Music of the week (Spanish):

Home| Bound State Bosonic Quantum Harmonic Oscillator Born Rule Bell Inequality Alternative Quantum Mechanics

Alternative Quantum Mechanics

See:

- **Nonlinear quantum mechanics**
- **Quaternionic quantum mechanics**
- **Split complex number**
- *Bicomplex number*

Papers:

- Quantum Theory: Reconsideration of Foundations (2003) - A. Khrennikov local pct. 50

Your comments are very much appreciated. Suggestions, questions, critique, ... ?

Bell Inequality

See **Bell's Theorem**.

Your comments are very much appreciated. Suggestions, questions, critique, ... ?

Born Rule

Papers:

- Quantenmechanik der Stoßvorgänge (1926) - M. Born local pct. 979 - The original paper. Interestingly Born first got it wrong in that he thought that the probability is given by the wavefunction. He made a correction in a footnote, which probably is one of the most important footnotes in the history of science. -

Documents:

- The Born Rule and its Interpretation - N. P. Landsman local

Links:

- WIKIPEDIA - Born Rule

Your comments are very much appreciated. Suggestions, questions, critique, ... ?

Bosonic Quantum Harmonic Oscillator

One dimensional bosonic quantum harmonic oscillator

Invoking the (bosonic) correspondences $x \leftrightarrow \hat{x}$ and $p \rightarrow \hat{p} = -i\hbar\frac{\partial}{\partial x}$ between classical and quantum variables yields the Hamilton operator

$$\begin{aligned}\hat{H}_B &= \frac{1}{2}\,m\omega^2\hat{x}^2 - \frac{1}{2m}\,\hbar^2\partial_x^2 \\ &\equiv \frac{1}{2}\,\hbar\omega(\hat{X}^2 - \hat{P}^2)\end{aligned}$$

with

$$\hat{X} \equiv \frac{\hat{x}}{\ell_c} = \frac{\hat{x}}{\sqrt{\frac{\hbar}{m\omega}}}$$

and

$$\hat{P} \equiv \frac{\partial_x}{p_c} = \frac{\partial_x}{\sqrt{\frac{m\omega}{\hbar}}}$$

where we have introduced the **Canonical Variables** ℓ_c, the **Characteristic Length** and p_c, the **Characteristic Momentum**. (Note, that $\ell_c \cdot p_c = 1$).
This way we have rendered both terms dimensionless and put them on the same footing in respect to dimensions.

The eigenvalue equation one gets by letting $\hat{H}$ act on a scalar function $\Phi(x)$ is the **(time independent) Schrödinger equation**

$$\hat{H}_B\Phi(x) = E\Phi(x)$$

Solutions

Solutions are given by

$$\Phi_n(x) = \sqrt{\frac{1}{2^n\,n!}} \cdot \left(\frac{1}{\pi\ell_c^2}\right)^{1/4} \cdot e^{-\frac{1}{2}\left(\frac{x}{\ell_c}\right)^2} \cdot H_n\left(\frac{x}{\ell_c}\right), \qquad n = 0,1,2,\ldots$$

where H_n are the **Hermite Polynomials**

$$H_n(x) = (-1)^n e^{x^2}\,\frac{d^n}{dx^n}\,\left(e^{-x^2}\right)$$

The corresponding energy levels are

$$E_n = \hbar\omega\left(n + \frac{1}{2}\right)$$

which are equidistant in case of the harmonic oscillator - a very important fact.

"Vacuum"

For the ground state the wavefunction takes the form

$$\Phi_0(x) = \left(\frac{1}{\pi\ell_c^2}\right)^{1/4} \cdot e^{-\frac{1}{2}\left(\frac{x}{\ell_c}\right)^2}$$

i.e. the "vacuum"-solution is Gaussian-shaped.
As

$$\frac{\Phi_0(\ell_c)^2}{\Phi_0(0)^2} = \frac{1}{e}$$

the characteristic length can be interpreted as a measure of the "width" of the wavefunction. (One is free to rescale ℓ_c by an arbitrary factor, due to the arbitrariness of its definition).
The characteristic length is also relevant for **coherent states** as these are "shifted" vacuum states, i.e. they all have the same shape. (See also, *displacement operator*).

