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The revival of General Relativity at Princeton: Daring Conservatism

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Abstract. After General Relativity was established in essentially its present form in 1915 it was celebrated as a great success of mathematical physics. But the initial hopes for this theory as a basis for all of physics began to fade in the next several decades, as General Relativity was relegated to the margins of theoretical physics. Its fate began to rise in the 1950's in a revival of interest and research that over time made gravitational physics one of the hottest research topics it is today. One center of this renaissance was Princeton, where two relative newcomers explored new and different approaches to gravitational physics. Robert Dicke showed that gravity is not as inaccessible to experiment as was thought, and John Wheeler propelled it into the mainstream by proposing highly original and imaginative consequences of Einstein's theory. We will concentrate on these ideas that, in his characteristically intriguing style, Wheeler called "Daring Conservatism" -- a term well known to his associates, but one he never mentioned in print. With the aid of unpublished manuscripts and notes we will explore Daring Conservatism's origin and motivation, its successes and failures, and the legacy it left behind.

After Einstein's founding of General Relativity in 1915, and its initial spectacular success, there were several decades when it was relegated to the margins of theoretical physics. The reason, we feel, was two-fold. There were no further fundamental experiments to test the theory, and on the theory side there was no program that could bring general relativity back into contact with the part of physics that was making the great advances in such areas as quantum, nuclear, particle, light and solid state physics. The 1950's marked the beginning of a renaissance in both experimental and general relativity, which propelled it to the hot research topic it is today. An important center of this re-awakening was Princeton, where new experiments and fresh ideas were being developed, primarily by Robert Dicke and John Wheeler. Figure 1 shows them at this most creative time.

Robert Dicke was able to test the basis of a fundamental theory like General Relativity by measurements of unprecedented accuracy that was made possible by the new electronics available after the war. To assess the significance of high precision experiments he

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considered alternative theories patterned after Mach's Principle, and formalized in Brans-Dicke theory. The history of his contributions has been expertly told by Peebles [1]. Wheeler's path to General Relativity is less familiar (except through his autobiography [2]), and worth telling today.

Figure 1. Robert Dicke, Walter Bleakney and John Wheeler, detail from a faculty photograph, Department of Physics, Princeton University, about 1950

1 Particles

When his position at Princeton after the war allowed Wheeler to think about fundamental physics, it was not clear which of the new theoretical ideas being developed would be lasting and fundamental. Instead of engaging in such free inventions, as he called them, he preferred the conservative approach and asked, can one exclude the presence, in the physics we already know, of concepts more fundamental than the rest, which promise to explain all of physics? The spirit of the explanation itself, however, was to use fertile, "anything goes" imagination. As Feynman (apocryphally?) remarked

Some people think Wheeler's gotten crazy in his later years, but he's always been crazy.

A master of coining catchy phrases, Wheeler later gave his grand vision a more polite name, Daring Conservatism. This phrase is well-known to his associates from that time, but has never appeared in print. (In fact, some remember it as radical conservatism or dynamic conservatism.) Wheeler himself attributes Daring Conservatism to Bohr:

His judgment and courage, his daring conservatism, carried him to wonderful conclusions of a kind that free invention has not strength to reach, nor conviction to maintain.

At first the fundamental concept was that "everything is particles," specifically electrons. He showed that electrons and positrons can bind together into "polyelectrons" [3], and suggested this, rather than Yukawa field theory, as the explanation of mesons. Due to the discrete, quantized nature of particles, their continuous fields are required to be replaced by direct action between particles. First instances are the papers with Feynman [4] in which action at a distance between charges is shown as a complementary description to the field theory of classical electrodynamics. The radiative forces of this theory gave Wheeler the hope to explain nuclei, as expressed in a question to Bohr [5]:

