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Yuki Sato

Space-Time Foliation in Quantum Gravity

Doctoral Thesis accepted by
Nagoya University, Nagoya, Japan

Springer

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… I am inclined to believe from this that four-dimensional symmetry is not a fundamental property of the physical world.

—P. A. M. Dirac in his paper, "*The Theory of Gravitation in Hamiltonian Form*."

Supervisor's Foreword

It has been one of the outstanding problems in theoretical physics to formulate a quantum theory of gravity. A naive quantization had been made of Einstein's theory of gravity, which is well established as a classical theory of gravity with space-time regarded as a dynamical object. However, this procedure turns out to lead to mathematical inconsistency, because the Einstein's theory is not renormalizable. This may imply that for a proper formulation of quantum gravity, we need a new ingredient that is missing in our current understanding of the physical laws. As an example, it is often argued that string theory is one of the most promising candidates of a quantum gravity. In string theory, the most fundamental degree of freedom in nature is regarded as a string rather than a point-particle. Furthermore, a lattice quantum gravity has been studied intensively so far. In this framework, a continuous space-time is approximated with a discretized manifold that is composed of a number of simplices. Dynamical triangulation (DT) is formulated by replacing a path integral over continuous space-times with a sum over all the way of the discretizations. It is found that DT succeeds in defining quantum gravity in lower dimensions but results in pathologies in realistic four-dimensional quantum gravity. In order to resolve this problem, causal dynamical triangulation (CDT) proposes to incorporate space-time causality into DT. The configurations to be summed over in CDT are restricted by requiring them to be consistent with causality. It is then expected to obtain a consistent quantum gravity in four-dimensional space-time.

One of the main topics in this thesis is to investigate some quantum gravity models in two dimensions using CDT. First, this thesis studies a two-dimensional CDT coupled to dimers. A path integral over the configuration space is made by combinatorics. It is important that the thesis found a new multicritical point that describes the CDT model in a continuum limit. Furthermore, it is argued that this formulation enables one to generalize the CDT model coupled to dimers so that it allows creation and annihilation of baby universes. Next, this thesis discusses a two-dimensional CDT with extended interactions by means of a string field theory technique. In this framework, one can formulate a generalized CDT model with extended interactions using creation and annihilation operators of a baby universe. As well, it is shown that equivalent descriptions based on a matrix model exist.

This thesis also discusses classical gravity with an aim to extend Einstein's theory of gravity. A key idea is to allow only a foliation preserving diffeomorphism rather than full diffeomorphism. A typical example is Hořava-Lifshitz, which is supposed to be a UV-finite quantum gravity. This thesis comes up with a new gravity theory called the n-DBI model, whose action contains infinitely many higher derivative terms. It is argued that in this model the cosmological constant is given as an integration constant that emerges after solving an equation of motion. Moreover, it is shown that this model allows an extra degree of freedom of a physical, propagating graviton.

It is worth mentioning that this thesis is unique; in that, it puts a great emphasis on the foliation structure of space-time and its causality as a guiding principle throughout the thesis.

Nagoya, March 2014 Tadakatsu Sakai

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I would like to dedicate this thesis to my dear grandmother, Kikue Hakozaki, who passed away during the completion of this work.

Lastly, I would like to take this opportunity to say a few words about one of my good friends, Takayuki Hikichi. He was a Ph.D. student at Nagoya University,

Japan. His attitude toward physics was earnest: I often saw him asking questions with passion at regular seminars. He was always constructive and brave: without being afraid of authority he insisted on what he believed to be right. Due to his daily diligent effort, he had almost finished his own work on some computer simulations of 3-dimensional causal dynamical triangulations. I was shocked and very saddened to hear of Takayuki's loss during the publication process of this thesis. I would like to dedicate my thesis to my dear friend Takayuki Hikichi, as well.

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List of Published Articles

Parts of this thesis have been published in the following journal articles:

1. F. S. Coelho, C. Herdeiro, S. Hirano and Y. Sato, "Scalar graviton in n-DBI gravity," Phys. Rev. D **86** (2012) 064009.
2. J. Ambjørn, L. Glaser, A. Görlich and Y. Sato, "New multicritical matrix models and multicritical 2d CDT," Phys. Lett. B **712** (2012) 109.
3. C. Herdeiro, S. Hirano and Y. Sato, "n-DBI gravity," Phys. Rev. D **84** (2011) 124048.
4. H. Fuji, Y. Sato and Y. Watabiki, "Causal Dynamical Triangulation with Extended Interactions in 1 + 1 Dimensions," Phys. Lett. B **704** (2011) 582.