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Torsten Asselmeyer-Maluga *Editor*

At the Frontier of Spacetime

Scalar-Tensor Theory, Bells Inequality, Machs Principle, Exotic Smoothness

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Editor

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To Carl

Preface

In 2015, we celebrated the 100th anniversary of the development of general relativity theory (GRT). Einstein presented his theory at the Prussian Academy of Science in Berlin on November 25th, 1915. In GRT, he replaced the absolute space and time of Newton in favor of a changing arena called "spacetime," in which gravity appeared as curvature. The equivalence principle linked every acceleration locally with gravitation. In principle, GRT poses the possibility of understanding all forces in the world using geometry. Galileo Galilei expressed this thought nearly 400 years ago when he pronounced: *He who understands geometry, understands anything in the world*. Therefore it was logical that Einstein continued this program even after completing his GRT, with the development of proposals for a unified field theory.

Carl H. Brans chose to investigate such theories for his undergraduate thesis at Loyola University in New Orleans. It was the beginning of a lifelong engagement with GRT. Even the mathematical beauty of GRT and the unified field theory attracted him. As a 10-year-old boy, he taught himself differential and integral calculus, and difficult books on mathematics and mathematical physics held a great appeal for him. His preference for GRT was a little bit unusual at the time. Since the 1920s, the GRT had lost its prominent role in theoretical physics. The advent of quantum mechanics and elementary particle physics, together with new work on quantum electrodynamics, inspired more interest among physicists in those days.

In the 1950s, the situation began to change. John A. Wheeler, at Princeton University, started to develop geometrodynamics as a new representation of GRT. At the same time, Wheeler established his by-now famous working group, which focused on problems in GRT and on the foundations of quantum mechanics. In parallel, Robert Dicke, Wheeler's colleague at Princeton, began to work on the experimental problems in GRT during his sabbatical year of 1954. He also became interested in Mach's principle, which Einstein had used as a guide during the development of GRT. Dicke considered Mach's principle to imply: *The gravitational constant, κ, should be a function of the mass distribution in the universe*. Paul A.M. Dirac had earlier conjectured that there is a relation between the coupling constant of gravity and the mass and radius of the universe (now known as Dirac's "large number conjecture"). For an expanding universe, one thereby obtains a variable gravitational coupling constant!

In 1957, Carl Brans arrived in Princeton to undertake his graduate study and Ph.D. thesis. In his contribution to this book, he writes extensively about that time. He heard some lectures and visited the seminar of Wheeler, who had established his famous group. Charles Misner, who had recently completed his Ph.D. thesis, introduced Carl to fiber bundle theory. Hence, Carl planned to write his Ph.D. thesis about the application of fiber bundles in physics. At that time, he also began to be interested in the mathematical structure of spacetime. But the time was not yet ripe for these ideas; fiber bundles would only become commonly used in theoretical physics in the 1970s. Instead, Misner recommended that Carl should contact Dicke, who was searching for a theoretical physicist. It was the beginning of a lifelong and fruitful collaboration.

Mach's principle and Dirac's large-numbers hypothesis formed the basis for the discussions between Dicke and Brans. They wondered if they could create a version of GRT with a variable gravitational coupling. Brans pursued the idea and developed it in his Ph.D. thesis in 1961. Today this renowned theory is known as the Brans-Dicke theory. They introduced a scalar field to represent the variable coupling. Pascual Jordan had described a similar theory in his 1955 book, *Schwerkraft und Weltall*, though Jordan's work was not well known at the time. Brans and Dicke's work quickly received much more attention within the physics community, helping to establish the importance of "scalar-tensor" theories of gravitation, as Carl describes further in his contribution to this volume.

In the Brans-Dicke theory, one arbitrary parameter (usually denoted by ω) quantifies the coupling between the scalar field and spacetime curvature. Dicke proposed to express ω in terms of other physical constants; failing that, most experimental tests of the theory concentrated on possible restrictions on ω. An outstanding experimenter, Dicke was strongly interested in the experimental verification of the Brans-Dicke theory. As an important side-effect of these efforts, many effects of GRT were tested with unprecedented precision. Among them included classic experiments like the Eötvös experiment to confirm the weak equivalence principle, as well as various NASA missions. Martin McHugh's contribution in this volume presents an overview of these experiments, as well as Dicke's endeavor to confirm the Brans-Dicke theory.

In 1961, Brans and Dicke's paper appeared in the *Physical Review*. Following its publication, the Brans-Dicke theory had wide repercussions. The meaning and importance of scalar fields in physics increased significantly, from their role in spontaneous symmetry breaking, as in the Higgs mechanism, to the dynamics of the very early universe, as in models of cosmic inflation. Other theories, which incorporated a scalar field to model variable cosmological effects, such as quintessence, used Brans-Dicke theory as a prototype. Interest in Brans-Dicke theory increased further during the 1980s and 1990s in the context of string theory. Finally, the discovery of the Higgs boson in 2012 marked the first experimental detection of a fundamental scalar field in nature.

The present volume includes a collection of invited papers by renowned colleagues. The contributions range over various aspects of scalar fields to Mach's principle, Bell's inequality, and spacetime structure. Together, the chapters illustrate how Carl's ideas have been developed even further over the years. The volume is organized into three parts, reflecting the scientific foci of Carl's career.

