SPACE AND TIME 62 YEARS AFTER THE BERNE CONFERENCE

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Abstract
In 1955, an international conference took place in Berne at which the state of relativity theory and its possible generalizations were presented and critically discussed. I review the most important contributions to that conference and put them into the perspective of today’s knowledge about the nature of space and time.
1 Historical Context

From July 11 to July 16, 1955, a conference took place in Berne celebrating the fiftieth anniversary of the special theory of relativity. This was perhaps the first international conference devoted to an overview of relativity theory, its ramifications, and applications. The main goal of that conference was neither historical nor was it restricted to special relativity; in fact, most of the topics deal with general relativity and its generalizations, both in classical and quantum directions, along with cosmology and with mathematical structures. The list of participants contains an impressive number of famous figures together with a selection of young scientists. The Proceedings of that conference were published in 1956 and contain most of the presented talks together with a record of the discussions (Mercier and Kervaire 1956). In my contribution, I will heavily rely on these Proceedings, the title page of which is displayed in Fig. 1.

The Berne Conference became later known as the GR0 Conference, the numbering referring to the series of conferences organized by The International Society on General Relativity and Gravitation (GRG). This society was founded at the GR6 conference, which took place in Copenhagen in 1971, and grew out of the International Committee on General Relativity and Gravitation, which was responsible for the earlier conferences. Several of the GRG Presidents were, in fact, participants of the Berne Conference, among them Christian Møller, Nathan Rosen, Peter Bergmann, and Yvonne Choquet-Bruhat.

The conference was organized by the Seminar for Theoretical Physics of the University of Bern, located at the Institute for Exact Sciences at Sidlerstrasse 5. The President of the Organization Committee was Wolfgang Pauli (Zürich), the Scientific Secretary André Mercier from Berne. The lectures themselves took place in the lecture hall of the Natural History Museum. Figure 2 shows the building at Sidlerstrasse at the time of the conference. It was there that Einstein delivered his lectures as a privatdozent in Berne. These were the lectures on molecular theory of heat (Molekulare Theorie der Wärme) in the summer term 1908 (with three attendants, which were his friends), and on the theory of radiation in the winter term 1908/09 (with four attendants, even including a student), see Fölsing (1994, p. 274).

Between 1959 and 1963, the new building shown in Fig. 3 was erected, designed by the architect couple Hans and Gret Reinhard. It clearly demonstrates the new spirit of the day.

In his foreword to the Proceedings, the secretary André Mercier made the

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1One of the younger participants, Walter Gilbert, was awarded the 1980 Nobel Prize in chemistry.
2See isgrg.org
3See unibe.ch/university/portrait/history/
following interesting remarks on the theory of relativity:

The theory of relativity marks all in all one term: it is the achievement of a physics of cartesian spirit that gives an account of the phenomena by figures and by motions . . . One hears today the saying that we live in the atomic era. Should we not also speak of the relativistic era?\footnote{This is my translation from the original French which reads: “La Théorie de la Relativité marque en somme un terme: elle est l’achèvement d’une physique d’esprit cartésien rendant compte des phénomènes par figures et par mouvements. . . . On entend dire aujourd’hui que nous vivons à l’ère atomique. Ne pourrait-on aussi bien parler de l’ère relativiste?” (Mercier and Kervaire (1956), p. 19)}

This, of course, alludes to the fact that the theory of relativity was not very popular in the 1950s, apparently overshadowed by quantum theory and its applications to atomic and nuclear physics.
Of interest is also the welcome speech of a local politician, a certain Dr. V. Moine, *Directeur de l'instruction publique du Canton de Berne*. He reflects about the philosophical spirit of the conference’s location:

This city, enclosed like a jewel by the crown of the river Aare, with its military and political past which made it the head of the old Switzerland, practical and empirical as a farmer’s wife, has always valued the positive and immediate higher than the theoretical. Its symmetric streets, its order, the equilibrium which is brought out by its buildings, the traditional caution of its laws make it more a city of Aristotle than of Platon. . . .

(The building shown in Fig. 3 perhaps also gives testimony of this Aristotelian attitude.) This practical spirit is also seen in the organization of the conference.

