Gravitation an Introduction to Current Research*, First Edition edition (John Wiley & Sons, 1962), 372.

For the use of the universe as an experimental device, the idea is that light changes its properties over long distances in the case of discrete spacetime, which produces birefringent effects. [673] The theoretical basis is that a wave propagating in a discrete spacetime will violate Lorentz invariance, which can be a "test" for quantum gravity models. But spacetime discrepancy is not a sufficient condition for Lorentz non-invariance: a counterexample is the causal sets which are discrete structures and do not appear to violate it.

3.3.2. Loop quantum gravity

Loop quantum gravity (LQG) attempts to unify gravity with the other three fundamental forces starting with relativity and adding quantum traits. It is based directly on Einstein's geometric formula.

In LQG, space and time are quantified just like energy and momentum in quantum mechanics. Space and time are granular and discrete, with a minimal size. The space is considered to be an extremely fine fabric or network of finite loops, called spin networks or spin foam, with a size limited to less than the order of a Planck length, about 10^{-35} meters. Its consequences apply best to cosmology, in the study of the early universe and Big Bang physics. Its main, unverified prediction involves an evolution of the universe beyond the Big Bang (Big Bounce).

Any theory of quantum gravity must reproduce Einstein's theory of general relativity as a classical limit. Quantum gravity must be able to return to classical theory when $\hbar \rightarrow 0$. To do this, quantum anomalies must be avoided, in order to have no restrictions on Hilbert physical space without a correspondent in classical theory. It turns out that quantum theory has less degrees of freedom than classical theory. Lewandowski, Okolow, Sahlmann and Thiemann[674] on the one hand, and Christian Fleischhack[675] on the other, have developed theorems that establish the uniqueness of the loop representation as defined by Ashtekar. These theorems exclude the existence of other theories in the LQG research program and so, if LQG does not have the correct semiclastic limit, this would mean the end of the LQG representation as a whole.

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[673] Rodolfo Gambini and Jorge Pullin, "Quantum Gravity Experimental Physics?," *General Relativity and Gravitation* 31, no. 11 (November 1, 1999): 1999, https://doi.org/10.1023/A:1026701930767.

[674] Jerzy Lewandowski et al., "Uniqueness of Diffeomorphism Invariant States on Holonomy–Flux Algebras," *Communications in Mathematical Physics* 267, no. 3 (November 1, 2006): 267 (3): 703–733, https://doi.org/10.1007/s00220-006-0100-7.

[675] Christian Fleischhack, "Irreducibility of the Weyl Algebra in Loop Quantum Gravity," *Physical Review Letters* 97, no. 6 (August 11, 2006): 97 (6): 061302, https://doi.org/10.1103/PhysRevLett.97.061302.

The canonical quantum gravity program treats the spacetime metric as a field and quantizes it directly, with space divided into three-dimensional layers. The program involves rewriting the general relativity in "canonical" or "Hamiltonian" form,[676] through a set of configuration variables that can be encoded in a phase space. The evolution in time of these variables is then determined, the possible physical movements in the phase space, a family of curves, are quantized, and the dynamic evolution is generated with the help of the Hamiltonian operator.[677] Thus, some constraints of the canonical variables imposed after quantification appear.

In loop quantum gravity, Ashtekar used a different set of variables with a more complex metric,[678] solving the constraints more easily. By the changes introduced in the program, all standard geometrical features of general relativity can be recovered.[679] The advantage of this version is a greater (mathematical) control over the theory (and its quantification).

The LQG program requires that a theory of spacetime be independent of the background, as opposed to the string theory where spacetime is treated as a fixed background. LQG uses the Hamiltonian or canonical formulation of GR. The advantage of a canonical formulation of a theory is the ease and standardization of quantification. The loops in the LQG give us a description of the space. At the intersection of the loops there appear nodes that represent basic units of the space, which is thus discretized; two nodes connected by a link represent two space units side by side. The surface is determined by the intersections with the loops. Thus, one can imagine a graph (spin network)[680] made from certain quantum numbers attached to it. The numbers determine the surfaces and volumes of space.[681] The problem of time in LQG is to incorporate time into this image.

The LQG considers GR as a starting point, at which it applies a quantification procedure to arrive at a viable quantum theory of gravity. In the quantification procedure, called canonical quantization, it is necessary to reformulate the GR as a Hamiltonian system, thus allowing a time evolution of all the degrees of freedom of the system. The respective Hamiltonian formulas divide

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[676] Kuchař, "Canonical Quantization of Gravity."

[677] Weinstein and Rickles, "Quantum Gravity."

[678] Carlo Rovelli, "Notes for a Brief History of Quantum Gravity," *ArXiv:Gr-Qc/0006061*, June 16, 2000, http://arxiv.org/abs/gr-qc/0006061.

[679] Lee Smolin, "The Case for Background Independence," *ArXiv:Hep-Th/0507235*, July 25, 2005, 196–239, http://arxiv.org/abs/hep-th/0507235.

[680] The spin network is a graph whose nodes represent "slices" of space and whose links represent surfaces that separate these pieces, representing a quantum state of the gravitational field or space.

[681] Keizo Matsubara, *Stringed Along Or Caught in a Loop?: Philosophical Reflections on Modern Quantum Gravity Research* (Filosofiska Institutionen, Uppsala universitet, 2012).

the spacetime in a foliation of three-dimensional space hypersurfaces, through a formalism called ADM after its authors (Richard Arnowitt, Stanley Deser and Charles Misner). ADM formalism assumes metrics induced on spatial surfaces as "position" variables and a linear combination of the outer curvature components of these hypersurfaces encoding their incorporation into 4-dimensional space-time as canonically conjugated "momentum" variables with metrics. [682] The resulting Hamiltonian equations are not equivalent to the Einstein field equations. To make them equivalent, restrictions must be introduced, resulting in certain conditions for the initial data. The first family of constraints encodes the freedom of choosing the foliation (Hamiltonian constraint), and the second set of constraints concerns the freedom to choose the coordinates in the 3-dimensional space (vector constraints), resulting in a total of four constraint equations. In the LQG there is a family of additional constraints related to internal symmetries. So far, only two of the three families of constraints have been resolved. The canonical quantization procedure is carried out according to Paul Dirac, [683] transforming the canonical variables into quantum operators that act on a space of quantum state.

The use of ADM formalism was hit by insurmountable technical complications, so in the 1980s Abhay Ashtekar introduced new variables that simplified the equations of constraints, with the disadvantage of losing the direct geometric significance of ADM variables. In this case the spacetime geometry is captured by a "triad field" which encodes the local inertial frames defined on spatial hypersurfaces, rather than the metrics. The transition from ADM to the Ashtekar variables represents a reinterpretation of the Einstein field equations. The generalized theory of reinterpreted relativity is then subjected to the canonical procedure as above. [684]

In many approaches to quantum gravity, including string theory and LQG, space is no longer a fundamental entity, but merely an "emergent" phenomenon that results from basic physics. [685] Christian Wüthrich states that it is not clear whether we can formulate a physical theory in a coherent way in the absence of space and time. [686]

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682 Christian Wuthrich, "In Search of Lost Spacetime: Philosophical Issues Arising in Quantum Gravity" (2011).

683 Dirac, *Lectures on Quantum Mechanics*.

684 Wuthrich, "In Search of Lost Spacetime."

685 Wuthrich.

686 Wuthrich, "To Quantize or Not to Quantize," 72 : 777-788.

A newer approach is the use of so-called "spin foam" models, [687] which use path integration to generate spacetime. The evolution in time of spin networks is assumed to represent spacetime in terms of spin foam.

LQG is a vast active research program, developed in several directions with the same hard core. [688] Two directions of development are more important: the more traditional canonical LQG, and the covariant LQG, called the spin foam theory.

The loop quantum gravity resulted from an attempt to formulate a quantum theory independent of the background. This takes into account the general relativity approach that spacetime is a dynamic field and, therefore, a quantum object. The second hypothesis of the theory is that the quantum discreteness that determines the behavior similar to the particles of other field theories also affects the structure of space. The result is a granular structure of space at Planck length. The quantum state of spacetime is described by means of a mathematical structure called a spin network. Spin networks do not represent quantum states of a field in space, but quantum states of spacetime. The theory was obtained by reformulating the general relativity with the help of the Ashtekar variables. [689] Currently, there are several positive heuristics based on which the dynamics of the theory develop.

The black hole thermodynamics tries to reconcile the laws of thermodynamics with the black hole event horizons. A recent success of the theory is the calculation of the entropy of all non-singular black holes directly from the theory and independent of other parameters. This is the only known derivation of this formula from a fundamental theory, in the case of generic black holes that are not singular. The theory also allowed the calculation of quantum gravity corrections at entropy and radiation of black holes.

In 2014, Carlo Rovelli and Francesca Vidotto suggested, based on LQG, that there is a Planck star inside a black hole, thus trying to resolve the protection of the black hole and the paradox of the black hole information.

Loop quantum cosmology (LCC) predicted a Big Bounce before the Big Bang. LCC was developed using methods that mimic those of LQG, which predicts a "quantum bridge" between contracting and expansive cosmological branches. Through the LCC, the singularities of Big Bang, Big

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[687] John W. Barrett and Louis Crane, "Relativistic Spin Networks and Quantum Gravity," *Journal of Mathematical Physics* 39, no. 6 (June 1998): 32:3296–3302, https://doi.org/10.1063/1.532254.

[688] Dirac, *Lectures on Quantum Mechanics*.

[689] Abhay Ashtekar, "New Variables for Classical and Quantum Gravity," *Physical Review Letters* 57, no. 18 (November 3, 1986): 57 (18): 2244–2247, https://doi.org/10.1103/PhysRevLett.57.2244.

Bounce, and a natural mechanism for inflation were predicted. But the results obtained are subject to restriction due to the artificial suppression of the degrees of freedom. The avoidance of singularities in the LCC is done through mechanisms available only in these restrictive models; the avoidance of singularities in the complete theory can only be achieved by a more subtle feature of the LQG.

The GR reproduction as a low-energy limit in LQG has not been confirmed yet, and the scattering amplitudes have not yet been calculated.