The energy of the ground state is given by

$$E_0 = \frac{1}{2}\,\hbar\omega$$

Thus "the quantum harmonic oscillator is never at rest", it has a **zero point energy**.

Propagator

The propagator of the one-dimensional quantum harmonic oscillator is given by

$$K(x,x';t) = \frac{1}{\tilde{\ell}_c}\exp\left(-\frac{((x^2+x'^2)\cos\omega t - 2xx')}{\tilde{\ell}_c^{\,2}}\right)$$

with

$$\tilde{\ell}_c \equiv \sqrt{2\pi i \sin\omega t}\;\ell_c$$

For derivations, see [1].

Cutoffs

Mathematically seen x and p can be arbitrarily large. Yet, from the physics point of perspective it is reasonable to assume that x is smaller than a value of the order of the **Hubble radius** and p is not so large as to allow for resolving scales below the **Planck length**.
(Such UV- and IR-cutoffs also play a crucial role in **quantum field theory**).

Thus one has the conditions

$$\ell_c < R_0$$

and

$$\ell_c > \ell_P$$

This results in conditions for the mass of the oscillator

$$M > \frac{\hbar}{R_0^2\omega}$$

and

$$M < \frac{\hbar}{\ell_P^2\omega}$$

The energy is quantized in units of $\hbar\omega$. Thus $Mc^2 = (N+\frac{1}{2})\hbar\omega \equiv N'\hbar\omega$ where N is the number of quanta.
If we substitute ω in the two relations, we get

$$M > \frac{N'\hbar}{R_0 c} > \frac{\hbar}{2R_0 c} \approx \frac{1}{2}\,m_{min}$$

and

$$M < \frac{N'\hbar}{\ell_P c} \approx N m_P \Rightarrow N > \frac{M}{m_P}$$

respectively, where m_P is the **Planck mass**.

Hence according to this model the mass of the "lightest" bosonic quantum particle in the cosmos better had to be larger than of the order of the **minimal mass**. This is interesting in respect to the question if - for instance - a **photon can really be massless**. On the other hand it gives credit to the idea that the modes of **dark energy** could have a mass comparable to the minimal mass (which is consistent with the derivation under **"dark energy for dummies"**).

For the second relation (at least) two different interpretations seem plausible:

1. The mass of the universe belongs to one oscillator. But then, keeping its current mass fixed, it would not be allowed to ever evolve into less than a $N \approx 10^{61}$-particle state. (This constraint seems a bit "out of the blue").

2. One could allow for the evolution into the vacuum state. But then one is lead to decompose the universe

into at least $N \approx 10^{61}$ classically distinguishable quantum harmonic oscillators. In this case the superposition principle has to break down for objects having a mass larger than the Planck mass. (E.g. a **phase transition** could occur upon raising the energy of an object above an energy around the Planck energy). In other words, there cannot be a fully quantum mechanical, i.e. *unitarily* evolving object having a mass larger than the Planck mass. (Interestingly this coincides with the mass of a **biological cell**).

Some observations:

- The second relation also applies to a nucleon, if one makes the substitutions $\ell_P \to \ell_F$ and $M \to m_n$, where ℓ_F is the Fermi length which is of the order of the size of a nucleon and m_n is its mass. In this case we should allow for an evolution to the ground state, i.e. $N = 0$ - hence the second interpretation above applies.
Then

$$m_n < \frac{1}{2} \frac{\hbar}{\ell_F c} \approx 10^{-27} \text{ kg}$$

which is of the order of the mass of a nucleon. Adding further energy would lead to **deconfinement**. Thus, sticking to analogy, this suggests that the second interpretation is the better one in case of our universe.

- ... further remarkable things are to follow - so stay tuned ...