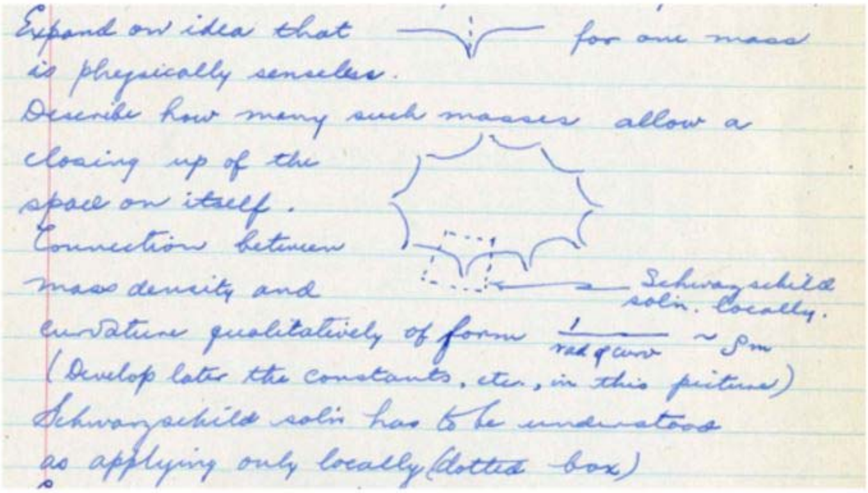
Is it possible to exclude a picture of elementary particle constitution based entirely on positive and negative electrons?

Bohr may have affirmed the exclusion, there is no record of further work on this idea.

For the same reason of particle atomicity, in mass as well as in charge, Wheeler felt that it should in principle be possible to dispense with the concepts of continuous space and time in Einstein's theory of the gravitational field. He proposed the elementary concepts of world line and light cone as the basis of the description of nature [6]. Points on a world line are to be specified by a parameter (proper time), and light rays provide the connection, called a liaison (later [7]: association), between these points and those on any other world line. Liaisons can lead to future as well as past points on the other world line, similar to half advanced, half retarded potentials of Wheeler-Feynman electrodynamics. This makes them a candidate for implementation of Mach's principle, which Wheeler considered an essential basis for a theory of gravity. For a number of years Wheeler searched for an action written only in terms of liaisons that would yield equations of motion for the particle world lines and would reproduce the Einstein-Hilbert action in the limit of a large number of world lines [8]. The last notebook entry is from 1953, without any clear conclusion.

2 Teaching and Transition

No event was more important in Wheeler's search than his 1952 assignment to teach the graduate course on relativity at Princeton, for he practiced his often-quoted credo that one can only learn by teaching – and he prepared "to give the best possible course", started a new notebook [9], planned to publish his course as a book, and involved his students with reports and research-level problems. His new and daring ideas pervaded the course, and made him confront the unfinished nature of creations like liaison theory and Mach's principle, as well as the nitty-gritty details of differential geometry calculations vis-à-vis their physical meaning. Firmly believing in Mach's principle he did not favor the physically unexplained asymptotic Minkowskian region of the Schwarzschild solution, for "Geometry cannot be part of physics in some regions and not part of physics in others." Instead, Mach was taken to demand that the universe should be closed. Here is how he explained this to his class on March 31, 1952.



Expand on idea that for one mass
is physically senseless.
Describe how many such masses allow a
closing up of the
space on itself.
Connection between
mass density and
Schwarzschild soln. Locally.
curvature qualitatively of form $\frac{1}{\text{rad of curv}} \sim \rho_m$
(Develop later the constants, etc., in this picture)
Schwarzschild soln has to be understood
as applying only locally (dotted box)

Figure 2. Bottom half of p.103 of Wheeler's Notebook I. We acknowledge the American Philosophical Society for supplying this copy.

A passage from the next notebook page shows his strong feeling about space closure:

> Question raised in class whether mass density enough to permit open or closed universe, in view of expansion rate.
>
> Answer: Conclude from above that closure comes first; density knowledge too poor to permit proof of contradiction; closure so fundamental to whole Mach idea that in present state of knowledge think of density value having to yield precedence to Mach principle.