The first part concerns the scalar-tensor theory. In the decades since the development of Brans-Dicke theory, scalar fields have come to play a diverse set of roles in physics, from the inflaton that drove cosmic inflation, to the axion that breaks chiral symmetry in QCD, to the Higgs boson that generates mass for elementary particles and the dilaton field that breaks global scale invariance (Weyl symmetry). Chapters in this part focus on this diversity of scalar fields in the context of GRT.

David Kaiser (MIT, USA) describes the role of Brans-Dicke (or non-minimal) couplings between scalar fields and spacetime curvature in the context of inflationary model-building. As he discusses, recent observational data, such as collected by the *Planck* satellite, place strong constraints on models of early-universe inflation. Models with Brans-Dicke couplings provide a natural way of realizing inflation while matching all the latest observations. Yasunori Fujii (Waseda University, Japan) focuses on a possible relation between microscopic physics and the cosmological model of Brans and Dicke. According to Brans-Dicke theory, the mass of an electron would not be constant in an expanding universe. However, Fujii demonstrates, one may introduce a massive scalar field (akin to a dilaton) to address this feature, and further estimate the dilaton mass. Roman Jackiw (MIT, USA) and So-Young Pi (Boston University, USA) focus on a special version of Brans-Dicke theory which is independent of the underlying scale (Weyl symmetry), which should affect short-scale behavior.

The appearance of different scalar fields naturally leads to the question of how those fields might relate or interact with each other. Friedrich Hehl (University of Cologne, Germany, and University of Missouri-Columbia, USA) addresses such questions. First he shows that the dilaton and axion fields appear naturally in the context of Einstein−Cartan theory. Next he constructs the metric as well as the axion and dilaton fields directly from an electromagnetic model of the universe ("premetric electrodynamics").

Many researchers have implicitly assumed that Brans-Dicke theory would yield small deviations from the usual predictions of GRT. But what about more radical departures, such as contributions that are quadratic in the curvature? This question is discussed by Tirthabir Biswas (Loyola University New Orleans, USA) in collaboration with Alexey Koshelev (Universidade da Beira Interior, Portugal) and Anupam Mazumdar (Lancaster University, UK). They demonstrate the appearance of the Brans-Dicke model as a stable solution to physically well-motivated consistency conditions.

What is the influence of the scalar field on objects in the universe and on the universe as a whole? These fascinating questions are investigated by Eckehard W. Mielke (Universidad Autónoma Metropolitana Iztapalapa, Mexico) and Israel Quiros (Universidad de Guanajuato, Mexico). As shown by Mielke, the gravitational collapse of a boson cloud of scalar fields would lead to a boson star as a new type of a compact object. Moreover, as a coherent state (like the vortices of Bose–Einstein condensates), such collapse would allow for rotating solutions with quantized angular momentum. Quiros focuses on the cosmological impact of Brans-Dicke theory. Is the standard model of cosmology (the so-called ΛCDM model) a stable solution of Brans-Dicke theory? Assuming a Friedmann-Robertson-Walker metric in the Brans-Dicke theory, he demonstrates that the de Sitter solution of GRT is an attractor of the Jordan frame (dilatonic) Brans-Dicke theory only for special values of the coupling constant ω and for special scalar-field potentials. Only for these values does one obtain the ΛCDM model from Brans-Dicke theory.

The first part of the volume closes with the contribution by Martin McHugh (Loyola University New Orleans, USA) about the history of the Brans-Dicke theory and its experimental tests. Dicke became famous for this experimental work and was a popular contact to discuss unexplainable experimental results. At the end of 1965, he received a call from Arno Penzias and Robert W. Wilson at nearby Bell Laboratory, who had found a mysterious microwave signal. They had spent nearly a year searching for the cause of the signal in their antenna. Dicke immediately identified the signal as the long-sought cosmic microwave background (CMB), which he had dubbed the "ash of the Big Bang." In 1978, Penzias and Wilson received the Nobel Prize for their discovery.

The Brans-Dicke theory occupied Carl Brans for twenty years after its initial publication in 1961, and he continued to return to the topic after that. But Brans made contributions to several other topics as well. (Indeed, even beyond the research topics covered in this volume, Carl made additional, important contributions to the Petrov classification, numerical GRT, and complex GRT.) The second part of this volume includes contributions reflecting on Carl's work during the 1980s.

The original motivation for Brans-Dicke theory concerned Mach's principle, and the notion that the gravitational constant, κ, should be a function of the mass distribution of the universe. In his contribution for this volume, Bahram Mashoon (University of Missouri-Columbia, USA) describes the application of Mach's principle to particles' inertial property of spin. The inertia of intrinsic spin is studied via the coupling of intrinsic spin with rotation, a coupling which has recently been measured in neutron polarimetry. The implications of the inertia of intrinsic spin are critically examined in the light of the hypothesis that an electromagnetic wave cannot stand completely still with respect to an accelerated observer.