The most pressing problems of the LQG are our lack of understanding of the dynamics (the inability to solve the Hamiltonian constraint equation), and the failure to explain how the classic smooth space appears (how GR succeeds in this case).

Another LQG problem is a general problem of quantum mechanics: time. Carlo Rovelli and Julian Barbour tried to formulate quantum mechanics in a way that does not require external time, replacing time by relating events directly with one another. [690]

The effects of quantum gravity are difficult to measure because the Planck length is much too small, but we try to measure the effects from astrophysical observations and gravitational wave detectors. It has not yet been shown that the LQG description of spacetime on the Planck scale has the correct continuous limit described by the general relativity with possible quantum corrections. Other unresolved issues include dynamics of theory, constraints, coupling with matter fields, renormalization of graviton. [691]

There is still no experimental observation for which LQG made a different prediction from the Standard Model or general relativity. Due to the lack of a semiclassic boundary, LQG did not reproduce the predictions made by general relativity.

The LQG has difficulties in trying to allow the theory of general relativity at the semiclassical limit, among which

- There is no operator that responds to infinitesimal diffeomorphisms, it must be approximated by finite diffeomorphisms and thus the structure of the Poisson brackets of

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[690] Carlo Rovelli, "Relational Quantum Mechanics," *International Journal of Theoretical Physics* 35, no. 8 (August 1996): 35 : 1637-1678, https://doi.org/10.1007/BF02302261.

[691] Hermann Nicolai, Kasper Peeters, and Marija Zamaklar, "Loop Quantum Gravity: An Outside View," *Classical and Quantum Gravity* 22, no. 19 (October 7, 2005): 22(19): R193–R247, https://doi.org/10.1088/0264-9381/22/19/R01.

classical theory is not exactly reproduced. The problem can be circumvented by introducing constraints. [692]

- The difficulty of reconciling the discrete combinatorial nature of quantum states with the continuous nature of classical theory of the fields.
- Difficulties arising from the structure of the Poisson brackets that involve spatial diffeomorphism and Hamiltonian constraints. [693]
- The developed semiclassic mechanisms are only suitable for operators who do not change the graph.
- The problem of formulating observables for general relativity due to its nonlinear nature and the invariance of spacetime diffeomorphism. [694]

LQG is a possible solution of quantum gravity, just like string theory but with differences. In contrast to the string theory which postulates additional dimensions and unobserved additional particles and symmetries, LQG is based only on quantum theory and general relativity, and its scope is limited to understanding the quantum aspects of gravitational interaction. In addition, the consequences of LQG are radical, fundamentally altering the nature of space and time.

3.4 String theory

In quantum field theory, the main obstacle is the occurrence of the untreatable infinities in the interactions of the particles due to the possibility of arbitrary distances between the point particles. Strings, as extended objects, provide a better framework, which allows finite calculations. [695] String theory is part of a research program in which point particles in particle physics are replaced by one-dimensional objects called strings. It describes how these strings propagate through space and interact with one another. At larger scales, a string looks like an ordinary particle, with mass, charge and other properties determined by the vibrational state of the string. One of the vibrational states of the strings corresponds to graviton, the hypothetical particle in quantum mechanics for gravitational force. [696] String theory is usually manifested at very high energies, such as in black hole physics, early universe cosmology, nuclear physics, and condensed matter physics. String

[692] Thomas Thiemann, *Modern Canonical Quantum General Relativity*, 1 edition (Cambridge, UK ; New York: Cambridge University Press, 2008).

[693] Thiemann.

[694] B. Dittrich, "Partial and Complete Observables for Hamiltonian Constrained Systems," *General Relativity and Gravitation* 39, no. 11 (November 1, 2007): 39 (11): 1891–1927, https://doi.org/10.1007/s10714-007-0495-2.

[695] Dawid, "Scientific Realism in the Age of String Theory."

[696] Katrin Becker, Melanie Becker, and John H. Schwarz, *String Theory and M-Theory: A Modern Introduction* (Cambridge ; New York: Cambridge University Press, 2007), 2–3.

theory tries to unify gravity and particle physics, and its later versions try to modify all the fundamental forces in physics. [697]

The purpose of string theory was to replace elementary particles with one-dimensional strings in order to unify quantum physics and gravity.

The string theory research program is based on a 1930 assumption that general relativity resembles the theory of a field of spin-two without mass in the Minkowskian flat space. [698] The quantification of such a theory has been shown not to be perturbative renormalizable, implying infinities that cannot be eliminated. This early theory was abandoned until the mid-1970s, when it was developed as a one-dimensional string theory.

It should be noted that the string theory was initially developed, in the late 1960s and early 1970s in particle physics - the bosonic string theory, which only dealt with bosons. After a temporary success as a hadron theory, quantum chromodynamics has been recognized as the correct hadron theory. In 1974 Tamiaki Yoneya discovered that the theory provides a massive particle of spin 2, considered to be a graviton. John Schwarz and Joel Scherk reintroduced Kaluza-Klein's theory for additional dimensions, recovered the abandoned bootstrap program, and thus began the string theory research program in quantum gravity. A typical example of reinvigorating a research program in the sense of Lakatos (bootstrap program) and changing the direction of research of another program (string theory) whose heuristics, by adding an additional theory (Kaluza-Klein), has proved to be a lot more useful in a different direction than originally envisaged. Later it was developed in the *superstring theory*, based on the supersymmetry between bosons and fermions, [699] and then appeared other versions of the theory. In the mid-1990s, scientists focused on developing a unifying research program, an eleven-dimensional theory called the *M theory*.

The strings do not have quantum numbers, but they differ in their topological form (open or closed, modes of compacting) and their dynamics (modes of oscillation). They can be perceived on a macroscopic scale as point particles with certain quantum numbers. The change of the oscillation mode corresponds to a transformation to another particle. The strings at the fundamental level do not have coupling constants. The interaction between them corresponds to their dynamics. [700]

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[697] Becker, Becker, and Schwarz, 3, 15–16.

[698] A. Capelli, "The Birth of String Theory Edited by Andrea Cappelli," Cambridge Core, April 2012, https://doi.org/10.1017/CBO9780511977725.

[699] Becker, Becker, and Schwarz, *String Theory and M-Theory*, 4.

[700] Vincent Lam, "Quantum Structure and Spacetime.," *Metaphysics in Contemporary Physics*, January 1, 2016, 81–99, https://doi.org/10.1163/9789004310827_005.

For each version of string theory there is only one type of string, such as a small loop or string segment, which can vibrate in different ways. In the string theory research program, the characteristic string length scale is of the order of Planck length (10^{-35} meters), over which the effects of quantum gravity are considered significant. [701] At ordinary dimensions, such objects cannot be distinguished from zero-dimensional point particles. There are several variants of the superstring theory: type I, type IIA, type IIB and two types of heterotic strings, SO (32) and E8×E8.

String theories require additional dimensions of spacetime for mathematical consistency. In bosonic string theory, spacetime is 26-dimensional, while in superstring theory it is 10-dimensional, and in M-theory it is 11-dimensional. These additional dimensions will not be observed in experiments, [702] due to their compaction by which they "close" on themselves forming circles. At the limit, when these extra dimensions tend to zero, they reach the usual spacetime. In order for the theories to properly describe the world, the compacted dimensions must be in the form of the Calabi-Yau manifolds. [703]

Another way to reduce the number of dimensions is by using the membrane cosmology scenario ("brane-world"), considering the observable universe as a three-dimensional subspace of a multi-dimensional space. In these models, gravity appears from the closed strungs in a space with several dimensions, thus explaining the lower power of gravity compared to the other fundamental forces. [704] In string theory, a *brane* (the abbreviation for "membrane") generalizes the notion of a point particle to dimensions other than zero. Branes are physical bodies that obey the rules of quantum mechanics. [705]

A particularity of the theories in this research program are the "dualities", mathematical transformations that identify the physical theories within this program between them, drawing the conclusion that all these theories are subsumed into one, the M-theory. [706] Two theories are dual if they are exactly equivalent in terms of observational consequences, although they are constructed differently and may involve different objects and topological scenarios. [707] The different theories within the string theory research program are linked by several relationships, one being the specific

[701] Becker, Becker, and Schwarz, *String Theory and M-Theory*, 6.

[702] Barton Zwiebach, *A First Course in String Theory*, 2 edition (Cambridge ; New York: Cambridge University Press, 2009).

[703] Shing-Tung Yau, *The Shape of Inner Space*, Reprint edition (Basic Books, 2012), chap. 6.

[704] Randall and Sundrum, "An Alternative to Compactification," 83 (23): 4690–4693.

[705] Gregory Moore, "What Is... a Brane?," *Notices of the American Mathematical Society* 52, no. 2 (November 28, 2005): 214, https://www.researchwithrutgers.com/en/publications/what-is-a-brane.

[706] Becker, Becker, and Schwarz, *String Theory and M-Theory*, 9–12.

[707] Dawid, "Scientific Realism in the Age of String Theory."

correspondence relation called duality S. [708] Another relationship, called duality T, considers strings that propagate around an additional circular dimension. In 1997, the anti-de Sitter/conformal field theory correspondence (AdS/CFT) was discovered, [709] which links the string theory with a quantum field theory. [710] In a more general framework, AdS/CFT correspondence is a duality that correlates string theory with other physical theories better understood theoretically, with implications in the study of black holes and quantum gravity, but also in nuclear physics[711] and condensed matter. [712]

The dualities in string theory have been linked by philosophers with issues specific to philosophy, such as underdetermination, conventionalism and emergency/reduction. Thus, spacetime has come to be considered by some physicists as an emergent entity, which depends, for example, on the coupling power that governs physical interactions. According to the ADS/CFT duality, a 10-dimensional string theory is observationally equivalent to a 4-dimensional gauge theory - the "gauge/gravity" duality. It follows from these dualities that the theories, being equivalent, are not fundamental, and therefore neither spacetime described is fundamental, but an emergent phenomenon. [713] In this program, gauge theory and gravitational theory are classic limits of a more comprehensive, unifying quantum theory. Philosophers question whether two dual theories are physically distinct or only notational variants of the same theory. [714] [715]

In 1995, Edward Witten suggested that the five families of theories in the string theory research program are special limiting cases of an 11-dimensional theory called M-theory. [716] In 1997, Tom Banks, Willy Fischler, Stephen Shenker and Leonard Susskind proposed a matrix model for the

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[708] Becker, Becker, and Schwarz, *String Theory and M-Theory*.