Papers:

- A New Look at the Quantum Mechanics of the Harmonic Oscillator (2006) - H. A. Kastrup local pct. 13
- [1] Three Methods for Calculating the Feynman Propagator (2003) - F. A. Barone, H. Boschi-Filho, C. Farina local pct. 12
- From Quantum Oscillators to Landau-Fock-Darwin model: A Statistical Thermodynamical Study (2010) - J. Kumar, E. Kamil local pct. 0

Lectures:

- Harmonic Oscillator and Coherent States - R. A. Bertlmann local

Documents:

- Stoffzusammenfassung/Skript: Theoretische Quantenmechanik und Anwendungen (2007) - J. Krieger local

Links:

- WIKIPEDIA - Quantum Harmonic Oscillator

Videos:
A brilliant lecture series:

- 007 Back to Two-Slit Interference, Generalization to Three Dimensions and the Virial Theorem (2009) - J. Binney - Harmonic oscillator, from min. 34 onwards.
- 008 The Harmonic Oscillator and the Wavefunctions of its Stationary States (2009)
- 009 Dynamics of Oscillators and the Anharmonic Oscillator (2009)

Animations:

- 2-D Quantum Harmonic Oscillator Applet
- 3-D Quantum Harmonic Oscillator Applet

Your comments are very much appreciated. Suggestions, questions, critique, ... ?

Bound State

In relativistic **quantum field theory**, a stable **Bound State** of n particles with masses $m_1, \ldots, m_n$ shows up as a pole in the **S-matrix** with a center of mass energy which is less than $m_1 + \ldots + m_n$.

An unstable bound state (a resonance) shows up as a pole with a complex center of mass energy.

Papers:

- Introduction to QCD - a Bound State Perspective (2011) - P. Hoyer local pct. 1

Presentations:

- Bound States in Field Theory (2011) - P. Hoyer local

Links:

- WIKIPEDIA - Bound State

Your comments are very much appreciated. Suggestions, questions, critique, ... ?

BRST Quantization

BRST Quantization (or the **BRST Formalism**) is a differential geometric approach to performing consistent, **anomaly**-free **perturbative** calculations in a non-abelian **gauge theory**. It is due to C. M. Becchi, A. Rouet, R. Stora and I. V. Tyutin.
In the BRST approach, one selects a perturbation-friendly **gauge fixing** procedure for the action principle of a gauge theory using the differential geometry of the gauge bundle on which the field theory lives. One then quantizes the theory to obtain a Hamiltonian system in the **interaction picture** in such a way that the "unphysical" fields introduced by the gauge fixing procedure resolve **gauge anomalies** without appearing in the asymptotic states of the theory. The result is a set of *Feynman rules* for use in a **Dyson series** perturbative expansion of the **S-matrix** which guarantee that it is *unitary* and **renormalizable** at each loop order - in short, a coherent approximation technique for making physical predictions about the results of scattering experiments.

After quantization there remains a **nilpotent**, odd, **global symmetry** involving transformations of both fields and **ghosts** which is called **Becchi-Rouet-Stora-Tyutin (BRST) Symmetry**.

Links:

- SCHOLARPEDIA - Becchi-Rouet-Stora-Tyutin Symmetry

Your comments are very much appreciated. Suggestions, questions, critique, ... ?

Bunch-Davies Vacuum

De **Sitter space** has a large family of **de Sitter-invariant vacua** for a free scalar field. The **Bunch-Davies Vacuum** (a.k.a. **Birrell-Davies Vacuum**, **Euclidean Vacuum** or **Adiabatic Vacuum**) is regarded as the most natural vacuum among them because it satisfies the Hadamard condition. The Hadamard condition postulates that the short distance behavior of the *two point function* of the field should be the same for *Klein-Gordon fields on curved space-time* as for the corresponding Minkowskian free field. (The fact that the Hadamard condition selects a unique vacuum state for linear fields has actually been established for a wide class of space-times with bifurcate Killing horizons, of which de Sitter space-time is an example).