The second chapter in this part, by Michael J.W. Hall (Griffith University Brisbane, Australia), concerns Bell's inequality. Carl's colleague A.R. Marlow (Loyola University New Orleans, USA) notes that Carl developed an interest in quantum logic and interpretational problems in quantum mechanics. In particular, Carl became interested in Bell's theorem and the effort to decide whether any hidden variables determine the outcomes of measurements, or if the probabilistic framework of quantum mechanics is complete. In 1988, Carl published an article in which he noticed a circular argument in the derivation of Bell's theorem. Bell had to assume that an experimenter's selection of detector settings in an experimental test of quantum entanglement was entirely uncorrelated with any possible hidden variables that could affect the outcomes of those measurements—even though the events that determined the detector settings presumably shared an enormous causal past with any events that could have influenced the outcome of the measurements. Put another way, whatever hidden variables could have classically determined the outcomes of measurements could also have determined the experimenter's selection of detector settings. Hence, in order to derive strong no-go results like Bell's inequality, one must assume "measurement independence." Hall discusses the importance of such an assumption as well as means to relax it within the context of Bell's inequality. He further generalizes Brans's 1988 model to demonstrate that no more than 2 log d bits of prior correlation between the hidden variables and the detector settings are required for a local deterministic model to reproduce the quantum-mechanical predictions for any d-dimensional system.

More recently, Carl's research has focused on the structure of spacetime, and in particular on exotic smoothness. These topics occupy the third part of the volume. As noted above, Charles Misner introduced Carl to such questions with his lecture on fiber bundle theory in 1957, and Norman Steenrod's book on *The Topology of Fiber Bundles* (1951) provided further inspiration. Exploiting similar methods, including cobordism theory, John Milnor made an unexpected discovery in 1956: there exist exotic 7-spheres.

To appreciate the importance of this result, one must dig deeply into manifold theory. The weak equivalence principle in GRT implies the usage of the manifold concept: every neighborhood of a point in spacetime must be locally flat, that is, it must be a subset of $\mathbb{R}^n$. Then spacetime is a smooth manifold, i.e. it is covered by smooth charts with smooth transition functions forming an atlas. A smooth atlas is a smoothness structure. Conventional wisdom had long held that every topological manifold could be smoothed (by smoothing the corners), so that there would only be one smoothness structure (given by the smoothness structure of the $\mathbb{R}^n$). But Milnor found seven 7-dimensional spheres S^7 which agreed topologically but differed in their smoothness structure, thereby providing the first counterexample to the higher-dimensional Poincaré conjecture. Milnor thus founded the new topic of differential topology and received the highest mathematical honor, the Fields medal, in 1962.

As Carl noticed, this revolution occurred only "some doors away from him" at Princeton university. From the physics point of view, the 7-sphere is not particularly interesting, except perhaps in string theory (in which Edward Witten used it to cancel the global gravitational anomalies in 1985). Moreover, exotic smoothness is difficult to visualize, because no exotic smoothness structure exists in dimension smaller than four. For dimension 5 and higher, there are only finitely many exotic smoothness structures, as shown by Kervaire and Milnor in 1963. But what about 4-manifolds as models of our spacetime?

The riddle was solved in the 1980s with the work of many mathematicians, including Michael Freedman, Simon Donaldson, Robert Gompf, and Clifford Taubes. Most compact 4-manifolds admit (countable) infinitely many different smoothness structures, whereas most non-compact 4-manifolds—including $\mathbb{R}^4$—admit (uncountable) infinitely different ones. Therefore, the physical dimension 4 is mathematically distinguished from any other dimension!

Carl attended a lecture by Ron Fintushel at Tulane University to hear about these results. It is typical for Carl that he immediately asked about their relevance for physics. In his first article in collaboration with the mathematician Duane Randall, Brans published the first deep results. It was the start of a long and fruitful collaboration between mathematicians and physicists on this topic. Indeed, many of Carl's questions remain open to this day. His questions helped to shape the direction for current research.

A driving force was the Brans conjecture from 1994. In an article from that year, Carl constructed an exotic $\mathbb{R}^4$ in which the exoticness is localized (now known as small exotic $\mathbb{R}^4$). The Brans conjecture is that this localized exoticness can act as a source for some externally regular field, just as matter or a wormhole can. This conjecture was partly proven by Jan Sładkowski and Torsten Asselmeyer-Maluga. In a 2002 paper by Brans and Asselmeyer-Maluga, this conjecture was extended:

"… *In summary, what we want to emphasize is that without changing the Einstein equations or introducing exotic, yet undiscovered forms of matter, or even without changing topology, there is a vast resource of possible explanations for recently observed surprising astrophysical data at the cosmological scale provided by differential topology. …*"

Results in this area of research up through 2007 may be found in Brans and Asselmeyer-Maluga's book, *Exotic Smoothness and Physics* (World Scientific, 2007), which has become a standard reference for the topic. An introduction to the topic may also be found in Carl's contribution to the present volume. The third part of this book describes more recent developments.

Jan Sładkowski (University of Silesia Katowice, Poland) aims to describe spacetime structure from the physics point of view. He considers the algebra of all real functions over a manifold containing the information about the topology of the manifold. A generalization of these functions leads to Alain Connes's model of noncommutative geometry as a possible description of the standard model in elementary particle physics.

Jerzy Król (University of Silesia Katowice, Poland) studies model-theoretic aspects of exotic smoothness, uncovering unexpected relations to noncommutative spaces and quantum theory. Forcing, as a special extension of the axioms in set theory, is used to obtain the deformation of the algebra of usual complex functions to the noncommutative algebra of operators on a Hilbert space. The results in the context of the Epstein-Glaser renormalization in QFT are also discussed.