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5 This is my translation from the original French which reads: “Cette ville, enserrée comme un joyau dans la couronne de l’Aar, au passé militaire et politique qui fit d’elle la tête de la vieille Suîsse, pratique et empirique comme une paysanne, a toujours plus apprécié le positif et l’immédiat que le théorique. Ses rues symétriques, son ordonnance, l’équilibre qui se dégage de ses édifices, la prudence traditionnelle de ses lois en font plus une cité d’ARISTOTE que de PLATON. . . .” (Mercier and Kervaire (1956), p. 25)
Three languages (English, French, German) are used interchangeably, and in the discussions they are often mixed in an interesting way; an example is the discussion after Bergmann’s talk with its mélange of the three languages (Mercier and Kervaire (1956), pp. 95/96).

Albert Einstein had been invited to this conference, but he died on April 18, 1955, three months before the Berne Conference. Anyway, he had not envisaged to attend the meeting. In his reply to a letter of invitation by Louis Kollros, Einstein had written:

> We two are no spring chickens anymore! As for me, I cannot think about a participation. . . .

It is left entirely to our imagination to figure out what would have happened if Einstein had been able to attend the Berne meeting.

## 2 Classical General Relativity and Beyond

The year 1955 marked the 40th anniversary of Einstein’s general theory of relativity. Since it was difficult in those years to test the theory empirically beyond the classic tests (redshift, light deflection, perihelion motion), much attention was focused on theoretical and mathematical developments. This concerned, in particular, the structure of the Einstein field equations, notably the initial value problem and the problem of motion. As for the former, two of the main figures, André Lichnerowicz and Yvonne Choquet-Bruhat (at that time Fourès-Bruhat) were present at the meeting. As for the latter, Leopold Infeld was the main figure who was present.

The well-posedness of the initial value problem (Cauchy problem) is of great importance. Only if there exist initial data, that is, data on a three-dimensional hypersurface that determine the evolution according to the Einstein equations uniquely, can one use the theory to predict physical processes, for example, the emission of gravitational waves from coalescing compact objects. Today, well-posedness is generally granted as established, see, for example, Isenberg (2014). It is a key ingredient in numerical relativity.

By the time of the Berne Conference, a first theorem on the initial value problem had already been proven by Choquet-Bruhat in 1952. A more general theorem was proven in a 1969 paper of Choquet-Bruhat and Robert Geroch, see Isenberg

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6Louis Kollros (1878–1959) was a Swiss mathematician; from 1909 to 1948 he was professor at ETH Zürich.

7This is my translation from the original German which reads: “Wir sind beide keine Jünglinge mehr! Was mich betrifft, so kann ich nicht an eine Beteiligung denken. . . .” (Mercier and Kervaire (1956), p. 271)
(2014) and Chruściel and Friedrich (2004) for a detailed discussion and references. The theorem proven by Choquet-Bruhat and Geroch can be stated as follows (see Isenberg (2014), p. 307):

**Theorem:** For any smooth set of initial data \((h_{ab}, K_{cd})\), where \(h_{ab}\) is the three-metric and \(K_{cd}\) is the extrinsic curvature (second fundamental form), on a specified three-manifold which satisfies the vacuum constraint equations, there exists a unique (up to diffeomorphism) maximal globally hyperbolic development.

Further developments are discussed in the above cited references. One concerns the extension to the non-vacuum case: the theorem also holds, for example, for the physically relevant case of the Einstein–Maxwell theory. On the mathematical side, it has been shown that the required degree of regularity can be weakened. Other developments concern the stability of Minkowski spacetime under long-time evolution, the stability of de Sitter space, and investigations on the cosmic censorship conjecture. The latter conjecture – in its weak form stating that the singularities arising from gravitational collapse cannot influence future null infinity – was formulated by Roger Penrose in 1969. Most of these later investigations made heavy use of the global methods (Penrose–Carter diagrammes) developed in the 1960s, which were unavailable at the time of the Bern Conference.