[709] Becker, Becker, and Schwarz, 14–15.

[710] Zwiebach, *A First Course in String Theory*, 376.

[711] Igor R. Klebanov and Juan M. Maldacena, "Solving Quantum Field Theories via Curved Spacetimes," *Physics Today* 62, no. 1 (January 1, 2009): 62 (1): 28–33, https://doi.org/10.1063/1.3074260.

[712] Subir Sachdev, "Strange and Stringy," *Scientific American* 308 (December 1, 2012): 308 (44): 44–51, https://doi.org/10.1038/scientificamerican0113-44.

[713] Tiziana Vistarini, "Emergent Spacetime in String Theory," 2013, 103.

[714] Joseph Polchinski, "Dualities of Fields and Strings," *ArXiv:1412.5704 [Hep-Th]*, December 17, 2014, http://arxiv.org/abs/1412.5704.

[715] Rickles, "A Philosopher Looks at String Dualities," 42: 54–67.

[716] Michael J. Duff, "The Theory Formerly Known as Strings," *Scientific American* 278 (February 1, 1998): 278 (2): 64–9, https://doi.org/10.1038/scientificamerican0298-64.

11-dimensional M theory, where the reduced energy limit of this model is eleven-dimensional supergravity. [717]

Feynman regards quantum gravity as "just another quantum field theory" such as quantum electrodynamics. The different types of existing particles are different excitations of the same string. Since one of the modes of string oscillation is a spin-2 massless state that identifies with graviton, string theory necessarily includes quantum gravity. String theory modifies the point gravity of particles at short distances by exchange of massive states of strings. [718] In string theory, the spacetime dimension is not an intrinsic property of the theory itself, but a property of the particular solution.

While string theory cannot currently provide falsifiable predictions, it has, however, inspired new and imaginative proposals for solving outstanding problems in particle physics and cosmology. Early string theory, when dealing with hadron physics, can explain why fermions come in three hierarchical generations, and mixing rates between generations of quarks. [719] In the second period when it approached quantum gravity, the theory addressed the paradox of information about the black hole, [720] counting the correct entropy of the black holes and the processes of changing the topology. [721] The discovery of AdS/CFT correspondence led to a formulation of string theory based on quantum field theory, better understood, and provided a general framework for solving black hole paradoxes, [722] such as in Hawkins radiation of black holes (information paradox). [723] Through his research program, he led to many theoretical discoveries in mathematics and gauge theory.

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[717] T. Banks et al., "M Theory as a Matrix Model: A Conjecture," *Physical Review D* 55, no. 8 (April 15, 1997): 55 (8): 5112–5128, https://doi.org/10.1103/PhysRevD.55.5112.

[718] Feynman et al., *Feynman Lectures on Gravitation*.

[719] Jonathan J. Heckman and Cumrun Vafa, "Flavor Hierarchy From F-Theory," *Nuclear Physics B* 837, no. 1–2 (September 2010): 837 (1): 137–151, https://doi.org/10.1016/j.nuclphysb.2010.05.009.

[720] Andrew Strominger and Cumrun Vafa, "Microscopic Origin of the Bekenstein-Hawking Entropy," *Physics Letters B* 379, no. 1 (June 27, 1996): 379 (1–4): 99–104, https://doi.org/10.1016/0370-2693(96)00345-0.

[721] A. Adams et al., "Things Fall Apart: Topology Change from Winding Tachyons," *Journal of High Energy Physics* 2005, no. 10 (October 11, 2005): (10): 033, https://doi.org/10.1088/1126-6708/2005/10/033.

[722] Sebastian de Haro et al., "Forty Years of String Theory Reflecting on the Foundations," *Foundations of Physics* 43, no. 1 (January 1, 2013): 2, https://doi.org/10.1007/s10701-012-9691-3.

[723] Leonard Susskind, *The Black Hole War: My Battle with Stephen Hawking to Make the World Safe for Quantum Mechanics*, Reprint edition (New York: Back Bay Books, 2009).

String theory is considered to be a useful tool in investigating the theoretical properties of the thermodynamics of black holes, [724] respectively their entropy. [725] The theoretical basis for these investigations has taken into account the case of idealized black holes, with the smallest possible mass compatible with a given task. [726] This result can be generalized to any theory of gravity, [727] being able to extend to non-extreme astrophysical black holes. [728]

In the Big Bang theory, part of the predominant cosmological model for the universe, the initial rapid expansion of the universe, is caused by a hypothetical particle called inflaton. The exact properties of this particle are not known. They should be derived from a more fundamental theory, such as string theory. [729] The development of this subprogram within the string theory research program is under development. [730]

In brane theory, brane D was identified with black hole supergravitation solutions. Leonard Susskind identified the holographic principle of Gerardus' t Hooft with common states of thermal black holes.

Recently, some experiments in other fields, such as condensed matter physics, have used theoretical results of string theory. [731] And the quantum inseparability in superconductors is largely based on the ideas of duality and additional spatial dimensions developed in string theory. With the help of the duality between 4-dimensional gauge theories and 5-dimensional gravity, string theorists have predicted the experimental value of plasma entropy, a result not obtained by any other theoretical model, but these are not absolute experimental validations. [732] [733]

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[724] de Haro et al., "Forty Years of String Theory Reflecting on the Foundations," 2.

[725] Yau, *The Shape of Inner Space*, 189.

[726] Yau, 192–93.

[727] Andrew Strominger, "Black Hole Entropy from Near-Horizon Microstates," *Journal of High Energy Physics* 1998, no. 02 (February 15, 1998): (2): 009, https://doi.org/10.1088/1126-6708/1998/02/009.

[728] Alejandra Castro, Alexander Maloney, and Andrew Strominger, "Hidden Conformal Symmetry of the Kerr Black Hole," *Physical Review D* 82, no. 2 (July 13, 2010): (2): 024008, https://doi.org/10.1103/PhysRevD.82.024008.

[729] Becker, Becker, and Schwarz, *String Theory and M-Theory*, 533.

[730] Becker, Becker, and Schwarz, 539–43.

[731] Sachdev, "Strange and Stringy," 44–51.

[732] Dawid, *String Theory and the Scientific Method*.

[733] Paul Verhagen, "Understanding the Theory of Everything: Evaluating Criticism Aimed at String Theory" (Amsterdam University College, 2015),

It is hoped that the additional dimensions can be observed with the Hadron Collider (LHC) from CERN, Geneva, but a possible denial would not mean refuting the theory.

For many researchers, gauge theory is considered the only way to renormalize relationships, and string theory is the only option to eliminate the infinities of a unifying program of quantum physics and gravity. The string theory was initially experimentally corroborated as a theory of particle physics, but in the current development it is considered to be far from being falsifiable. The continuation of the program is based on the confidence that theory is the best candidate for a total unifying program. Its credibility is enhanced by the interconnections created during its development, as in the case of supersymmetry and cosmology of black holes.

String theory still does not have a satisfactory definition in all circumstances. The theory uses perturbative techniques, [734] but has not yet clarified the aspects of determining the properties of the universe, [735] so it has attracted criticism from scientists, questioning the value of research in this direction. [736]

Critics of string theory draw attention to the large number of possible solutions described by the string theory. According to Woit,

> "The possible existence of, say, 10^{500} consistent different vacuum states for superstring theory probably destroys the hope of using the theory to predict anything. If one picks among this large set just those states whose properties agree with present experimental observations, it is likely there still will be such a large number of these that one can get just about whatever value one wants for the results of any new observation." [737]

The supporters of the theory argue that this can be an advantage, allowing a natural anthropic explanation of the observed values of the physical constants. [738]

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http://www.uva.nl/binaries/content/documents/personalpages/h/a/s.deharo/en/tab-three/tab-three/cpitem%5B8%5D/asset.

[734] Becker, Becker, and Schwarz, *String Theory and M-Theory*, 8.

[735] Becker, Becker, and Schwarz, 13–14.

[736] Zee, *Quantum Field Theory in a Nutshell, 2nd Edition*.

[737] Peter Woit, *Not Even Wrong: The Failure of String Theory and the Search for Unity in Physical Law*, Reprint edition (Basic Books, 2007), 242.

[738] Woit, 242.

Another criticism focuses on the dependence of the background theory, as opposed to general relativity. Lee Smolin argues that this is the main weakness of string theory as a theory of quantum gravity. [739]

The solutions of the theory are not unique, and there is no perturbative mechanism to select a particular solution or to choose the true vacuum. Thus, the perturbative formulation of string theory loses its predictive power. Also, there is no perturbative mechanism to select solutions that support low energy spectra that are not supersymmetrical. [740]

Paul Verhagen asks how we should evaluate string theory; can a theory that has considerable difficulties with experimental verification to be classified as a science? to answer this question we must analyze the origins of the different concepts used in theory, evaluate the need for a large unified theory, and focus on evaluating its scientific situation. Some argue that string theory has failed, while others point to its theoretical progress. There is a "meta-paradigmatic rift" between experimentalists and theorists in this regard. [741]

Chalmers believes that a theory must be falsifiable in Popper's sense[742] in order to be scientific: "If a statement is unfalsifiable, then the world can have any properties whatsoever, and can behave in any way whatsoever, without conflicting with the statement." [743] In this sense, string theory is considered as non-falsifiable. [744] The current technology is not precise enough to develop experiments to verify string theory. But the theory is "potentially" falsifiable; makes some predictions, such as the existence of additional dimensions, but they cannot be verified, at least for now. And not yet all the mathematical consequences of the axioms have been elaborated to detect possible conflicts with the observed reality. But efforts are being made in this direction, both for the experimental and the theoretical part.

String physicists are accused of ignoring empirical testability and that are replacing this criterion with mathematical arguments. Some of the questions of physicists and philosophers are:

1. Does a theory need to be testable, or are mental experiments sufficient?
2. Does a theory need to make verifiable predictions, or is indirect testability sufficient?
3. A theory without predictions, with only probability distributions, is considered testable?

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[739] Smolin, *The Trouble With Physics*, 184.