In the contribution by Duane Randall (Loyola University New Orleans, USA), a question of Milnor is answered: is there always an exotic n–sphere for $n > 6$ and $n \neq 12, 61$? In the next chapter, Torsten Asselmeyer-Maluga (German Aerospace Center Berlin, Germany) extensively discusses the following questions: Is it possible to construct a quantum gravity theory by using exotic smoothness? Is it possible to construct quantum gravity directly, i.e. without any quantization of a classical theory? In his chapter, the richness of exotic smoothness in dimension 4 is used to construct a quantum gravity theory directly. The use of this geometrical approach implies one problem: one has to construct a geometrical expression for a quantum state (the ψ–ontic interpretation as implied by current experiments). This construction, using wild embeddings (like Alexander's horned sphere), gives a fractal space. Moreover, quantum fluctuations arise from an unpredictable chaotic dynamics. The consequences for decoherence, the measurement problem, and cosmology are discussed.

The contributions in this volume are dedicated to Carl Brans on the occasion of his 80th birthday, and were written exclusively for this volume. The chapters were contributed by renowned colleagues who collaborated directly with Carl or who were inspired by his ideas. Though Carl never founded a formal school or group, his influence has been felt by many young scientists, across many countries and communities.

Throughout his career, colleagues and students have appreciated Carl's critical questions and his ambition to understand problems at a very deep level. Always approachable, Carl has inspired generations with his deep questions and important insights. Israel Quiros expressed it best in his dedication: "He is one of the greatest minds of the twentieth century." It is a great pleasure to honor Carl Brans with this collection. Happy Birthday, Carl!

Berlin Torsten Asselmeyer-Maluga
January 2016

Acknowledgements

At first I want to thank my wife Andrea and daugther Lucia for the idea of this volume and overall support.

Special thanks go to Anna Brans for support and corrections as well looking for some photographs.

In particular I acknowledged the impressive work of all contributors in this volume. In my opinion, it is a great collection of papers honoring Carl H. Brans.

Furthermore, I want to thank Dave Kaiser for the help to include more contributors as well for all corrections in the preface and Paul Schultz for reading my own contribution carefully. Special thanks go to Friedrich Hehl for many advices during the preparation process. I want to thank Angela Lahee from Springer for the support and assistance.

Torsten Asselmeyer-Maluga

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About Carl H. Brans

Thoughts of Colleagues, Friends, Family

With this volume, the 80th birthday of Carl H. Brans will be celebrated. Instead of a single foreword, colleagues and friends will present her/his personal view on Carl H. Brans and his influence (Fig. 1).

Fig. 1 Anna and Carl Brans (December, 13th 2015), 80th birthday of Carl

Carl's Influence on the Movie **Interstellar**

The ideas that Newton's gravitational constant G might change from place to place and time to time, and might be controlled by some sort of nongravitational field, were hot topics in the Princeton University physics department when I was a PhD student there in the early 1960s. These ideas had been proposed by Princeton'Ăs Professor Robert H. Dicke and his graduate student Carl Brans in connection with their "Brans-Dicke theory of gravity", an interesting alternative to Einstein's general relativity. The Brans-Dicke theory has motivated a number of experiments that searched for varying G, but no convincing variations were ever found. These ideas and experiments motivated my interpretation of some of *Interstellar*'s gravitational anomalies and how to control them: bulk fields control the strength of G and make it vary. The Professor's equation, as used in this movie and shown on a blackboard in one sequence, builds on these ideas.

Kip Thorne, Caltech
(see **The Science of Interstellar** by Kip Thorne, Norton & Company 2014)

Carl as Colleague

I have known Carl since 1964 when I came back to Loyola having graduated from there in 1952 a few years prior to Carl. I consider my career as somewhat unusual in having it sandwiched between a brief acquaintance with Charles Misner at Notre Dame and a long friendship with Carl, two extraordinary physicist. Unfortunately brilliance doesn't osmose and Carl has had to be very patient with my dumb questions and ever ready to discuss my mathematical and theoretical questions. He has over the years conducted numerous weekly seminars in relativity for the benefit of interested undergraduates and a few faculty and is even currently doing so with discussions of such mysterious topics as the Unruh effect and Bell's inequalities.

One thing that has puzzled me about Carl is why he returned and stayed at Loyola ever since completing his degree at Princeton. I have never asked him about this but my conjecture is that Carl is such and independent, innovative thinker and, importantly, disciplined hard worker that he doesn't need the intellectual stimulation produced by a larger department. Call it the *Keiffer conjecture*. Happy birthday Carl.

David Keiffer, Loyola University New Orleans

Unsurprisingly, I had worked on several different versions of Brans-Dicke theory before I actually met Carl during my job interview at Loyola. Thankfully, I didn't know that I was actually meeting Carl Brans (somehow I missed his profile on the Loyola physics faculty listings) because that would have completely overwhelmed me. It was only halfway through the interview that I realized that I was talking to someone who knew a lot more gravity than I did. Since then, we have become very