Currently there is much interest in classical generalizations of general relativity; concrete examples are the \(f(R)\) theories, where \(R\) is the Ricci scalar. Whether those theories also enjoy a well-posed initial value problem is far from clear. It is thus too early to make statements about the range of validity for those theories. It is imaginable that they can only be applied in more restricted situations and not, for example, to the non-pertrubative treatment of gravitational wave emission.

The subject of gravitational waves, which after their first direct detection in 2015 is of central importance today, received little attention in 1955. Nathan Rosen, in his talk, basically reviewed his work with Einstein of 1937 in which they had expressed doubts about the existence of gravitational waves in the full non-linear theory. According to them, the plane wave solutions of the linearized theory do not correspond to any exact solution of the full theory. Today we know, of course, that they were in error and that gravitational waves indeed exist.

The experimental situation with general relativity was not in a good shape at the time of the conference. Still, the state of the art of the two classic tests concerning gravitational redshift and light deflection (as well as the state of cosmology, see below) was addressed. The gravitational redshift (time dilation) is, for a constant field with gravitational acceleration \(g\), given by the standard formula

\[ \delta \approx \frac{c^2}{2g} t^2. \]

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8The subtitle of the volume Chruściel and Friedrich (2004) in fact reads “50 Years of the Cauchy Problem in General Relativity”. 

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\[
\frac{\Delta \nu}{\nu} = \frac{gh}{c^2}.
\] (1)

In his contribution, Robert Trumpler reported on recent (from 1954) observations in the spectral lines of the white dwarf 40 Eridani B and gave a list with the redshifts measured for 18 other stars. The historic experiments by Pound and Rebka, determining the redshift in a laboratory experiment using the newly discovered Mössbauer effect, were still four years ahead. Those new types of experiments are of much higher accuracy than the stellar observations which have thus lost their significance. Today, the gravitational redshift effect is part of everyday life, for example through the use of the Global Positioning System (GPS). For a detailed discussion of the current experimental situation, see Will (2014); frequency shifts have been measured over a height of 1/3 of a metre.

The second classic test discussed at Berne was light deflection. For a grazing ray near the Sun, the deflection angle is given by

\[
\delta = \frac{4GM}{Re^2} \equiv \frac{2R_S}{R},
\] (2)

where \( R \) is the solar radius, \( M \) the solar mass, and \( R_S \) is the Schwarzschild radius. It is convenient to parametrize this effect by a post-Newtonian parameter \( \gamma \), which assumes the value \( \gamma = 1 \) in general relativity,

\[
\delta \approx \frac{1 + \gamma^2}{2} \cdot 1.7505.
\] (3)

The first observations were the famous ones performed at Sobral and on Principe at the occasion of the solar eclipse on May 29, 1919. The accuracy there was about 30 percent. In his talk at Berne, Trumpler reported about results from other eclipses, those of 1922, 1929, 1947, and 1952. The accuracies there were not much better than in 1919. Today, light deflection has been confirmed to an accuracy of 0.01 percent (Will 2014). This is mainly due to the development of very-long-baseline radio interferometry (VLBI). As is evident from Will (2014), the progress in experimentally testing general relativity since 1955 has been tremendous, and the status of the theory in this regard is similar to elementary particle physics.

There have been many developments since that no-one could have imagined in 1955. These concern, in particular, the field of relativistic astrophysics, which more or less started in 1963 with the discovery of the first quasar 3C 273 by Maarten Schmidt. For the study of active galaxies, neutron stars, and black holes, general relativity has proven indispensable. The very concept of a black hole was not understood in 1955 and played no role at the conference. Today, we can insight the coalescence of black holes and neutron stars by investigating the
gravitational waves they emit. A single black hole can be studied by its influence on the surroundings; a prominent example is the supermassive black hole in the centre of our Milky Way (Eckart et al. 2017).