[740] Feynman et al., *Feynman Lectures on Gravitation*.

[741] Verhagen, "Understanding the Theory of Everything: Evaluating Criticism Aimed at String Theory."

[742] Popper, *Conjectures and Refutations*.

[743] Alan F. Chalmers, *What Is This Thing Called Science?*, 3 edition (Indianapolis: Hackett Publishing Co., 1999), 63.

[744] H. Georgi and Paul Davies, *Grand Unified Theories, in The New Physics* (Cambridge University Press, 1992).

4. Should the tests be necessarily empirical, or can mathematical consistency checks be considered tests?
5. If contradictory or unacceptable results are obtained from the mental tests by reduction to the absurd, what is the value of these tests?
6. When can testability be requested? Is the possibility of future testing valid?
7. How important is testability in relation to other epistemic desires? Is a theory easy to test but with a low explanatory value preferred over a non-testable theory but with a higher explanatory power? But if the testable theory is too complicated and the non-testable one is simple and elegant?
8. Are predictions of new phenomena more important than pre- or retrodictions of already known phenomena? [745]

Reiner Hedrich suggests[746] that the current failure of string theory could be due to the wrong mathematical device chosen, using the mathematics of the continuum. It is possible that when the theory finds its fundamental principle, it may lead to a more appropriate mathematical basis. An independent background formulation and holographic principle could help heuristic in finding this principle. But it is possible that the principle will never be found, possibly due to the wrong basic assumptions.

Currently, string theory is the dominant research program in the theoretical physics of high energy, [747] considered by some scientists as no viable alternative. [748] Peter Woit regards this status of theory as unhealthy and detrimental to the future of fundamental physics, its popularity largely due to the financial structure of the academic environment and the fierce competition of limited resources. [749] Roger Penrose expresses similar views, saying: "The often frantic competitiveness that this ease of communication engenders leads to bandwagon effects, where researchers fear to be left behind if they do not join in." [750]

Logical positivists considered that the scientific method means the deduction of nature models from observations. String theory was initially developed based on an observed fact, the Regge slopes, which at present is no longer considered to be explained by this theory. And the theory has so far not been confirmed by any empirical experiment or observation. But it continued to develop,

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745 Helge Kragh, "Fundamental Theories and Epistemic Shifts: Can History of Science Serve as a Guide?," *ArXiv:1702.05648 [Physics]*, February 18, 2017, http://arxiv.org/abs/1702.05648.

746 Reiner Hedrich, "The Internal and External Problems of String Theory: A Philosophical View," *Journal for General Philosophy of Science / Zeitschrift Für Allgemeine Wissenschaftstheorie* 38, no. 2 (2006): 261–278.

747 Penrose, *The Road to Reality*, 1017.

748 Woit, *Not Even Wrong*, chap. 16.

749 Woit, 239.

750 Penrose, *The Road to Reality*, 1018.

supported by the belief of many physicists that it is much better than quantum field theory for quantum gravity, and in the hope that it will help unify gravity with other fundamental forces. Most supporters seem to be completely indifferent to experiments and observations, being rather concerned with the "elegance" of mathematical formulation of the theory. [751] For this reason, a reconciliation between string theory and logical positivists seems impossible. [752]

Richard Dawid argues that string theory is based on observations, but its problem would be the huge "theoretical distance" between observable phenomena and scientific concepts. Some researchers argue that the principle of empirical underdetermination of scientific theories does not admit that this "theoretical distance" can be made to allow reliable claims about nature. To this end, Dawid believes that the principle of underdetermination must be replaced by arguments that support string theory. The problem of this theory is, according to Dawid, arbitrariness in choosing its fundamental principles. The theory has a certain set of physical postulates, but there is a continuous erosion of these postulates that follows a uniquely determined linear path. Thus, Dawid asserts that the disagreement between string theorists and phenomenological physicists on string status disappears due to a dramatic change in the characteristics of scientific theory: the old concept of underdetermination of scientific theories in modern particle physics gradually loses ground against the theory of uniqueness. String theory would induce a new understanding of what may be called a scientific statement about nature: the claim of theoretical uniqueness is sufficient for the adoption of a new scientific theory. [753]

In 1995, from the unification of string theories was born the most demanding, unifier gravity research program, the 11-dimensional M-theory, [754] in order to unify gravity with all other fundamental forces in physics.

3.4.1 Heuristics of string theory

The logical positivists would have considered string theory as a speculative metaphysics. The instrumentalist aspect of logical positivism does not correspond with the opinions of string theorists.

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[751] F. David Peat, *Superstrings and the Search for the Theory of Everything*, 1 edition (Place of publication not identified: McGraw-Hill Education, 1989), 276.

[752] Verhagen, "Understanding the Theory of Everything: Evaluating Criticism Aimed at String Theory."

[753] Dawid, "Scientific Realism in the Age of String Theory."

[754] Duff, "The Theory Formerly Known as Strings," 278 (2): 64–9.

From the point of view of Popper's falsifiability, [755] we clearly distinguish between the context of discovery and the context of justification. In the context of discovery, there are no methodological rules, but there are strict rules for testing hypotheses, avoiding *ad hoc* hypotheses as much as possible, which must be independently verifiable anyway. The string theory has not yet been tested and has already entered an *ad-hoc* hypothesis phase. But it has not been refuted so far, and the theory allows testing through experiments, even though there is not yet the technology needed to develop these experiments. An unexpected situation for Popper?

Kuhn adopted an externalist perspective in the philosophy of science. Scientific motivations do not always succeed in explaining paradigm shifts, as other external causes, including social ones, can enter this equation. [756] Kuhn's theory is rather a retrospective account of the history of science, never intended to provide a normative force methodology. [757] Thomas Kuhn's theory of scientific revolutions by changing "paradigms" can also be applied to string theory as a new paradigm in high energy physics. But a paradigm shift involves renouncing the old paradigm, going through a period of "crisis" in which anomalies occur, and observations that contradict the old paradigm. [758] The anomalies are discrepancies between theory and experiment. But in string theory there are no experiments, and problems of a theoretical nature have been known from the beginning. Thus, the new paradigm does not look any better than the old one.

Since string theory has not been able to explain phenomena to date, it may seem that this confirms Feyerabend's view that there is no "method" of science. And yet, string theory is still the most active research program for quantum gravity. But, compared to other non-falsifiable theories, this has something extra, especially: mathematical language, with a clear logic of deductions. Up to a point it can reproduce classical gauge theories and general relativity. And there is hope that in the not too distant future experiments can be developed to test the theory.

String theory is called by Keizo Matsubara a "research program" and this is in the sense of Lakatos. [759] Hacking took over Lakatos theory, [760] but not as a methodological norm, rather as a method of

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[755] Popper, *The Logic of Scientific Discovery*.

[756] Thomas S. Kuhn and Jim Conant, *The Road Since Structure: Philosophical Essays, 1970-1993, with an Autobiographical Interview* (University of Chicago Press, 2000), 286–87.

[757] Matsubara, *Stringed Along Or Caught in a Loop?*

[758] Lakatos, *The Methodology of Scientific Research Programmes*, 202.

[759] Keizo Matsubara, "Realism, Underdetermination and String Theory Dualities," *Synthese* 190, no. 3 (2013): 471–489.

[760] Ian Hacking, "Representing and Intervening by Ian Hacking," Cambridge Core, October 1983, https://doi.org/10.1017/CBO9780511814563.

rational reconstruction of the periods of the history of science. Keizo Matsubara supports Lakatos methodology, highlighting its main features in string theory: [761]

Hard core:

1. The fundamental objects are not punctual particles, but extended objects, strings or branes.
2. Acceptance of the basic assumptions of quantum mechanics as given.
3. The necessity of the supersymmetry of the theory.

Protective belt:

- Different variants of string theory are different theoretical formulations, not different theories.
- Compact dimensions are too small to be observed with current technology.
- Explaining the values of the constants of nature, assuming a landscape of universes.

Positive heuristics:

1. Explaining the diversity of the particles as mere manifestations of a fundamental type of objects.
2. Deriving the constants of nature
3. Unification of the standard model with gravity.

Negative heuristics:

1. No modus tollens argument is allowed to be directed against the hard core.

Compared to other programs, string theory seems to be more progressive in a more general sense. And the distinction between progressive/degenerative program cannot be made because empirical tests are lacking. But the failed attempts of the theorists over a large period to determine the constants of nature starting from the principles of the theory can be considered as a degenerative phase in the sense of Lakatos in which the empirical findings determine the theoretical development, although in this case the empirical results were known in advance, and had not predicted. Matsubara's conclusion is that string theory is a degenerative program, so it should be rejected if there would be such a progressive rival program. [762] Unfortunately, at present the other research programs are at least as inconclusive.

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[761] Matsubara, *Stringed Along Or Caught in a Loop?*

[762] Matsubara.

> "I hold Lakatos theory, MSRP, to be the most reasonable analysis of scientific development; it fits quite a number of episodes from history of science and I think it strikes the right balance between a descriptive and a normative account of science. It is also, to some extent, useful for discussing string theory and its competitors, mainly loop quantum gravity. However one cannot really say that one programme is progressive and one degenerative, because the distinction and comparison is made in terms of theoretical and empirical development, and no empirical development has occurred. On the other hand, without using Lakatos criteria and instead merely relying on our somewhat vague notion of development, one is tempted to say that string theory has been theoretically progressive, but not empirically progressive. One could say that adherents to string theory believe that theoretical progressiveness is sufficient for continuing work on the theory, whereas critics think it's not."[763]

Cartwright and Frigg reached similar conclusions by analyzing string theory from the perspective of Lakatos methodology, evaluating the degree of progressivity of the theory according to: the range of empirical applications, the predictions of success, the reproduction of new technologies, the answer to problems, the coherence, the elegance, the explanatory power, the truth. Their conclusion was that string theory was progressive as explanatory and unifying power, but this is insufficient to state the progressiveness of the theory as a whole. But the authors do not recommend rejecting the theory, appealing to the methodological tolerance proposed by Lakatos. [764]

Reiner Hedrich states that currently "string theory" is not a theory at all, but a labyrinth structure of mathematical procedures and intuitions. His only motivations over loop quantum gravity are the mutual incompatibility of the standard model of quantum field theory and general relativity, and the metaphysics of the physics unification program. [765] Delaying a philosophical decision on string theory after the consolidation of the research program could lead to more appropriate conditions for an evaluation.