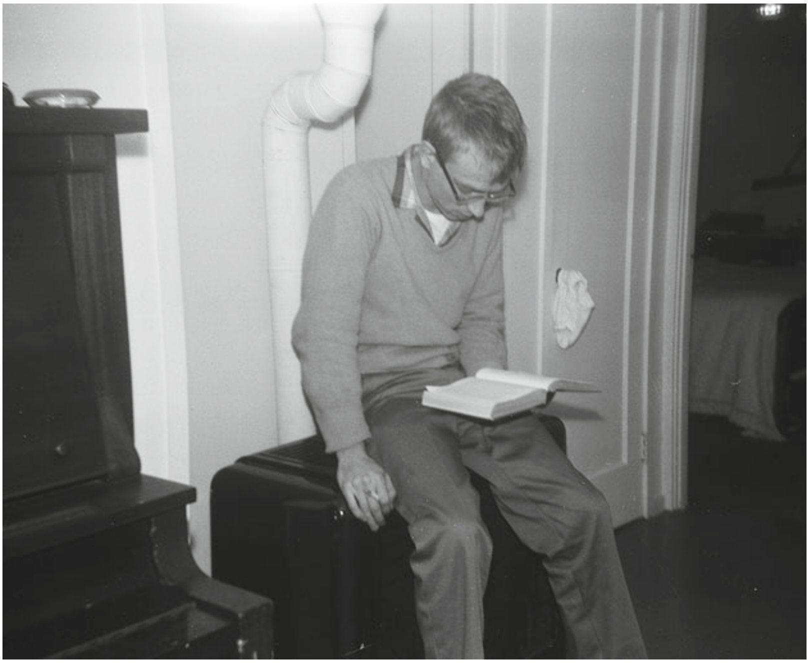

Fig. 2 Carl in Princeton (1959) “This picture has me “studying”(?) while sitting on the heater in student apartment. I was always cold!”

good friends, his good nature, his humility, and his commitment to rigor is something that I cherish and I am inspired by. So, here is to Carl for showing the path that many others like me could follow (Fig. 2).

Tirthabir Biswas, Loyola University New Orleans

Supporting Young Scientists

I first met Carl Brans about twenty years ago, in the mid-1990s, when I was a graduate student. Carl invited me to visit him at Loyola University in New Orleans, and he and his wife Anna kindly hosted me in their beautiful home. Our first meeting has always stood out in my mind: Carl picked me up at the airport, drove me straight to his office, and handed me a piece of chalk. I was to give him a lecture, right there at the blackboard, about cosmic inflation. I launched in, as best I could, and after a fun discussion Carl announced that it was time to pause and get some seafood gumbo; after all, we were in New Orleans. Ever since my first visit, I have found it terrifically inspiring to talk with Carl and to try to sharpen my own ideas in the face of his excellent questions, which he has always delivered in a gentle and encouraging way.

David I. Kaiser, MIT

In 1983, as a 12-years old boy living in the GDR, the socialist part of Germany, I came across the name Carl H. Brans while reading the book “The View of Modern Physics” (“Das Bild der modernen Physik”, Urania Verlag). At the end of the chapter “Relativity?, I found a discussion about a variable coupling constant in General Relativity together with this footnote: “This extension of General Relativity was essentially developed by P. Jordan, C. Brans and R. Dicke in 1961.”. I was deeply impressed and hoped to one day work with these scientists. But I lived on the wrong side of the iron curtain and was forbidden to have contacts with people in the USA. Eventually the political situation began to evolve as I started my study of Physics in September 1990, one month before the unification of East and West Germany. In the second semester I joined a lecture group on algebraic topology which included a discussion of the existence of exotic $\mathbb{R}^{\not 4}$ and the exceptional role of exotic smoothness in dimension four. I was very excited about the possible relationship between this new mathematics and the classical dimension of space-time. So I enthusiastically began to learn everything I could about Exotic Smoothness. In 1992, I came across the paper written by Brans and Randall with many intriguing ideas. A professor at my university helped me to get an invitation to the summer school on Gravity and Torsion in Erice (Italy) where I met Friedrich Hehl who had been a colleague of Brans as a visitor to the Princeton Physics department in 1973. In September 1995, Hehl was organizing a Heraeus seminar “Relativity and Scientific Computing—Computer Algebra, Numerics, Visualisation” and invited Brans to talk about his work with exotic smoothness and physics. It was at this conference that I met Carl and we immediately recognized our common enthusiastic interest in modern differential topology. This then led to some intensive email exchanges.

In 1997, Carl offered me a scholarship (LaSpace Grant) to visit him in New Orleans the next year. It was then that we began to write our book “Exotic smoothness and physics”. Carl was very impressed by the story above about a 12-years-old boy behind the “wall” who had a dream to someday meet him. Of course, in New Orleans there is always life after work and I still remember the warm welcome (with a seafood gumbo) by Carl’s wife Anna. That was the beginning of our wonderful friendship and successful collaboration. I feel so privileged to have had the opportunity to work with him on numerous occasions (Fig. 3).

Torsten Asselmeyer-Maluga, German Aerospace Center

His Family:

Carl Henry Brans was born at St. Paul’s Hospital in Dallas, Texas on Friday, December 13, 1935. For his parents, Carl Brans, who worked in the maintenance

Fig. 3 Carl in the student apartment (1957)

department at Sears Roebuck, and Delia Elizabeth Murrah, a housewife and talented pianist, Friday the thirteenth represented good luck from then on. Carlie was an only child, but had the support of a large extended family in Dallas.

Both of Carl's paternal grandparents had come to America as children, his grandfather from Anholt, Germany and his grandmother from Austria. The men in

Fig. 4 Anna and Carl in Mississippi City (1957) "It is a "selfie" taken on our honeymoon."