At the conference, some interest was also devoted to classical generalizations of Einstein’s theory. In the last few decades of his life, Einstein himself was very much concerned with attempts to constructing a unified field theory of gravity and electromagnetism. One might thus have expected that those attempts (and similar ones by Schrödinger and others) met with great interest at Berne. But this was not the case. Only Bruria Kaufman, Einstein’s last collaborator, gave a main talk on the mathematical structure of the non-symmetric field theory, in which the Christoffel symbols $\Gamma^a_{ik}$ are not required to be symmetric. The discussion after that talk contains only one mathematical comment from Marie-Antoinette Tonnelat.

The indifference towards Einstein’s final attempts can well be understood. It had become obvious at least since the 1920s that quantum theory is needed to describe the atomic and subatomic world. The strong and weak interactions relevant for the microscopic regime are not taken into account in Einstein’s work. Most physicists thus suspected (rightly) that an essential part of the world was missing in Einstein’s attempts at a classical unification of gravity and electromagnetism. This opinion is clearly expressed in a letter of Pauli to Einstein from September 19, 1946:

My personal opinion still is . . . that the classical field theory in every form is a squeezed out lemon, out of which it is impossible to get anything new.9

From a modern point of view, a more promising idea for a generalization was presented at the Berne meeting by Pascual Jordan. He gave an example of a theory with a ‘varying gravitational constant’. Such a theory can be represented as a scalar-tensor theory of gravitation, in which a scalar field $\phi$ is added to the gravitational sector (see e.g. Fuji and Maeda (2003)). The action for such ‘Jordan–Brans–Dicke theories” (as they were called later after the contributions by Brans and Dicke) reads

$$S_{JBD} = \int d^4x \sqrt{-g} \left( \phi R - \frac{\omega}{\phi} \phi_{,\mu} \phi_{,\nu} g^{\mu\nu} + \mathcal{L}_m \right),$$

where $\omega$ is a new dimensionless parameter of the theory. Such theories (and generalizations thereof) are of much interest today, for example in connection with dark energy or the assumed inflationary phase of the early universe.

9This is my translation from the original German which reads: “Meine persönliche Überzeugung ist nach wie vor …. daß die klassische Feldtheorie in jeder Form eine völlig ausgepreßte Zitrone ist, aus der unmöglich noch etwas Neues herauskommen kann!” (von Meyenn (1993), p. 384)
At the Berne conference, Jordan’s contribution was received with scepticism. In his conference summary, Pauli ‘buried’ (an expression by Engelbert Schücking) Jordan’s theory as follows:

By the magic of his mathematical theorems, Mr. Jordan has unfortunately prevented us from hearing something about his physical reasons to assume a variation of the gravitational constant; this would have surely interested all of us . . .

In our days, investigations into the variation of fundamental constants find general acceptance. The main reason for this is the expectation that a more fundamental theory than general relativity arises from the implementation of quantum theory (see below). In some of these theories, “constants” of Nature are described at high energies by time- and space-dependent fields. Despite various searches, however, no time or space variation of “constants” was observed so far.

3 Cosmology

With the advent of Einstein’s theory of general relativity, it was for the first time possible to provide a consistent description of the Universe as a whole. Assuming the cosmological principle, one arrives at the ‘Robertson–Walker form’ of the metric, from which the ‘Friedmann–Lemaître equations’ can be obtained from the Einstein equations. Today, one often speaks of ‘Friedmann–Lemaître–Robertson–Walker’ (FLRW) world models. On the observational side, not much was known at the time of the Berne Conference beyond Hubble’s law and some crude age determinations. Still, cosmology was an important topic at the conference, certainly more important than one would have expected in retrospect. There were major reviews by Walter Baade (Mount Wilson Observatory) from the observational and by Howard Robertson (California Institute of Technology) from the theoretical side. Baade did not deliver a manuscript to the Proceedings, so no statements can be made about his contribution. Robertson has sent a detailed manuscript which contains also a comparison of theory with observation.