During the years of the course it became apparent that fields may be a more fundamental basis for physics than particles. To Wheeler it was not an abrupt break with the previous particle picture, but part of a *Study (or Critique) of Classical Field Theory*. This was the name of a series of papers [4, 11, 12] that starts with electromagnetic action at a distance as a tool to analyse the field concept, continues with the Wheeler-Feynman papers that account for EM interaction without involving the EM field, and ends with structures built purely from fields or geometry. These six papers may be taken to define Wheelerian Daring Conservatism.

3 Daringly Conservative about Fields and Geometry

In 1954 Wheeler was ready to announce this program to the world of physics in the Twelfth Richtmyer Memorial Lecture [10]:

I propose that we should raise at the head of our enterprise the flag of daring conservatism. Let us be conservative in the sense of staying on the solid ground of what is firm and harmonious and well established; ... conservative in the sense that we repel free invention of new theories; daring in the sense that we follow out the consequences of our already existing ideas to the uttermost extremes; daring in the sense that we use what we already know to enter into quite new fields of thought.

He discusses five most fundamental concepts that conservatism would allow for building new structures (particles): electromagnetism, gravitation theory, quantization, the neutrino, and electron theory. He mentions meson theory, the cosmological constant, and unified field theory as examples of free invention that should be rejected. He singles out gravitation as a field with physical consequences that have been little investigated, such as laws of test particle motion that follow from the field equation. Comparing this to the motion of hurricanes as a consequence of hydrodynamics he asks
How different is a particle from a kind of hurricane in the fields of zero rest mass?
and outlines such a structure as an electromagnetic disturbance held together by gravitational attraction. Arthur Wightman suggested the name Kugelblitz, but it was later called a geon. For small geons quantum effects are expected to lead to a spectrum of masses, therefore
In what points of principle, if any, do the disturbances of smallest mass differ from elementary particles?
This field point of view leads him to question electron theory:
Is the theory incomplete because it regards the electron as a primitive entity, endowed with a rest mass of its own? If instead the electron is a special kind of disturbance in the electromagnetic field and in other fields of zero rest mass, will there not be many phenomena ... in which it is not legitimate to think of primordial mass as done in the Dirac theory?

The incomplete transcript of the Richtmyer lecture stops abruptly at this point, before accounting for the electron charge in terms of sourceless electromagnetic fields.

A way to account for electric charge appeared less than 8 months after the Richtmyer lecture in the famous geon paper [11]. Here Wheeler shows detailed calculations for spherical geons, and introduces graphically a doubly connected space, later called a wormhole (originally, in Notebook II: woodchuck hole). He also gives estimates for transformations of, and interactions between, geons. The geon calculations involved a careful analysis of high frequency and high angular momentum EM waves, proof that a sufficiently spherically symmetric distribution is possible, and a reduction of the Einstein-Maxwell equations to three coupled differential equations of the eigenvalue type. The solution required numerical integration, one of the first uses of electronic computers in General Relativity. The start of the geon calculation, according to Notebook II, was on January 25, 1954, and he received the computer results on March 24 together with a bill of $195 for 6½ hours of computer time.

The mathematics of the model of electric charge as wormholes with trapped flux was published with Misner as the final Part VI of the Critique series [12]. For those working in General Relativity as “index pushers” this paper was the first introduction to the modern mathematics of differentiable manifolds and differential forms as applied to physical problems. It also contained a new point of view of the well-established physics of Maxwell and Einstein, for it showed a way of stating the content of Maxwell’s equations purely in terms of the curvature that Einstein’s equations prescribe for a spacetime containing Maxwell fields. This procedure yields purely geometrical equations, which both unify and keep unchanged gravitation and electromagnetism – an “already unified theory”.

This final paper of the Critique series summarizes the essential results of Daring Conservatism in a paradoxical form, which Wheeler had already used in talks and lectures to promote his ideas and insights: Empty Curved Space can provide

- Gravitation without gravitation
- Electromagnetism without electromagnetism
- Charge without charge
- Mass without mass

but not (yet)

- Spin without spin
- Elementary particles without elementary particles.

To these he would add

- Equations of motion without equations of motion
- Law without Law.