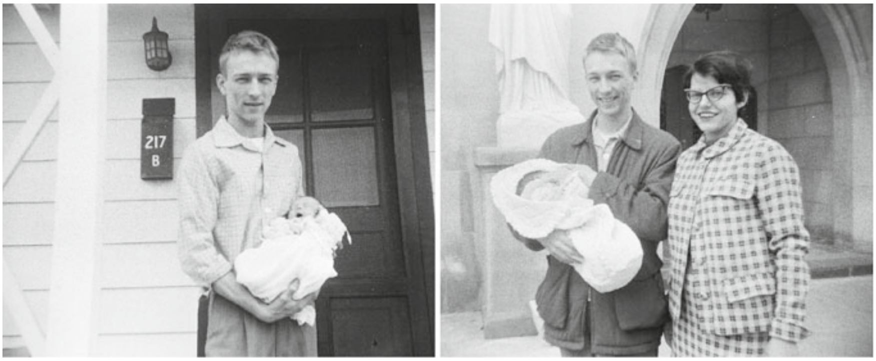

Fig. 5 1958: Carl with the first son Tommy in front of the student apartment (*left*) and Anna, Carl and Tommy in front of the church in Princeton when the son Tommy was baptized (*right*)

the family were brick masons. His maternal grandmother, Mary Mc Namara was born in Dallas to Irish immigrants, whereas his maternal grandfather, who was a blacksmith, came from a family with deep American roots, which led back to England.

On May 5, 1956, I met Carl on a blind date for the Physics Department's annual end of year crawfish boil. It was the end of his junior year and the end of my sophomore year as a major in Sociology. This was the beginning of a beautiful relationship. On February 9, 1957 we were married and went to Princeton together in September of that year. During the 3 long lean years of living on NSF fellowships, our oldest son was born.

After 58 years of marriage, our little dynasty numbers nineteen descendants: Four sons, Thomas Joseph, Henry Robert, Patrick David and John Edward. A daughter, Mary Elizabeth, died in infancy of hydrocephalus.

Our later years were enriched as we saw our progeny flourish. We now have eight grandchildren who have given us seven great-grandchildren (so far) (Figs. 4 and 5).

Anna Dora Monteiro Brans
September, 2015

Chapter 1
65 Years in and Around Relativity

Carl H. Brans

At the very beginning I must thank all of the contributors to this book for taking their valuable time to add to it. Of course, my special thanks goes to Torsten Asselmeyer-Maluga, not only for organizing this work, but also for his friendship as well as his expert advice and tutelage in the mathematics of differential topology over the last 20 (or more) years we have known each other. As always, "Much thanks to you Torsten!"

1.1 Undergraduate Days, 1953–1957

I was not exposed to anyone with expert knowledge about current research in mathematical physics until I got to Princeton at about 20 years of age. Until then I mostly learned on my own, as many of us probably did. Later experience confirmed to me that indeed there is a good bit of the truth in the old saying: "A self taught person has a fool for a teacher." Also, I think this background made it difficult for me to work well in groups or to collaborate, except recently with Torsten. More importantly when I arrived at Princeton University I had a lot of holes in my knowledge of mathematics and physics, and felt quite intimidated by both faculty and other graduate students who had more solid foundations in mathematics and physics. In spite of this, I managed to muddle through and passed both oral and written qualifying exams at the end of my first year.

For me perhaps the most fascinating and motivating aspect of modern physics, primarily relativity and quantum theory, is the marvelously counter-intuitive models for reality beyond that which we can directly observe with more or less "everyday" experience. Of course much of the apparent mystery is a result of trying to describe these "worlds" beyond our everyday experience in natural language which has developed

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exclusively from such direct, human-scaled, experiences. When natural language is inadequate, it has been replaced by mathematics, often using formalisms previously thought to be purely abstract, and unrelated to "common sense." Fortunately for me, I had developed a taste (if not a real skill) in pure mathematics. One of the most interesting things for me was finding that much of the mathematics needed by relativity and quantum theory had been developed before these needs were known. In turn, these physical fields have inspired the further development of mathematical structures. I was very interested in the often asked question: "What is this curious interaction between physics and mathematics?"

Also, I was re-discovering the fact that questioning old assumptions is fun. I enjoy turning to books such as *Counterexamples in Topology* [1]. To paraphrase a remark that I heard from John Wheeler, "Aren't we so very lucky to be paid to do something that we otherwise would do as a hobby."

As an undergraduate at Loyola, I delved into as much mathematics and mathematical physics as I could. So from our library I got a taste of topology from the books *Introduction to Topology* and *Algebraic topology,* by Lefschetz and a bit of measure theory from the book of Halmos. For differential geometry and relativity I read mostly from Sokolnikoff's *Tensor Analysis* and especially Einstein's *Meaning of Relativity*, 3rd edition. I was most fascinated by the Appendix on a unified field theory constructed by generalizing the standard symmetric metric to an asymmetric one. Although this did not turn out to be a widely explored direction in the quest for the classical unified field theory, I found it fascinating and wrote a primitive review of the subject as my senior thesis for my Physics degree from Loyola in 1957 [2] (unpublished). My original readings on quantum theory were probably from the book Lande, my introduction to Quantum Field theory the book by Wentzel. Of course I also tried to read some of the available articles in the Physical Review (only one issue then) and the Annals of Mathematics.