It is not surprising that Robertson based his analysis on the homogeneous and isotropic Robertson–Walker metric. But he included the following important comment (p. 135 of the Proceedings):

10See Harvey (1999), p. 11.
11This is my translation from the original German which reads: “Nun hat uns leider Herr Jordan mit dem Zauber seiner mathematischen Sätze verhindert, etwas darüber zu hören, was eigentlich seine physikalischen Gründe sind, um eine Veränderung der Gravitationskonstante anzunehmen; das hätte uns ja sicher alle sehr interessiert . . . ”. (Mercier and Kervaire (1956), p. 265)
It is to be emphasized that we have not required the real universe to be one satisfying the uniformity conditions imposed above; we are merely examining the nature of the idealized model of the real world in which the obvious and all-important inhomogeneities are ironed out. We are not imposing the uniformity as a ‘cosmological principle’ . . . to which the real world must adhere.

In his contribution, Robertson discusses the observational status from a rather modern point of view. He presents a diagramme displaying the age of the universe against the matter density, and he allows for any value of curvature and cosmological constant $\Lambda$. The empirical value of the Hubble constant, $H_0$, at that time was given by 180 km/s Mpc, much higher than today’s value. The discrepancy of the historic value with today’s value lies in the very crude distance measurements of the day, which have greatly improved since then.

Given the (too high) value of $H_0$ and conservative lower limits for the age of the Universe, Robertson finds that “…we are forced to reintroduce $\Lambda > 0$ in order to save this time scale …”. Today we know that $\Lambda$ (or its generalization in form of dark energy) is positive, although for a different reason than the one given by Robertson: it is because the Universe is found to be currently accelerating.

In addition to Baade’s and Robertson’s overviews, various shorter contributions on cosmology have been presented at the conference, including talks by Max von Laue, Oskar Klein, and Otto Heckmann. Heckmann, for example, presented a world model of Newtonian cosmology with expansion and rotation, which he had developed together with Engelbert Schücking. They had found that the introduction of rotation leads to a model without initial (‘big bang’) singularity. One might therefore wonder whether this can also happen in general relativity. This is, however, not the case. As the singularity theorems proven in the 1960s by Roger Penrose and Stephen Hawking show, singularities are unavoidable given some general assumptions. But those theorems were not available at the time of the Berne Conference.

In 1955, the expansion of the Universe was not yet generally accepted. Ten years before the discovery of the Cosmic Microwave Background (CMB), it was still possible to seriously uphold the alternative model of a steady-state universe. Two of the main proponents of that model, Hermann Bondi and Fred Hoyle, were present in Berne and gave two short contributions. Today, this is of historic interest only.

12The current value from the Planck Collaboration (2018) is (67.4 ± 0.5) km/s Mpc, a bit more than one third of the 1955 value. There is currently a tension between cosmological and non-cosmological measurements of $H_0$. With the Hubble Space Telescope and the Gaia parallax measurements one gets (73.52 ± 1.62) km/s Mpc, see Riess et al. (2018).
Max Born, in his account of “Physics and Relativity”, describing personal remembrances of the years around 1905, remarks that the importance of general relativity lies in the revolution which it has produced in cosmology. This is a remark that can certainly be appreciated today much more than in 1955.

4 Quantum Theory and Gravity

In the 1950s, quantum theory and its applications were at the centre of physics research worldwide. This is not surprising. In the realm of atoms, nuclei, and particles, plenty of new experimental results were found, and quantum theory, in its mechanical as well as field theoretical version, was believed to be the correct theory for their description. It is for this reason that the relation between quantum theory and relativity was discussed at length at the Berne Conference, too.

Eugene Wigner presented a major lecture on “Relativistic invariance of quantum-mechanical equations”. He reviewed his important work on the representations of the Poincaré group, but also discussed its extension to the de Sitter group. This is very interesting from a modern point of view, because current observations indicate that our Universe is asymptotically approaching a de Sitter phase. Wigner emphasized that massive particles must then be characterized by the statement that their Compton wavelength is much smaller than \(\frac{c}{H}\), where \(H\) is the (constant) Hubble parameter of de Sitter space. The relevance of de Sitter space for the formulation of asymptotic conditions is emphasized in Ashtekar et al. (2015).