The great asset of the theory is the hope that it will succeed in unifying the two seemingly incompatible theories, quantum and general relativity, and implicitly all the fundamental forces, in a great unified theory. In addition, the theory conformed to an approach considered fundamental in the scientific methodology by Einstein, Duhem, and others: simplification. String theory unified

[763] Matsubara, 43.

[764] N. Cartwright and Roman Frigg, "String Theory Under Scrutiny" (2008), 14–15.

[765] Hedrich, "The Internal and External Problems of String Theory."

the standard model and general relativity, in this sense being a "better" model even though it still does not make predictions. [766] Greene also appreciates his "elegance".[767]

3.4.2. Anomalies of string theory

Some of the predictions made by string theorists, such as microscopic black holes and low-energy super-symmetrical particles, were falsified by observation. [768] But these problems do not refute the theory, because they are indirect observations, rather than direct results of the theory.

In the case of string theory, the experimental aspects are beyond our technological capacity. [769] But the fact that all predictions of the theory have so far been falsified is a problem. In addition, the landscape problem is another problem that makes the theory not falsifiable. To solve this problem, it was proposed to use the anthropic principle, according to which we can choose from different permutations those universes that create conditions suitable for the appearance of life, [770] but this principle is controversial. [771] Another problem concerns dark matter/energy, which are not predicted by string theory.

As the string theory changed its scope (and in this context also all the requirements of a research program, including strategy) from hadron physics to quantum gravity, internal problems began to emerge that, by trying to eliminate them with ad-hoc hypotheses, led to other internal problems, resulting in a growing self-referentiality and a simultaneous removal of phenomenology. Her empiricism dropped steadily, remaining a labyrinth mathematical structure of unclear physical relevance.

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[766] Hakon Enger, “String Theory and the Scientific Method,” 2003, http://home.simula.no/~henger/publ/mnvit-essay.pdf.

[767] Brian Greene, *The Elegant Universe: Superstrings, Hidden Dimensions, and the Quest for the Ultimate Theory*, 2nd ed. edition (New York London: W. W. Norton & Company, 2010), 137.

[768] Matthias Blau and Stefan Theisen, “String Theory as a Theory of Quantum Gravity: A Status Report,” *General Relativity and Gravitation* 41, no. 4 (April 1, 2009): 743–55, https://doi.org/10.1007/s10714-008-0752-z.

[769] Richard P Feynman, “The Feynman Lectures on Physics,” 2013, http://www.feynmanlectures.caltech.edu/.

[770] Verhagen, “Understanding the Theory of Everything: Evaluating Criticism Aimed at String Theory.”

[771] Lee Smolin, “A Perspective on the Landscape Problem,” *Foundations of Physics* 43, no. 1 (January 2013): 21–45, https://doi.org/10.1007/s10701-012-9652-x.

In addition, the theoretical developments have led to a self-immunization of the theory against empirical refutations, including in the case of supersymmetry. [772] String theory does not make predictions for supersymmetric particle masses; thus, if future experiments in accelerators do not discover these particles, it can be argued that they have masses beyond the range of the experimental device. [773] It has thus become that the inability to make quantitative forecasts is used as a strategic advantage for auto-immunization, a unique aspect in physics. [774]

Dawid believes that a confirmation of a scientific theory is based on three main factors:

1. the existence of alternative solutions to a particular problem (string theorists claim that their theory is the only viable option for unification);
2. the degree of connection with the already confirmed theories (string theorists consider their program as a natural continuation of the particle physics research program);
3. number of unexpected intuitions/predictions.

Confidence in theory would depend on conformity with these factors, even in the absence of empirical confirmation. Basically, Dawid suggests a switch from empirical falsifiability to a Bayesian model that defines probability not "how often something happens" but "what degree of confidence we should have in our knowledge."

Some physicists propose to evaluate alternative theories to string theory. The main difference would be that the string theory aims to solve the problem of quantum gravity in the context of unification. Unfortunately, many of the problems of string theory remain in the alternative theories. The main rival, loop quantum gravity, has not yet been developed sufficiently to make falsifiable statements. Smolin claims the alternatives have been consistently neglected. [775] The problem with alternatives is that at present there is not sufficiently developed and consolidated theory to take the place of string theory. [776] Looking for "everyone's theory" there seems to be no other way than to continue working on string theory (the argument "There are no alternatives.") [777]

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[772] Richard Dawid, "On the Conflicting Assessments of the Current Status of String Theory," Preprint, April 2008, 984–96, http://philsci-archive.pitt.edu/4009/.

[773] Greene, *The Elegant Universe*.

[774] Hedrich, "The Internal and External Problems of String Theory."

[775] Smolin, *The Trouble With Physics*.

[776] Joanes Lizarraga et al., "Fitting BICEP2 with Defects, Primordial Gravitational Waves and Dust," *Journal of Physics: Conference Series* 600 (April 28, 2015): 600 (2015): 012025, https://doi.org/10.1088/1742-6596/600/1/012025.

[777] Richard Dawid, Stephan Hartmann, and Jan Sprenger, "The No Alternatives Argument," Preprint, February 24, 2013, 66.1 (2014): 213-234, http://philsci-archive.pitt.edu/9588/.

A scientific realist would only consider a well-tested mature theory that predicted new facts. String theory does not meet these requirements. The dualities of string theory reinforce this belief. The underdetermination of theories by data is a problem that concerns scientific realism. Realists will differentiate by simplicity, lack of *ad-hoc*, explanatory power, etc., between theories. Alternatively, it can be argued that underdetermination involves only two ways of describing the same theory. Undetermination should force the scientific realist to abandon either semantic or epistemic realism. [778]

Traditional logical positivists are kind of anti-realists, considering that the significant cognitive part of a theory is limited to its empirical content. So, string theory would not be accepted in the current situation. If string theory were to have empirical success in the future, the dualities would only be considered as semantic equivalents, because only the empirical content would be considered relevant.

3.5 Other theories of quantum gravity

Bimetric gravity is a class of modified theories of gravity in which two metric tensors are used instead of one, [779] the second metric being used at high energies. If the two metrics interact, two types of gravitons appear, one massive and one massless. The set of theories tries to explain the massive gravity. [780] Such theories are those of Nathan Rosen (1909-1995) [781] or Mordehai Milgrom's Modified Newtonian Dynamics (MOND). The evolutions of massive gravity have encouraged the emergence of new consistent theories of bimetric gravity, [782] but none have reflected physical observations better than general relativity theory. [783] Some of these theories (MOND, for example) are alternatives to dark energy. Other biometric theories do not take into account massive gravitons and do not change Newton's law, describing the universe as a variety of

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778 Matsubara, "Realism, Underdetermination and String Theory Dualities."

779 N. Rosen, "General Relativity and Flat Space. I," *Physical Review* 57, no. 2 (January 15, 1940): 57 (2): 147–150, https://doi.org/10.1103/PhysRev.57.147.

780 S. F. Hassan and Rachel A. Rosen, "Bimetric Gravity from Ghost-Free Massive Gravity," *Journal of High Energy Physics* 2012, no. 2 (February 24, 2012): 1202 (2): 126, https://doi.org/10.1007/JHEP02(2012)126.

781 Rosen, "General Relativity and Flat Space. I," 57 (2): 147–150.

782 Lisa Zyga, "Gravitational Waves May Oscillate, Just like Neutrinos," 2017, https://phys.org/news/2017-09-gravitational-oscillate-neutrinos.html.

783 Clifford Will, *The Renaissance of General Relativity, in The New Physics* (Cambridge: Cambridge University Press, 1992), 18.

two coupled Riemannian metrics, where matter interacts by gravity. Some of them stipulate the variable speed of light at high energy density. [784]

Rosen's bigravity (1940) [785] proposes that at every point of spacetime there is a Euclidean metric tensor in addition to the Riemannian metric tensor. Thus, at each point of spacetime there are two values. The first metric tensor describes the geometry of spacetime, and therefore the gravitational field. The second metric tensor refers to spacetime flat and describes the inertial forces. Rosen's bigravity satisfies the principle of covariance and equivalence. Rosen's bigravity and GR differ in the case of the propagation of electromagnetic waves, of the external field of a high-density star, and in the behavior of intense gravitational waves that propagate through a strong static gravitational field. The predictions of gravitational radiation from Rosen's theory were refuted by the observations of the Hulse-Taylor binary pulsar. [786]

Massive bigravity appeared in 2010, developed by Claudia de Rham, Gregory Gabadadze and Andrew Tolley (dRGT). [787] A non-dynamic "reference metric" appears in dRGT theory. The reference metric value must be specified manually. A further extension was introduced by Fawad Hassan and Rachel Rosen. [788]

Bohmian quantum gravity incorporates the real configuration in theory as the basic variable and stipulates that it evolves in a natural way suggested by symmetry and Schrodinger's equation. [789] The theory solves the problem of time (the same role as in GR), and partly the problem of diffeomorphism. It has no problems with the role of observers and observables because they play no role in this theory. The time-dependent wave function, which satisfies the Schrodinger equation, is not necessary here.

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[784] J. P. Petit and G. D'Agostini, "Cosmological Bimetric Model with Interacting Positive and Negative Masses and Two Different Speeds of Light, in Agreement with the Observed Acceleration of the Universe," *Modern Physics Letters A* 29, no. 34 (October 27, 2014): 29 (34): 1450182, https://doi.org/10.1142/S021773231450182X.

[785] Rosen, "General Relativity and Flat Space. I," 57 (2): 147–150.

[786] Will, *The Renaissance of General Relativity, in The New Physics*, 18.

[787] Claudia de Rham, Gregory Gabadadze, and Andrew J. Tolley, "Resummation of Massive Gravity," *Physical Review Letters* 106, no. 23 (June 10, 2011): 106 (23): 231101, https://doi.org/10.1103/PhysRevLett.106.231101.

[788] Hassan and Rosen, "Bimetric Gravity from Ghost-Free Massive Gravity," 1202 (2): 126.