I should also mention that I was very fortunate to have the strong support of Frank Benedetto, S.J., then chairman of the department who did his PhD work on cosmic rays under the Nobel prize winner, Victor Hess. At Loyola Benedetto continued observational work with cosmic rays involving an array of geiger counters with requisite very high voltage. In spite of my obvious difficulties with anything practical, Benedetto provided me with some much needed financial support by employing me to check this array occasionally. I know that at some point I was reaching across the apparatus, with exposed high voltage terminals, and then some undetermined time later I awoke on the concrete floor on my back, sore and somewhat confused. Probably I had received a high voltage shock. I suppose it must have rewired the synaptic patterns in my brain, but I will never know since I was too embarrassed to tell anyone about it at the time. Since then I have even more studiously avoided experimental equipment as much as possible. On a more positive note, during my senior year Benedetto encouraged me to apply to the National Science Foundation for one of their relatively new Research Fellowships. At his suggestion I also applied to Princeton, Einstein's last home. Somehow both applications were successful.

However, during this time the most important thing in my life was my marriage to Anna Monteiro who somehow has managed to raise our family and stay with me for almost 60 years now.

1.2 Arrival in Princeton 1957–1960: Misner, Dicke et al.

In the late fifties as a result of research related to WWII, times were very good for U.S. federal support of research in physics and mathematics in general and especially for people in my age bracket. The fairly new National Science Foundation was providing very generous research support for graduate student fellowships. This enabled me to concentrate entirely on research and fortunately no lab work or teaching was required.

When I arrived in Princeton, I was overwhelmed to be around people whose names I knew as world-class leaders in mathematics and physics. Most of them had even known Einstein personally. Unfortunately this did not include me since he died a couple of years before I arrived. It is now very clear to me that Misner and Dicke were most influential to me in these 3 years. Misner's relativity course opened my eyes to some of mathematical formalisms which were providing new (at least to me) tools and incentives for my nascent explorations into mathematical physics. I discovered Steenrod's fiber bundle book and was inspired by the potential tools presented by bundle structures. In fact, much of the foundation for work that would fascinate me the rest of my career was being done next door in Fine Hall, physically connected to Palmer Lab. Of course, the chief director and contributor to theoretical relativity at Princeton at that time was John Wheeler. Probably as a result of my early development in a somewhat isolated environment for mathematical physics, I have always found it hard to work in a group. So I didn't really "join" Wheeler's very productive group, although I did attend many of its seminars. As I matured later, I realize that I missed a golden opportunity to profit from working more closely with Wheeler himself. I do recall an unforgettable afternoon during this period when someone mentioned what might be an interesting seminar at some place about an hour's drive from Princeton. However, no one seemed to have a car except me so Wheeler asked me to give him and Dirac (who was visiting then) a ride to the seminar. Of course, I couldn't say no, but my ancient car had obviously seen much better days. Actually it was rather "beat up" (both mechanically and cosmetically) to use the common phrase. In spite of this I was looking forward to the prospect of spending a long ride with two such pre-eminent physicists when I was only beginning my graduate school experience. From what I recall, Dirac and Wheeler sat in the back and a long, mostly one sided, conversation ensued between the very taciturn Dirac and the very outgoing and loquacious Wheeler. As I recall, during this period much of Dirac's work concerned quantization of the first order metric field using then current quantum field theory techniques. On the other hand, I knew that Wheeler thought the special nature of geometry meant that any quantization would require an entirely different approach. The "conversation" consisted mostly of rather long, but always polite, questions from Wheeler, and usually only one syllable answers from Dirac. Looking back on this from almost 60 years later, I believe that had I recorded the conversation, it would not now seem to be entirely out of date. Fortunately, considering the prominence of the passengers, I was very happy that my poor car managed to hold up for the round trip.

Also, although I did not look carefully into it, but about that time, late 1950s, workers in quantum field theory and particle physics were beginning to explore symmetries and Lagrangian formulations in which the notions of bundle theory could provide the underpinning for the exploration of quantum force fields as connections on principal bundles. Actually this was presaged as early as 1918 by the work of Weyl on gauge transformations of the electromagnetic potential as being related to conformal transformation of the metric, thus providing some sort of geometric interpretation of the electromagnetic field. This particular approach to a unified field theory was not further studied for many reasons. But it was important as an introduction of what was later to be expressed as gauge symmetry in QFT. These gauge transformations were associated with spacetime scalars with perhaps some internal (bundle group) structure. This ultimately led to what is now referred to as the Higgs scalar and related work. So even before introduction of a scalar field into general relativity, scalars were blossoming in the QFT context.

Although I did not realize it at the time, much of the later surprising discoveries of exotic, i.e., non-standard, structures on topologically simple manifolds such as $\mathbb{R}^4$, $\mathbb{R} \times S^3$, were being presaged by the work of one of the most talented young mathematicians next door in Fine Hall, John Milnor. I refer especially to Milnor's exotic spheres, Σ^7, which are smooth manifolds that are homeomorphic to S^7 but not diffeomorphic to it in its standard structure inherited from $\mathbb{R}^8$. Milnor started with an S^3 bundle over S^4 but with non standard coordinate patch identification of the upper and lower hemispheres of the resulting Σ^7. Later I recognized that since Yang-Mills original non-commutative gauge group is equivalent to an S^3 bundle over $\mathbb{R}^4$, connections on Milnor's exotic spheres could be thought of as Yang-Mills models over compactified spacetime. These topics are in a branch of mathematics known as differential topology, which has held my interest for the last 20 years or so.