Further characteristics of the Bunch-Davies vacuum are, that

- it possesses the same maximal $O(4,1)$ symmetry in the **Hilbert space** of **states** as de Sitter Space,
- its **Green's-functions** are inherited from **S^4** by analytic continuation,
- it is the ground state at the infinite past for a time-dependent Hamiltonian of a scalar field,
- it is the unique **quantum state** (a.k.a. **Bunch-Davies State**) which is invariant under all the **isometries**,

- unlike in flat space, the construction of the Bunch-Davies state is not based on a diagonalization of any Hamiltonian nor any minimization of energy. In fact no suitable Hamiltonian operator with a spectrum bounded from below exists at all in de Sitter space, even for a free **QFT**,
- it does not exist for $m = 0$. The vacuum for $m = 0$ breaks de Sitter invariance and defines an $E(3)$ invariant vacuum state instead.

The Bunch-Davis vacuum plays an important role in modern **cosmology**.

See also:

- *De Sitter thermodynamics*
- **Stability of De Sitter space**

Papers:

- Quantum Field Theory in De Sitter Space: Renormalization by Point-splitting (1978) - T. S. Bunch, P. C. W. Davies local pct. 716
- [1] Quantum Theory of Scalar Field in de Sitter Space-time (1968) - local pct. 400
- Two-point Functions and Quantum Fields in de Sitter Universe (1995) - J. Bros, U. Moschella local pct. 137

Links:

- WIKIPEDIA - Bunch-Davies Vacuum

Your comments are very much appreciated. Suggestions, questions, critique, ... ?

Canonical Commutation Relation

A **quantum theory** or **quantum field theory** is (at least partially) defined by the **Canonical Commutation Relations** (**CCRs**) of its observables.

Examples

Quantum mechanics

$$\begin{aligned}[\hat{q}_i, \hat{p}_j] &= i\hbar\hat{1}\delta_{ij} \\ [\hat{q}_i, \hat{q}_j] = [\hat{p}_i, \hat{p}_j] &= \hat{0}\end{aligned}$$

Quantum field theory

Bosonic fields $\hat{\phi}_i$
The relevant (equal time) commutation relations are

$$\begin{aligned}[\phi(\vec{x},t), \pi(\vec{x}',t)] &= i\delta^{(3)}(\vec{x}-\vec{x}') \\ [\phi(\mathbf{x}), \phi(\mathbf{x}')] &= 0 \\ [\pi(\mathbf{x}), \pi(\mathbf{x}')] &= 0\end{aligned}$$

Fermionic fields Ψ
The relevant relations are (equal time) **Anticommutation Relations** in this case:

$$\begin{aligned}\{\psi_i(\vec{x},t), \psi_j^\dagger(\vec{x}',t)\} &= \delta^{(3)}(\vec{x}-\vec{x}')\delta_{ij} \\ \{\psi_i(\mathbf{x}), \psi_j(\mathbf{x}')\} &= 0 \\ \{\psi_i^\dagger(\mathbf{x}), \psi_j^\dagger(\mathbf{x}')\} &= 0\end{aligned}$$

which can alternatively be expressed in terms of the canonical field momentum $\boldsymbol{\pi} = i\boldsymbol{\psi}^\dagger$.

Links:

- WIKIPEDIA - Canonical Commutation Relation
- WIKIPEDIA - CCR and CAR Algebras

Your comments are very much appreciated. Suggestions, questions, critique, ... ?

Canonical Polyvector Klein-Gordon Field Quantization

As usually, we are going to quantize a simple example first, in our case the real **polyvector Klein-Gordon equation** (PKGE).
The primary goal is not to come up with a physically realistic model - if nevertheless we do so, fine - rather to dive into technicalities and potential subtleties of polyvector canonical quantization.
In fact the polyvector Klein-Gordon field is a bit artificial as

$$\Phi(\mathbf{X}) = \langle \mathbf{X}|\Phi\rangle = \langle \Phi(\mathbf{X})\rangle_0 + 0\sum_{i=1}\langle \Phi(\mathbf{X})\rangle_i$$

where $\langle \Phi(\mathbf{X})\rangle_i$ denotes the projection onto the i-th polyvector grade.
Thus the polyvector Klein-Gordon field can be seen as a truncated **polyvector Dirac field**, where the scalar part is projected out. Hence to be really serious one had to *quantize the polyvector Dirac field*.