[789] Sheldon Goldstein and Stefan Teufel, "Quantum Spacetime without Observers: Ontological Clarity and the Conceptual Foundations of Quantum Gravity," *ArXiv:Quant-Ph/9902018*, February 5, 1999, http://arxiv.org/abs/quant-ph/9902018.

Bohmian quantum gravity implies a simple transition from quantum mechanics, incorporating the actual configuration into theory as the basic variable and stipulating that it evolves in a natural manner suggested by Schrodinger's symmetry and equation.

3.6 Unification (The Final Theory)

The fields of application of general relativity (GR) and quantum field theory (QFT) are different, so most situations require the use of only one of the two theories. [790] The overlaps occur in regions of extremely small size and high mass, such as the black hole or the early universe (immediately after the Big Bang). This conflict is supposed to be solved only by unifying gravity with the other three interactions, to integrate GR and QFT into one theory. The string theory states that at the beginning of the universe (up to 10^{-43} seconds after the Big Bang), the four fundamental forces were a single fundamental force. According to physicism in philosophy, a physical final theory will coincide with a final philosophical theory.

Several unifying theories have been proposed. Great unification implies the existence of an electronuclear force. The last step in unification would require a theory that includes both quantum mechanics and gravity through general relativity ("the final theory"). After 1990, some physicists consider that the 11-dimensional M-theory, often identified with one of the five perturbative superstring theories, or sometimes with the 11-dimensional maximal-supersymmetric supergravity, is the final theory. The idea of M theory[791] took over from the ideas of the Kaluza-Klein theory, in which it was found that the use of a 5-dimensional spacetime for general relativity (with a small one) is seen, from the 4-dimensional perspective, like the usual general relativity along with Maxwell's electrodynamics. An important property of string theory is its supersymmetry (version of superstring theory) which, along with the additional dimensions, are the two main proposals for solving the problem. The additional dimensions would allow gravity to spread to the other dimensions, the other forces remaining limited in a 4-dimensional spacetime.

Attempts to use loop quantum gravity (LQG) in a final theory (FT) have failed, but supporters of this program are continuing their research. [792]

There are attempts to develop a final theory through other theories, such as the causal fermions systems theory, which contains the two current physical theories (general relativity and quantum field theory) as limiting cases. Another theory is that of causal sets. Another proposal is Garrett

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[790] Carlip, "Quantum Gravity," 64 (8): 885–942.

[791] Weinberg, *Dreams Of A Final Theory*.

[792] Sundance Bilson-Thompson et al., "Particle Identifications from Symmetries of Braided Ribbon Network Invariants," *ArXiv:0804.0037 [Hep-Th]*, April 1, 2008, http://arxiv.org/abs/0804.0037.

Lisi's E8, [793] which proposes unification within the Lie group. Christoph Schiller's Strand model attempts to reflect the gauge symmetry of the standard particle physics model, and another version involves ER = EPR, a conjecture in physics stating that entangled particles are connected by a wormhole (or Einstein–Rosen bridge). [794]

Jürgen Schmidhuber is for FT, stating that Gödel's incompleteness theorems[795] are irrelevant to computational physics. [796] Most physicists claim that Gödel's theorem does not imply the impossibility of a FT. [797] Some physicists, including Einstein, believe that theoretical models should not be confused with the true nature of reality, and argue that approximations will never reach a complete description of reality. [798] A philosophical debate is about whether a final theory can be called the *fundamental law of the universe*. [799] The reductionist FT supporters claim that theory is the fundamental law. Another view is that emerging laws (such as the second law of thermodynamics and the theory of natural selection) should be considered as fundamental, and therefore independent.

The name "final theory" is contradicted by the probabilistic nature of quantum mechanics predictions, sensitivity to initial conditions, limitations due to event horizons, and other deterministic difficulties. Frank Close contradicts the idea of FT claiming that the layers of nature are like layers of onion, and the number of these layers could be infinite, [800] implying an infinite

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793 A. Garrett Lisi, "An Exceptionally Simple Theory of Everything," *ArXiv:0711.0770 [Gr-Qc, Physics:Hep-Th]*, November 6, 2007, http://arxiv.org/abs/0711.0770.

794 Ron Cowen, "The Quantum Source of Space-Time," *Nature News* 527, no. 7578 (November 19, 2015): 527 (7578): 290–293, https://doi.org/10.1038/527290a.

795 Gödel's incompleteness theorems are two theorems of mathematical logic that establish limitations inherent in all axiomatic systems, except for the most trivial ones, capable of arithmetic. The first theorem states that any effectively generated theory, capable of expressing elementary arithmetic, cannot be both consistent and complete.

796 Jürgen Schmidhuber, "A Computer Scientist's View of Life, the Universe, and Everything. Lecture Notes in Computer Science," 1997, 201–208, http://people.idsia.ch/~juergen/everything/.

797 Jürgen Schmidhuber, "Hierarchies of Generalized Kolmogorov Complexities and Nonenumerable Universal Measures Computable in the Limit," *International Journal of Foundations of Computer Science* 13, no. 04 (August 1, 2002): 13 (4): 587–612, https://doi.org/10.1142/S0129054102001291.

798 Pais, *Subtle Is the Lord*, chap. 17.

799 Weinberg, *Dreams Of A Final Theory*.

800 Frank Close, *The New Cosmic Onion: Quarks and the Nature of the Universe*, Revised edition (New York: CRC Press, 2006).

series of physical theories. Weinberg[801] states that since it is impossible to accurately calculate even a real projectile in the Earth's atmosphere, we cannot speak of a FT.

Unification does not necessarily mean reduction. Quantum field theory and general relativity are unified theories themselves. General relativity is a gravitational generalization of the special theory of relativity that unified electromagnetism with classical non-gravitational mechanics, and quantum field theory is a combination of special relativity and quantum mechanics. The standard model is often presented as an example of successful unification. In trying to unify gravity with other forces, loop quantum gravity is a "minimalist" version (it is just an attempt to quantify general relativity). String theory tries to be the "theory of everything", in which a single type of interaction determines any other aspects of reality.

Between quantum theory and general relativity there are problems of conceptual compatibility in the development of quantum gravity: the background independence of general relativity due to the lack of a preferred frame of reference, is opposed to the geometry of quantum theory which implies a background dependence related to the existence of a preferred frame of reference. [802] The metric in general relativity determines the geometry of spacetime and acts as a potential. Because it is a dynamic variable, it turns out that geometry itself is dynamic. Quantum theory requires a fixed geometry, resulting in a very different treatment of spacetime compared to GR. A theory of quantum gravity can give up substance dependence, or quantum theory can be modified.

According to Reiner Hedrich, string theory is a mathematical construct without any empirical control, which seems to transcend more and more the context of physics, by increasing self-immunization, eventually becoming a metaphysical form of a mathematical inspiration nature. [803] The return to a metaphysical nature must be seen as a retrograde step. String theory can be understood as a return to the ancient ideal of a deepening of nature exclusively through our (mathematical) intellect, without observations or experimental devices. Jeremy Butterfield and Christopher Isham point out that the immense self-reference that is found in all theories of quantum gravity is a consequence of the absence of empirical data, of the metaphysical significance of hypotheses and bias, and of the mathematical apparatus and theoretical model on which those theories are conceived. [804]

The mathematical basis of string theory (an extended version of the quantum field theory apparatus) has not changed significantly during its evolution. There have also been attempts to unify gravity

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801 Weinberg, *Dreams Of A Final Theory*.

802 Weinstein, "Absolute Quantum Mechanics," 52: 67-73.

803 Hedrich, "The Internal and External Problems of String Theory."

804 Butterfield and Isham, "Spacetime and the Philosophical Challenge of Quantum Gravity," 33–89.

with other forces on mathematical bases, such as Einstein, Schrodinger, Misner and Wheeler's theories of geometrically unifying gravity and electromagnetism, but they have also failed. [805] All researchers, regardless of whether they are followers or critics of the Final Theory, are trying to find an answer to the question why this unification has not succeeded so far. After all, there is no consensus even on defining what unification actually is, and to what extent it can epistemically reflect this eventual ontic unity. Our epistemic boundaries could make such an exploration impossible.

Basically, the philosophers of science are skeptical of the philosophical motivations of this unification, and of its scientific success. [806]

[805] Robert Weingard, "A Philosopher Looks at String Theory," *PSA: Proceedings of the Biennial Meeting of the Philosophy of Science Association* 1988 (1988): 95–106.

[806] Nancy Cartwright, *The Dappled World: A Study of the Boundaries of Science* (Cambridge University Press, 1999).

4. Cosmology

At the cosmological level, the standard cosmological model contains Einstein's theory of gravity as part of the "hard core". Dark matter, dark energy, and inflation were added to the theory in response to observations. None of these ancillary hypotheses have yet been confirmed. The standard cosmological model does not have predictions of success, it is constantly adjusted following observations. The reproduction of the spectrum of temperature fluctuations in the cosmic microwave environment is considered a success of the model, but it was obtained by the forced modification of the model parameters, with inconsistencies with the values determined in other, more direct ways.

David Merritt[807] draws attention to an alternative research program, which was initiated in the early 1980s and made new predictions; the program of Mordehai Milgrom (MOND), initiated in 1983, whose specific principle states that the laws of gravity and motion differ from those of Newton or Einstein in the very low acceleration regime (at the level of galaxies). The program has a long list of other predictions, avoiding the assumptions of dark matter and dark energy.

In cosmology, metaphysics involves a wide range of questions beyond empirical evidence, sometimes using speculative inference. Epistemological analysis in cosmology helps model evaluation. The philosophical study provides a general framework for interpreting inferences that go beyond science. [808]

In cosmology there are some ontological principles that help to classify the models according to characteristics, to conceive the cosmic reality in a more transparent description and allow us to solve mathematical equations as central constructions of any model. These principles are: [809]

1. Homogeneity of space (uniform distribution of matter)
2. Homogeneity of time (structure independent of global cosmic time)
3. Isotropy of space (independence of structure from the direction of observation)
4. Homothety of space (independence of structure from scalar transformations)

Thus, the standard model (Hot Big Bang) includes the models (a, c), the stationary model includes (a, b, c), the hierarchical model includes (c, d).