The already unified theory took some ribbing

- A theory without a theory.

In fact, the already unified theory did not work in all situations. Asked about its status (at a Stevens meeting), Wheeler recounted being at a restaurant, worrying about the problems of this unification, when the fortune cookies came around. His read “If it became true, it wasn’t much of a dream” – and he accepted. Still, Wheeler persisted in the view that the ultimate nature of physics is geometry as described by some quantum version of the sourceless Einstein equations. Complementary to seeing a solution of the classical equations as a fixed spacetime, he promoted the view of it as a developing sequence of spacelike surfaces. Mathematicians had shown that the equations form a dynamical system of initial geometry and its time development. Wheeler gave it a name: Geometrodynamics.

4 Collapse

No paradoxical byword was associated with the most influential topic Wheeler proposed in the Richtmyer lecture for investigation by Daring Conservatism; it would be black holes in today's terms. At the time the question was whether an actual star would follow the same collapse scenario as Oppenheimer and Snyder's model of collapsing dust [12]. The answer to Wheeler's quest for the endstate of gravitational collapse was made possible by the 1960 publication (at Wheeler's urging) of Kruskal's paper [13] on the Maximal Extension of the Schwarzschild Metric. Wheeler analyzed and popularized in detail, from conservative Einstein theory without free invention, that the collapse produces a Black Hole. By 1963 Daring Conservatism had done its job in attracting attention to General Relativity, as the first "Texas Conference" [14] was devoted to theory and observation of this new physics.

The Texas Conference marked, in a sense, the end of strict Daring Conservatism with Wheeler, for he briefly violated one of its rules: no free invention. Interactions and transformations of black holes and ordinary physics suggested further properties. For example, Wheeler's question, what happens to the entropy of a system that falls into a Schwarzschild black hole, led to the idea that black holes themselves carry entropy (related to their mass). The similar question, what happens to (dimensionless) nucleon number conservation when a number of nucleons is dropped into a black hole, cannot be answered in the same way, for black holes have no "hair" other than (dimensionful) mass, charge, and angular momentum [15]. Wheeler therefore proposed that nucleon number is carried away by a new radiation he called delta rays [16]. He must have quickly dropped this free invention[1] for the only mention in print is one sentence in Hong-Yee Chu's introductory Report on the Texas Symposium in the conference proceedings [14].

5 Conclusion

The ideas from Daring Conservatism as paradoxically stated above all had an influence on the direction of General Relativity research but with varying longevity. Gravitation as geometrodynamics persists, with the latest confirmation of gravitational waves, but the already unified theory of electromagnetism fell by the wayside. Charge has become only one of many applications of topology in physics. The geon idea still appears in various connections [18] but the original geon, although providing stable orbits for each constituent photon, turned out unstable to collective collapse or dispersal of all its photons [19].

Wheeler tried many ideas for a geometrical model of spin but none were ultimately successful. Sum-over-histories quantization of geometry is also mentioned already in the Richtmyer lecture. Still a viable approach to quantum spacetime, it led Wheeler to the idea of its foam-like structure. Elementary particles were found to consist of quarks and gluons, not the fundamental massless fields Wheeler had in mind, but Wheeler rejoined [20]
... it would still seem reasonable to expect that one must have some perspective on what happens at 10^{-33} *cm* [scale of the foam] *before one can find the rationale of quarks and particles.*

Daring conservatism was a breath of fresh air in a field where many regarded exact solutions as the only sure way to explore the richness of Einstein's theory. In this search

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[1] His later view was that such conservation laws can be transcended [17].

physical meaning was often secondary, as when it was not clear whether a newly-discovered solution of the field equations described the same physics as a well-known one in new coordinates. Working with the same, well-established theories Wheeler produced constructions that were maybe weird or crazy, or only good approximations, but they were objects of physics, their appeal was undeniable, failure to recognize them was not an option. Most of all he gave his students and the whole GR community new hope and inspiration that there was much – or everything – of physics to be found in Einstein's theory.

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