The PKGE reads

$$\boldsymbol{\partial}\boldsymbol{\partial}^*\Phi(\mathbf{X}) - M^2\Phi(\mathbf{X}) = 0$$

The associated *Lagrangian* is given by

$$\mathcal{L} = M^2\Phi(\mathbf{X})^2 \pm (\partial^{X_A}\Phi(\mathbf{X}))(\partial_{X_A}\Phi(\mathbf{X}))$$

For the relativistic energy dispersion relation of a polyvector particle with mass M, momentum $\vec{k}$ and higher order momenta we have (see **polyvector invariant mass**)

$$\omega = \sqrt{M^2 - |\vec{k}|^2 \pm S_{\mu\nu}S^{\mu\nu} \pm \dots}$$

We introduce

$$\begin{aligned}\vec{K} &\equiv k_x\mathbf{e}_x + k_y\mathbf{e}_y + k_z\mathbf{e}_z + s_{xy}\mathbf{e}_{xy} + \dots \\ &= \vec{k} + s_{xy}\mathbf{e}_{xy} + \dots\end{aligned}$$

and

$$\begin{aligned}\vec{X} &\equiv x\mathbf{e}_x + y\mathbf{e}_y + z\mathbf{e}_z + a_{xy}\mathbf{e}_{xy} + \dots \\ &= \vec{x} + a_{xy}\mathbf{e}_{xy} + \dots\end{aligned}$$

which are imaginary parts of the respective polyvectors with the 1-vector component associated with time left out. These constructs are useful because we are going to work in the Hamiltonian formalism where time is singled out. Using them it is straightforward to generalize the standard formalism of canonical quantization to polyvector space, for all we have to do is to replace $\vec{k}$ by $\vec{K}$ and $\vec{x}$ by $\vec{X}$.
The energy dispersion relation then reads

$$\omega(\vec{K}) = \sqrt{M^2 - \vec{K}^2}$$

(Plane wave) solutions to the PGKE are given by

$$\Phi(\mathbf{X}, t) = \int e^{i\langle \vec{K}|\vec{X}\rangle_{\mathbb{R}}}\,\Phi(\vec{K}, t)d\vec{K}$$

We require $\Phi(\vec{K}, t) = \Phi^*(-\vec{K}, t)$ such that $\Phi(\vec{X}, t) \in \mathbb{R}$.
Inserting this into the PGKE and doing some manipulations, we get

$$(\partial_t^2 - \vec{K}^2 + M^2)\Phi(\vec{K}, t) = 0$$

But this can be mapped to the Hamiltonion H_{HO} of a **harmonic oscillator** via $\Phi(\vec{K}, t) \to x(t)$, $E \to H_{HO}$ and by fixing $\vec{K}$.
In other words, for every $\vec{K}$ we have a harmonic oscillator, or if we allow for $\vec{K}$ to vary a field of harmonic oscillators which "live" in a polyvector space.
The **quantization of the harmonic oscillator** is gold standard and as all the oscillators of our field are

independent, we get a free quantum field theory. Of course, if we enforce the second and higher orders of the polyvectors involved to vanish, we are supposed to get back the classical **Klein-Gordon quantum field**.

Your comments are very much appreciated. Suggestions, questions, critique, ... ?