[807] David Merritt, "Gravity: The Popper Problem," IAI TV - Changing how the world thinks, October 2, 2017, https://iai.tv/articles/gravity-the-popper-problem-auid-899.

[808] Petar V. Grujic, "Some Epistemic Questions of Cosmology," *ArXiv:0709.3191 [Physics]*, September 20, 2007, http://arxiv.org/abs/0709.3191.

[809] Grujic.

In order to epistemically evaluate cosmological models, we assume that the physical laws are valid and the same everywhere in the cosmos, in space and time. Isotropy of space is the only property of the cosmos that is easy to verify. Because the inference on physical properties and phenomena is always indirect and related to theoretical models, empirical evidence is based on the validity of these theoretical constructs. [810] In estimating the cosmic distances we take into account the color change of the spectral lines from these objects and we rely on the interpretation of this change, attributed to the Doppler effect (kinematic), gravitational phenomena (dynamic), space expansion (geometric), etc., depending on the ours model of the universe. Within the "epistemic space", the ontologically defined principles (a, b, c) are postulated, but the fourth (d) is no longer valid at sufficiently small scales, including probably the gravitational one. Part of the observable cosmos, cosmography, can be viewed as a structure built on particular elemental components.

Cosmographic models begin with the galaxy as an elemental unit. Cosmology treats galaxies as physical points, endowed with collective (coherent) and own (chaotic) movements.

In cosmology, the theoretical predictions or descriptions must be in accordance with the empirical evidence, it turns out that the models will be adapted to the new empirical situations, or new external elements may be introduced into the model, provided they do not contradict the initial structure. [811]

The test stone for a cosmological model is how it treats the problem of the Beginning, including the initial conditions and the eschatological problem. The Abderian approach is immune to these problems. In general, a good theory includes a formal mathematical model and the procedure of coupling with physical reality. Hawking proposed a solution that aims to formulate a model that is self-sufficient.

Thus, the research program for the standard cosmological model is a unifying program in the sense of the methodology of Lakatos' research programs, including several unified programs (such as the one for the Big Bang, stellar and galaxy evolution, gravitational singularities, etc.). These unified programs are at the same time research sub-programs of the unifying program because, even if they are created and developed without being required by the unifying program, they must take into account its requirements in order to be validated and included in it.

General relativity has emerged as an extremely successful model for gravity and cosmology, which has so far passed many unequivocal observational and experimental tests. However, there are

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[810] Grujic.

[811] P. Duhem, "La Théorie Physique, Son Objet Et Sa Structure," *Revue Philosophique de La France Et de l'Etranger* 61 (1906): 324–327.

strong indications that the theory is incomplete. [812] The question of quantum gravity and the question of the reality of spacetime singularities remain open. Observational data taken as evidence of dark energy and dark matter could indicate the need for new physics. Even as it is, general relativity is rich in possibilities for further exploration. Mathematical relativists seek to understand the nature of the singularities and fundamental properties of Einstein's equations, [813] while numerical relativists run increasingly powerful computer simulations (such as those describing black holes merging). A century after its introduction, general relativity remains a very active research area.

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[812] John Maddox, *What Remains to Be Discovered: Mapping the Secrets of the Universe, the Origins of Life, and the Future of the Human Race*, 1st Touchstone Ed edition (New York: Free Press, 1999), 52–59, 98–122.

[813] H. Friedrich, "Is General Relativity 'Essentially Understood'?," *Annalen Der Physik* 15, no. 1–2 (2006): 15 (1–2): 84–108, https://doi.org/10.1002/andp.200510173.

Conclusions

Through this paper I have developed the rational reconstruction of gravity based on the Lakatos' methodology of scientific research programmes, from Newton to the present, highlighting the main methodologies used in the evolution of this concept, and the current trends of development. The natural extension I proposed for the Lakatos methodology can successfully explain the new evolutions of physics in the case of quantum gravity.

When scientists formulate and develop new theories, they do not have an immediate understanding of the formalism of the theory. The description is approximate, and the reference to their terms may be vague. [814] Images developed by a theory have an important heuristic value, which may suggest possible extensions of the theory or inspire new hypotheses. A philosophical critical analysis of the history of the concept of gravity can help to better understand the evolution of science, how to approach this concept over time, and current trends and possibilities.

In Lakatos' opinion, there are multiple ways to reconstruct history, it all depends on what is considered to be rational. He proposes that the evaluation of these theories be made according to how well they manage to reconstruct the history of science while retaining the rationality of the "great science": "All methodologies function as historiographical (or meta-historical) theories (or research programmes) and can be criticized by criticizing the rational historical reconstructions to which they lead." Thus, research programmes are normative criteria for scientific rationality. [815]

The standard empiricism, which is part of the methodology of Lakatos research programmes, states that in science all theories must be evaluated impartially in terms of evidence, simplicity, unity or explanatory power. Some versions of standard empiricism give simplicity and explanatory power a more important role than other versions. Planck remarked at one point that: "Experiments are the only means of knowledge at our disposal. The rest is poetry, imagination," [816] and Poincare[817] said that "Experiment is the sole source of truth. It alone can teach us something new; it alone can give us certainty."

[814] Matsubara, "Realism, Underdetermination and String Theory Dualities."

[815] Sfetcu, "Reconstructia Rationala a Stiintei Prin Programe de Cercetare."

[816] Peter W. Atkins and Ronald S. Friedman, *Molecular Quantum Mechanics*, 5 edition (Oxford ; New York: Oxford University Press, 2010), xiv.

[817] Henri Poincare, *Science and Hypothesis* (CreateSpace Independent Publishing Platform, 2012), 140.

Lakatos, according to Larry Laudan, states that the methodologist cannot tell scientists what theories to reject or accept, renouncing the prescriptive force of the methodology. [818] But, says Laudan, one must not give up the methodological enterprise. The doctrine adopted by Lakatos is that of rationality, according to which most scientists have rationally made theoretical choices: "If we put forward a theory to resolve a contradiction between a previous theory and a counterexample in such a way that the new theory, instead of offering a content-increasing (scientific) *explanation*, only offers a content-decreasing (linguistic) *reinterpretation*, the contradiction is resolved in a merely semantical, unscientific way. *A given fact is explained scientifically only if a new fact is also explained with it.*" [819]

Keizo Matsubara concludes that "If it is possible to find dualities between seemingly very different formulations within one research programme one should acknowledge that it might not be suitable to only study one research programme. The hostility that from time to time has appeared between proponents of different research programmes in quantum gravity might be a serious mistake. If something like a duality would be found between the research programmes, then they could actually merge. A general methodological suggestion can be given to the effect that only if a research programme is empirically progressive, would it be rational to completely 'stick with the programme'. When a theoretical research programme does not produce empirical results then a broader perspective ought to be adopted." [820]

Unprecedented proliferation of the gravity theories requires an appropriate methodological approach, allowing logical relationships between these theories to explain the motivation of their emergence, their developmental modalities, and to evaluate future development trends. In this regard, I believe that Lakatos' methodology has sufficient flexibility and logic to address all these issues. The extension I proposed through bifurcated and unifying programs allows the explanation at methodological level and through the scientific rationality of this proliferation of post-Einsteinian theories and quantum gravity.

Einstein can best be understood from the perspective of his views on geometry and physics: "axiomatic geometry" must be supplemented with statements about the behavior of objects, which is a natural science which Einstein calls "practical geometry"; thus, the length measurements represent a practical geometry:

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[818] Larry Laudan, "Progress or Rationality? The Prospects for Normative Naturalism," *American Philosophical Quarterly* 24, no. 1 (1987): 19–31.

[819] Lakatos, *The Methodology of Scientific Research Programmes*, 34.

[820] Matsubara, "Realism, Underdetermination and String Theory Dualities."

> "I attach special importance to these views of geometry, because without it I should have been unable to formulate the theory of relativity. Without it the following reflection would have been impossible; in a system of reference rotating relatively to an inertial system, the laws of disposition of rigid bodies do not correspond to the rules of Euclidean geometry on account of the Lorentz contraction; thus if we admit non-inertial systems on an equal footing, we must abandon Euclidean geometry. Without the above interpretation the decisive step in the transition to generally covariant equations would certainly not have been taken." [821]

For Einstein, ether and absolute space and time were useless or inadequate. Unlike Einstein, who attributed properties or states to space, physicists in the 18th and 19th centuries could not conceive of such a thing, so they invented the ether to take over these attributes. Einstein revolutionized the concepts of space, time and matter, through a relational approach to physics.

All physical laws are based on a certain spacetime geometry. In this sense, there are three fundamental types of geometric structures: topology, connection and metric. Topology addresses the proximity of points or events, boundaries, continuity, connection and related concepts. The connection is a prescription of the parallel transport of the vectors (and tensors) along the curves, and therefore the comparison of the vector fields at different points to form (covariant) derivatives and differential equations. The metric attributes inner products to the vectors, length to curves, and in the relativistic theories determines the structure of the light cones and the causal relations. [822] In Einstein's theory, the connection and the metric - and the structures determined by them, such as the curvature - represent the gravitational field, resulting in it being part of the dynamic structure of spacetime geometry.

According to Clifford, the variation of spacetime curvature determines the motion of matter, and so the theory of general relativity explains gravity in terms of geometrical curvature of spacetime. [823] [824] Luciano Boi states that from the philosophical and scientific point of view, the most important finding of Einstein is that the way the gravitational field behaves depends on the nature of the geometry that characterizes spacetime.

Keizo Matsubara states that the existence of dualities in the context of string theory can only be interpreted correctly if certain semantic aspects are clarified. [825] The arguments about string duality

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[821] Einstein, *Geometrie und Erfahrung*, 235.

[822] Luciano Boi, "Theories of Space-Time in Modern Physics," *Synthese* 139, no. 3 (2004): 429–489.

[823] Wheeler, "On the Nature of Quantum Geometrodynamics."

[824] Luciano Boi, *Le problème mathématique de l'espace : Une quête de l'intelligible*, 1995 ed. (Berlin ; New York: Springer, 1995).

[825] Matsubara, "Realism, Underdetermination and String Theory Dualities."

seem to be compatible with a certain form of structural realism. String theorists do not believe that dual descriptions give rise to real alternatives. They are based on pragmatism. Thus, in some situations one description is better than another. But this is valid from a computational point of view. Physicists do not understand dualities as holding a vision in which everything in a theoretical formulation is considered literally true, not even an attempt. Although most physicists understand dualities similar to ontic or metaphysical structural realism, alternative opinions are also possible.