A major problem is the consistent unification of quantum theory with gravity. This was open in 1955 and is still open today, in spite of much progress that has happened since then. Only two major talks were devoted to this problem, by Peter Bergmann and by Oskar Klein. Bergmann reviewed the state of the canonical formalism, which can serve as the starting point for the quantization of the gravitational field. This formalism was pioneered by Léon Rosenfeld in Zürich in 1930 and later developed in parallel by Bergmann and his group in Syracuse as well as by Paul Dirac in Cambridge as well as by Arnowitt, Deser, and Misner (ADM) in the United States.\[13\] Bergmann’s talk was a bit dry in the sense that he restricted himself to pure formalism and did not address physical applications.

The real starting point of quantum gravity research is marked by a conference two years later. It took place at Chapel Hill, North Carolina, and became later known as the GR1 Conference. Many of the proponents of quantum gravity were present, including John Wheeler and Bryce DeWitt. Richard Feynman discussed there a gedanken experiment from which he concluded the necessity for quantizing the gravitational field, see Fig. 4.

\[13\]See, for example, Kiefer (2012) for details.
Figure 4: Stern–Gerlach type of gedanken experiment, in which the detectors for spin up respective spin down are coupled to a macroscopic ball. If the particle has spin right, which corresponds to a superposition of spin up and down, the coupling leads to a superposition of the ball being moved up and down, leading to a superposition of the corresponding gravitational fields. Figure adapted from DeWitt and Rickles, p. 251, see DeWitt (1957).

Feynman concludes\[14\]

...if you believe in quantum mechanics up to any level then you have to believe in gravitational quantization in order to describe this experiment. ...It may turn out, since we've never done an experiment at this level, that it's not possible ...that there is something the matter with our quantum mechanics when we have too much action in the system, or too much mass—or something. But that is the only way I can see which would keep you from the necessity of quantizing the gravitational field. It's a way that I don't want to propose. ...(DeWitt and Rickles, p. 251-2, see DeWitt (1957))

The Berne Conference was still far behind this level of physical discussion. But in his concluding speech, Wolfgang Pauli expressed very clearly the main difficulty in quantizing the gravitational field. He said:

This now leads to the border of knowledge, to the questions of the quantization of the field; it seems that a certain agreement existed in assuming that the mere application of conventional quantization methods probably will not lead to the goal. ...

It seems to me ...that it is not so much the linearity or non-linearity which forms the heart of the matter [the difficulty of quantizing the

\[14\]See also the discussion in Feynman et al. (1995).
Gravitational field, C.K., but the very fact that here a more general group than the Lorentz group is present.[15]

Standard ways of quantization assume the existence of a fixed background, which usually is taken to be Minkowski space. In general relativity, this background is absent – spacetime is dynamical, and the invariance is the diffeomorphism, not the Lorentz group. The quantization of the metric (which represents spacetime) has thus to be undertaken without any reference to Minkowski space with its Lorentz group; this is what Pauli is alluding to. Modern approaches to quantum gravity make use of this background independence (Kiefer 2012).

In this connection, it is interesting to quote a piece from a letter that Pauli wrote to Schrödinger on the occasion of the latter’s 70th birthday. In this letter, which is from August 9, 1957, he writes (von Meyenn 2011, p. 720):[16]

Also our difference in age of 13 years will soon appear as unessential, and one will count us as belonging to the same generation of physicists: to those who have e.g. not succeeded in making a synthesis of the mentioned subjects – general relativity and quantum theory – and who thus have left behind unsolved problems as essential as the atomistic nature of electricity (fine structure constant), self energy of the electron . . .[17]

In his response from August 15, 1957, Schrödinger writes (von Meyenn 2011, p. 722):

You are, of course, right, that we belong to the same generation of physicists; I also agree with your characterization of it. But the posterity usually judges in a milder way, it characterizes an epoch by what

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[15] This is my translation from the original German which reads: “Das führt nun hier an die Grenze des Wissens, an die Fragen der Quantisierung des Feldes; es scheint, daß eine gewisse Übereinstimmung darüber bestand, daß eine bloße Anwendung konventioneller Quantisierungsmethoden wahrscheinlich nicht zum Ziele führen wird. . . .