Constructive Quantum Field Theory

> Quantum field theory is a cornerstone of our tentative of interpreting the data obtained by our senses and instruments - the extensions of our senses - that constitute what we call real world. Quantum field theory is a tentative to go into some of the inmost folds of these perceptions, a look at scales so small and so far from the daily intuition that we can visualize them in our mind just by constructing a sort of toy models for helping our imagination.
> - Paolo Maria Mariano -

The goal of **Constructive Quantum Field Theory** is to construct interacting models based on the ideas of **renormalization** theory. As yet, success and failure lie close together: It proved possible to construct a whole family of interacting models in two spacetime dimensions such as the $P(\phi)_2$ models, the polynomial models. (Lower indices in this context always mean the spacetime dimension). Two models, ϕ^4_3 and Y_3, the **quartic interaction** and the **Yukawa coupling** were constructed in three spacetime dimensions but, the methods did not lead to any theories in the physical four dimensional spacetime. Instead it is believed that attempts to construct ϕ^4_4 or **quantum electrodynamics** in this way actually lead to free field models.

Implementations

The traditional basis of constructive quantum field theory is the set of *Wightman axioms*. The examples with $d < 4$ satisfy the Wightman axioms as well as the *Osterwalder-Schrader axioms*. They also fall in the related framework of **algebraic quantum field theory** based on the *Haag-Kastler axioms*.

Papers:

- Constructive Quantum Field Theory (2000) - A. Jaffe local pct. 22

Presentations:

- Constructive Quantum Field Theory (2009) - D. Colosi local

Links:

- WIKIPEDIA - Constructive Quantum Field Theory

Videos:

- (Perspectives on nearly 50 Years of) Constructive Quantum Field Theory (2012) - A. Jaffe

Your comments are very much appreciated. Suggestions, questions, critique, ... ?

Deformation Quantization

Deformation Quantization was introduced by Flato, Lichnerowicz and Sternheimer suggesting that " ... quantization be understood as a deformation of the structure of the algebra of classical observables rather than a radical change in the nature of the observables."

It can be understood as a successor of *Weyl quantization*.

Deformation quantization is defined in terms of a **star product** which is a formal deformation of the algebraic structure of the space of smooth functions on a **Poisson manifold**. The associative structure given by the usual product of functions and the Lie structure given by the **Poisson bracket** are simultaneously deformed.

The **Baker-Campbell-Hausdorff formula** is the source of most techniques achieving deformation quantization.

Papers:

- Deformation Quantization: Twenty Years After (1998) - D. Sternheimer local pct. 125
- Problematic Aspects of q-deformations and their Isotopic Resolutions (1993) - D. F. Lopez local pct. 8
- On the Deformation Theory of Structure Constants for Associative Algebras (2009) - B.G. Konopelchenko local pct. 3

Lectures:

- Deformation Quantization : An Introduction - S. Gutt local

Your comments are very much appreciated. Suggestions, questions, critique, ... ?

Delayed Choice Experiment

See also:

- **Delayed choice quantum eraser**
- **Delayed choice entanglement swapping**

Papers:

- Experimental Realization of Wheeler's Delayed-choice Gedanken Experiment (2006) - V. Jacques, E. Wu, F. Grosshans, F. Treussart local pct. 229
- Demystifying the Delayed Choice Experiments (2010) - B. Gaasbeek local pct. 0

Links:

- WIKIPEDIA - Wheeler's Delayed Choice Experiment

Videos:

- Horizon - The Anthropic Principle - Part 3 of 4

Your comments are very much appreciated. Suggestions, questions, critique, ... ?

Delayed Choice Quantum Eraser

See also:

- **Delayed choice experiment**
- **Delayed-choice entanglement swapping**

Papers:

- A Delayed Choice Quantum Eraser (1999) - Y.-H. Kim, R. Yu, S. P. Kulik, Y. H. Shih, M. O. Scully local pct. 210

Links:

- WIKIPEDIA - Delayed Choice Quantum Eraser

Videos:

- This will blow your mind - Delayed Choice Quantum Eraser

Your comments are very much appreciated. Suggestions, questions, critique, ... ?

Delayed-choice Entanglement Swapping

> I propose an even more paradoxical experiment, where entanglement is produced a posteriori, after the entangled particles have been measured and may no longer exist.
> - Asher Peres -

Delayed-choice Entanglement Swapping was formulated by Asher Peres in the year 1999 [1] and in the meantime has been experimentally demonstrated.