In the case of the dualities of the string theory, they deny the semantic realism, but in other situations the string theorists have opted for a realistic understanding, as in the case of the "landscape" of the string theory, in which the idea of a parallel and real universe appears. Thus, string theorists must balance between realism and anti-realism in their attitude to their theoretical constructs, often accepting an intermediate realism, a version of structural realism, more specifically ontic or metaphysical structural realism. [826] With this idea, Dawid[827] also agrees that dualities can undermine a vision that takes them seriously.

Erik Curiel[828] compared the current preference for quantum gravity with that for the hypothetical-deductive methodological model of the 17th century, when instead of being critically analyzed it was chosen only to express enthusiasm for its future possibilities. He believes that such an attitude harms science.

It is hoped that in the not too distant future, the energies generated by CERN' Large Hadron Collider will be sufficient to test aspects of quantum gravity, such as additional dimensions, supersymmetry, microscopic black hole behavior, etc. If supersymmetry is verified, this could be a "crucial test" for refuting or preserving string theory, but not for confirming it.

Sean Lorenz comes to a simple conclusion about quantum gravity: “we simply do not know yet." [829] He thinks that quantifying the general theory is wrong. One reason would be spacetime, which in string theory defies ontological simplicity in favor of mathematical consistency.

A theory of quantum gravity obtained from the theory of the quantum field of the standard model, combined with the general theory of relativity, is difficult to realize, especially for the explanation of some aspects that involve strong gravity (early universe, gravitational singularities). Curiel states

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[826] Matsubara.

[827] Dawid, “Scientific Realism in the Age of String Theory.”

[828] Curiel, “Against the Excesses of Quantum Gravity.”

[829] Sean Lorenz, “A Cautious Ontology of Spacetime in Quantum Gravity,” ResearchGate, 2015, https://www.researchgate.net/publication/268296604_A_CAUTIOUS_ONTOLOGY_OF_SPACETIME_IN_QUANTUM_GRAVITY.

that as long as there are no empirical results to disprove a theory, it remains viable,[830] but a theory that does not confirm long-term empirically loses credibility.

Another problem concerns the so-called *landscape problem*, a widely debated point of view in string theory: many of the fundamental constants of nature are the result of ways in which the Calabi-Yau varieties can be folded,[831] with more than 10^{500} different permutations with different values.[832] [833] Thus, experiments that seem to contradict the predictions of string theory can be rejected as a wrong permutation. A proposed but controversial solution is to reduce the number of universes only to the habitable ones, in this way the fundamental constants of the universe being the result of the anthropic principle, rather than those deduced from the theory.[834] The large number of permutations causes testing of all versions to be unrealistic. Thus, the string theory self-immunized against the refutations of such experiments and came to be regarded as pseudoscience by some researchers.

Rosenfeld was the first to attempt to build a theory of quantum gravity (in 1930), but later gave up because of the lack of experimental evidence on the quantum effects of gravity.[835] Rosenfeld denied its necessity and argued that the analogy between the gravitational field and the electromagnetic field is not convincing, stating that "the ultimate necessity of quantizing the electromagnetic field (or any other field) can only be founded on experience."[836] Rosenfeld seems to have been agreed with Bohr's view on the unity of physics, according to which quantum gravity cannot be a final theory that results from classical physics (and classical phenomena).

Skeptics believe that general relativity and quantum field theory, while not incompatible in a logical sense, are fundamentally incompatible as "immeasurable theories",[837] because "according to GTR [general relativity], gravity simply is not a force."[838] Some suspect that only the internal strategies of physics (for example, inductive generalization, expanding the scope of a set theory, or exploiting the explanatory capabilities of a set theory) are not sufficient to support such

[830] Curiel, "Against the Excesses of Quantum Gravity."

[831] Disalle, "Spacetime Theory as Physical Geometry."

[832] Leonard Susskind, "Lecture Collection | Topics in String Theory (Winter 2011)," YouTube, 2011, http://www.youtube.com/playlist?list=PL3E633552E58EB230.

[833] Adams et al., "Things Fall Apart," 347.

[834] Smolin, *The Trouble With Physics*.

[835] L. Rosenfeld, "On Quantization of Fields," *Nuclear Physics* 40 (February 1, 1963): 442–44, https://doi.org/10.1016/0029-5582(63)90279-7.

[836] Rosenfeld, 443.

[837] Wuthrich, "To Quantize or Not to Quantize," 778.

[838] Maudlin, "On the Unification of Physics," 129–144.

programs. But physicists use external arguments, for example a "dogma of unification",[839] [840] [841] using metaphysical principles (for example, "unity of nature"), meta-theoretical principles (for example, "economics of thought") or epistemological principles (for example, unification for its own sake, elimination of theoretical dualism), respectively philosophical reasons. [842] [843] [844]

Some researchers argue that Gödel's incompleteness theorem implies that it is not possible to construct a final theory, an idea also advocated by Stanley Jaki[845] and Freeman Dyson: "Gödel's theorem implies that pure mathematics is inexhaustible. No matter how many problems we solve, there will always be other problems that cannot be solved within the existing rules. […] Because of Gödel's theorem, physics is inexhaustible too. The laws of physics are a finite set of rules, and include the rules for doing mathematics, so that Gödel's theorem applies to them." [846] Stephen Hawking, although he initially believed in the final theory, after analyzing Gödel's theorem, thought: "Some people will be very disappointed if there is not an ultimate theory that can be formulated as a finite number of principles. I used to belong to that camp, but I have changed my mind." [847]

There are also scientists who ask how the relationship between general relativity and quantum theory could be conceived if the gravitational field is not quantified. [848] The "question of the question" is whether such a model would be (experimentally and observationally) relevant. Rosenfeld[849] argued that in such a case it is better to stick to semi-classical gravity, which combines a classical description of the gravitational field with a quantum treatment of all other fields of force

[839] Wuthrich, "To Quantize or Not to Quantize," 777–788.

[840] Maudlin, "On the Unification of Physics," 129–144.

[841] James Mattingly, "Is Quantum Gravity Necessary?," in *The Universe of General Relativity*, ed. A. J. Kox and Jean Eisenstaedt, Einstein Studies (Birkhäuser Boston, 2005), 327–38.

[842] Salimkhani, "Quantum Gravity."

[843] Wuthrich, "To Quantize or Not to Quantize," 777–788.

[844] Mattingly, "Is Quantum Gravity Necessary?," 327– 338.

[845] Stanley L. Jaki, *The Relevance of Physics*, First Edition edition (Chicago: University Of Chicago Press, 1966), 127–130.

[846] Freeman Dyson, "The World on a String," May 13, 2004, https://www.nybooks.com/articles/2004/05/13/the-world-on-a-string/.

[847] Stephen Hawking, "Gödel and the End of Physics," 2003, https://www.caltech.edu/campus-life-events/master-calendar/stephen-hawking-goumldel-and-the-end-of-physics.

[848] Butterfield and Isham, "Spacetime and the Philosophical Challenge of Quantum Gravity," 57.

[849] Rosenfeld, "On Quantization of Fields," 442–44.

and matter. In this case, quantum gravity would no longer be needed. Callender and Huggett comment on this:

> "Another philosophical position, ... might claim that general relativity describes certain aspects of the world, quantum mechanics other distinct aspects, and that would be that. According to this view, physics (and indeed, science) need not offer a single universal theory encompassing all physical phenomena. We shall not debate the correctness of this view here but we would like to point out that if physics aspires to provide a complete account of the world, as it traditionally has, then there must be a quantum theory of gravity [in the general sense of a connection between general relativity and quantum theory]. The simple reason is that general relativity and quantum mechanics cannot both be correct even in their domains of applicability." [850]

They claim that the two theories "... cannot both be universal in scope, for the latter strictly predicts that all matter is quantum, and the former only describes the gravitational effects of classical matter." With all the impressive empirical successes of the quantum theory, it does not predict that all matter is quantified, which results only in adopting an ontological interpretation of quantum theory. In Bohr's opinion, this idea can withstand the extent to which objects are neither quantum nor classical (even if in particular cases a predisposition appears).

A special problem in favor of decoupling the two theories is the problem of the cosmological constant: while the quantum field theory predicts a high astronomical value (indicating an extreme curvature of spacetime), an observer will find that spacetime is flat, or almost flat. . The problem of cosmological constant is considered by Weinberg[851] to be a "real crisis" for fundamental physics. He suggests that our understanding of the link between general relativity and quantum field theory is (so far) premature to rely on high-energy regime extrapolations. [852]

Richard Dawid argues that string theory is a new type of scientific theory that goes beyond the current sphere of experiment-based science. He suggests that physics undergoes meta-paradigmatic changes in which modern theories take it well ahead of experimental capabilities, and a new scientific method is needed to establish the validity of theories.

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[850] Callender and Huggett, *Physics Meets Philosophy at the Planck Scale*, 4.

[851] Steven Weinberg, "The Cosmological Constant Problem," *Reviews of Modern Physics* 61, no. 1 (January 1, 1989): 1–23, https://doi.org/10.1103/RevModPhys.61.1.

[852] Zinkernagel, "The Philosophy Behind Quantum Gravity."

But it is possible that physics at the Planck scale may be successfully described by a theory that has no connection with the current string theory or any other existing approach to quantum gravity): [853]

> "[...] nature is much more crazy at the Planck scale than even string theorists could have imagined"[854]

> "[...] it is unlikely that a final theory of quantum gravity - if indeed there is one - will look much like any of the current candidate theories, be they string theory, canonical gravity, or other approaches." [855]

The revolution in gravity physics remains incomplete. It is a problem that, if solved, will fundamentally change the way we think about the world.

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[853] Dawid, "On the Conflicting Assessments of the Current Status of String Theory," 984–96.

[854] G. 't Hooft, "Dimensional Reduction in Quantum Gravity," *ArXiv:Gr-Qc/9310026*, October 19, 1993, http://arxiv.org/abs/gr-qc/9310026.

[855] Weinstein and Rickles, "Quantum Gravity."

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