In addition to Misner's lectures I sat in other courses. One of these was Quantum Mechanics/Field theory, by Marvin Goldberger. I remember Goldberger's class especially since I found none other than Eugene Wigner sitting next to me and very politely asking questions and making comments. That was certainly a notable experience for a young student such as me. As is well known, Wigner was very kind and extremely polite. It was said that you could never follow Wigner through a door, he would always bow and open it for you.

At that time there was no class or grade requirement at Princeton just a comprehensive exam which I managed to pass at the end of the academic year 1957–1958. It was then time for me to start work on a thesis. Misner's course had exposed me to the mathematics I found most fascinating, so I asked his opinion on my idea to write my thesis on the application of bundle theory to physics. Instead, he suggested that a more realistic path would be to talk to Robert Dicke. He said that Dicke was looking for a theoretical student to develop some of his ideas. It is hard to believe now but at that time I had never heard of Bob and his group, even though he had already become one of the outstanding experimental physicist of his time. Dicke was very approachable and patient in explaining to me his thoughts on Mach's principle, the "large number coincidences," and finally Bob's ideas that

$$\frac{GM}{R} \approx 1 \tag{1.1}$$

for M and R as the mass and radius of the universe as known then might lead to a relativistic generalization of

$$G^{-1} \approx M/R \implies \nabla^2 G^{-1} \approx \rho_{mass} \tag{1.2}$$

Or on an expected local level

$$G^{-1} = G_0^{-1} + \Sigma \frac{m}{r} \tag{1.3}$$

Bob referred to (1.1) as the "large number coincidence," expressed in atomic units as

$$\frac{10^{-40} 10^{80}}{10^{40}} \approx 1 \tag{1.4}$$

as pointed out by Dirac [3] and others. Of course modern observational cosmology has caused drastic revisions to these ideas which seem simplistic to the modern reader, but they were more or less mainstream in terms of observations up to the 1950s. Bob was also very interested in Mach's ideas in terms of a possible causal relation of the state of motion of inertial reference frames relative to the fixed stars. Exactly what is meant by "Mach's Principle" has been debated probably for a century by now [4]. From what I recall Bob was most concerned about the fact that in almost all expositions, "inertial" forces are not granted the same status as "real" ones. Since both inertial and gravitational forces are proportional to the mass they act on, Bob thought that inertial forces should be as real as gravitational ones. In other words Bob wanted to understand inertial forces, such as centrifugal, in terms of gravitational ones due to acceleration relative to the fixed stars. He suggested that this might result in having inertial mass depend on the mass distribution of the universe.[1] To avoid dependence on choice of units, he suggested that this could be expressed in terms of a variable G. This part of the argument is somewhat involved. I think that Bob was rather disappointed that our formulation of a scalar-tensor theory does not seem to provide an explicit derivation of Newton's bucket, etc.

[1] And I believe so did Einstein. See the later discussion of this issue to which a good bit of my thesis was addressed.

As a start, Bob referred me to a paper by Sciama [5] which presented a toy model of vector gravity analogous to electromagentism. This turns out to produce gravitational forces to be seen by an observer accelerating relative to the shell. In the simplest model a mass m accelerating relative to a spherical shell of mass M and radius R would be subject to a gravitational force

$$\mathbf{F}^{\text{Sciama}} = \frac{GM}{R} m\mathbf{A} \tag{1.5}$$

when it has an acceleration $\mathbf{A}$ relative to the shell which represents the rest of the universe. This would be exactly the observed inertial force if $\frac{GM}{R} = 1$. Of course it was known that such a purely vector form could not replace Einstein's for general relativistic gravitation. Sciama presented it only as a toy model to understand inertial forces as gravitational ones. Dicke was fascinated by Sciama's work. Unfortunately for Bob, as far as I know neither scalar-tensor nor standard Einstein theory can reproduce anything as explicit as (1.5). Einstein had devoted a few pages of *Meaning of Relativity* to remark that he had incorporated Mach's Principle in his standard equations of general relativity by having the inertial mass depend on certain metric components and thus the mass in the entire universe. It seemed obvious that this must be purely a coordinate effect, and I later published a paper on it [6].

Another aspect of inertial and gravitational forces could be expressed in terms of the equivalence principle(s). Roughly, in modern usage the **weak principle** asserts that all point masses have same gravitational acceleration. The fact that point masses have a limit of zero self energy later turns out to be critical. The **strong principle** can be summarized as asserting that all gravitational effects are due to the metric alone which requires assumptions not necessarily made and observed in the weak principle.

For many years the work of Eötvös around 1900 was the standard test of the weak principle. However, on closer examination Dicke claimed that the experimental errors inherent in the experiment as done by Eötvös were much greater than believed. In fact, I recall his saying that that the accuracy of the Eötvös apparatus would be affected by human movement only a few meters away. So Bob and others set about re-designing the experiment with modern tools and the results were published in [7]. This seemed to be a very satisfactory confirmation of the **weak** principle of equivalence, but Bob was still intrigued by the fact that Einstein theory makes the implicit assumptions contained in the yet-to-be-tested strong principle. In the 1950s and early 1960s Bob was unaware of the implications of the later discovery by Ken Nordtvedt that a variable G (violation of the strong principle) would in fact result in a violation of even the weak principle for massive bodies. This will be discussed below.

In any event during the 1950s, Bob was highly motivated by Mach's principle, and still unaware of a connection between strong and weak principles. After a few visits, Bob suggested to me that I develop a rigorous formalism consistent with the weak but breaking the strong principle of equivalence incorporating a general relativistic