Es scheint mir . . ., daß nicht so sehr die Linearität oder Nichtlinearität Kern der Sache ist, sondern eben der Umstand, daß hier eine allgemeinere Gruppe als die Lorentzgruppe vorhanden ist.” (Mercier and Kervaire (1956), p. 266)

[16] I thank Norbert Straumann for drawing my attention on this and the following letter.

[17] This is my translation from the original German which reads: “Auch unser Altersunterschied von 13 Jahren wird bald als unwesentlich erscheinen, und man wird uns zur selben Physiker-Generation zählen: zu derjenigen, der z.B. eine Synthese der beiden genannten Themen – allgemeine Relativitätstheorie und Quantentheorie – nicht gelungen ist und die so wesentliche Probleme wie Atomistik der Elektrizität (Feinstrukturkonstante), Selbstenergie des Elektrons . . . ungelöst zurückließ.”

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it has achieved, much more rarely by what it has not completed.\footnote{This is my translation from the original German, which reads: “Natürlich hast Du recht, daß wir zu derselben Physikergeneration gehören; auch dem, wie Du sie kennzeichnest, stimme ich bei. Nur pflegt die Nachwelt milder zu sein, sie pflegt eine Epoche zu charakterisieren nach dem, was sie geleistet hat, viel seltener nach dem, was sie nicht fertig gebracht hat.”}

Even today, the problem of quantum gravity remains unsolved. The main approaches, more or less promising, are direct quantizations of general relativity in either its canonical or covariant form and string theory. The latter is characterized by the attempt to construct, at a fundamental level, a unified quantum theory of all interactions (sometimes called ‘theory of everything’), from which quantum gravity can be recovered in a certain limit. A central problem for all attempts is the current lack of experimental support. The only exception is an indirect test of linearized quantum gravity: adopting the inflationary scenario of the early Universe, the power spectrum of the CMB is proportional to the Planck time squared and needs the quantization of the metric for its calculation.\footnote{The Planck time is $t_P \equiv \frac{l_P}{c} = \sqrt{\frac{\hbar G}{c^5}} \approx 5.39 \times 10^{-44}$ s ($l_P$ is the Planck length.)} The density fluctuations in the CMB have been observed and are in accordance with this prediction. The influence of primordial gravitons has not been seen yet, but this is in principle possible; its observation would be a clear test of (linearized) quantum gravity.

Oskar Klein’s talk at Berne was of a more general nature. Like many other physicists at the time, he was worried about the divergences in quantum field theory. In his proposed generalization of general relativity he went beyond Einstein’s own attempts (which he didn’t cite) and discussed the five-dimensional theory which today is known as Kaluza–Klein theory (but he does not cite Kaluza here). For him, this theory is the most direct generalization of Einstein’s theory including gauge invariance and charge conservation. As a motivation, Klein directly referred to nuclear and mesonic physics, for which this theory should be relevant. He attributed a fundamental role to the five-dimensional Dirac equation in the sense that it is prior to geometry: the components of the Riemann tensor follow from the commutator of the covariant derivatives

$$\Delta_\mu \psi \equiv \left( \frac{\partial}{\partial x^\mu} - \Gamma_\mu \right) \psi, \quad (5)$$

where $\Gamma_\mu$ denotes the connection, and $\psi$ is the Dirac spinor. Gravity is supposed to play an important role when kinetic energies approach the Planck scale, and Klein speculated that gravity may serve as a natural regulator for the field theoretical divergences. In this, he directly related the compactification radius of the five-dimensional theory to the Planck length.

Higher dimensions play an important role in string (or M) theory, which is probably consistent only in 10 (or 11) spacetime dimensions. In this theory, as
well as in direct quantizations of general relativity, gravity may directly or indi-
rectly serve as a regulator for the field theoretic divergences, although the final
word has not been spoken yet.

5 Summary

One can state that the Berne Conference of 1955 marks a turning point in the
history of relativity. This fact is also emphasized in Blum et al. (2015). It was
the first truly international conference on general relativity and its generalizations.
The importance and prospects of those theories for the future is reflected in many
contributions to the Proceedings. Today, Einstein’s theory is empirically well
tested, and the fields of cosmology and quantum gravity occupy a central place
in current research.

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