Roughly speaking the effect can be understood as "spooky action into the past" which is the counterpart to Einstein's famous "spooky action at a distance" (see **EPR paradox**). In either case, no information is transmitted and thus there is no conflict with causality. That is to say, delayed-choice entanglement swapping does not lead to a backwards causation.

See also:

- **Delayed choice experiment**
- **Delayed choice quantum eraser**
- **Retrocausality**

Papers:

- [1] Delayed Choice for Entanglement Swapping (1999) - A. Peres local pct. 44
- Experimental Delayed-choice Entanglement Swapping (2012) - X.-S. Ma, S. Zotter, J. Kofler, R. Ursin, T. Jennewein, Č. Brukner, A. Zeilinger local pct. 20

Links:

- PHYSORG - Quantum Physics Mimics Spooky Action into the Past (2012)
- Ars technica - Quantum Decision Affects Results of Measurements taken earlier in Time (2012)
- WIRED Science - Quantum Entanglement Could Stretch Across Time (2011)

Your comments are very much appreciated. Suggestions, questions, critique, ... ?

Deterministic Quantum Mechanics

There is a widespread negative attitude towards the possibility of deriving **quantum**- from classical physics which relies on **Bell's inequalities**. However, although being clear that quantum mechanics at laboratory scales violates these inequalities, a common prejudice is that Bell's theorem should be true at all scales. As observed by **'t Hooft**, this need not be the case because such fundamental concepts as rotational symmetry, **isospin** or even **Poincaré invariance** - on which the usual forms of the Bell inequalities are based - may simply cease to exist at the **Planck scale**.

Papers:

- Dissipation and Quantization (2001) - M. Blasone, P. Jizba, G. Vitiello local pct. 94
- Equivalence Relations Between Deterministic and Quantum Mechanical Systems (1988) - G. 't Hooft local pct. 41
- How Does God Play Dice?(Pre-)Determinism at the Planck Scale (2001) - G. 't Hooft local pct. 22
- The Mathematical Basis for Deterministic Quantum Mechanics (2006) - G. 't Hooft local pct. 20
- Deterministic Models of Quantum Fields (2003) - H.-T. Elze local pct. 19
- Quantum Mechanics and Determinism (2001) - G. 't Hooft local pct. 19
- Quantum Behavior of Deterministic Systems with Information Loss: Path Integral Approach (2005) - M. Blasone, P. Jizba, H. Kleinert local pct. 17
- Quantum Limit of Deterministic Theories - M. Blasone, P. Jizba, G. Vitiello local pct. 14
- Quantum Mechanics Emerging from "Timeless" Classical Dynamics (2003) - H.-T. Elze local pct. 5

Videos:

- Superstring and the Foundation of Quantum Mechanics by Gerard 't Hooft (2013)
- The Future of Quantum Mechanics (2004) - G. 't Hooft

Your comments are very much appreciated. Suggestions, questions, critique, ... ?

Dissipative Quantum Computation

Papers:

- Quantum Computation and Quantum-state Engineering Driven by Dissipation (2009) - F. Verstraete, M. M. Wolf, J. Ignacio Cirac local pct. 299

Links:

- Entanglement Strengthened by Losing Information (2013)

Your comments are very much appreciated. Suggestions, questions, critique, ... ?

Dyson Series

In scattering theory the **Dyson Series** (or **Neumann-Liouville Expansion**) is a **perturbative** series (expansion), given by

$$\boxed{\hat{U}_I(t,t_0) = \sum_{n=0}^{\infty} \hat{U}_{I\,n}(t,t_0) = \mathcal{T} e^{-\frac{i}{\hbar}\int_{t_0}^{t} d\tau \hat{V}_I(\tau)}}$$

where $\hat{U}_I(t,t_0)$ is a *time evolution operator*, defined by its action on a **state** in the **interaction picture**,

$$|\Psi(t)\rangle_I = \hat{U}_I(t,t_0)|\Psi(t_0)\rangle_I$$

$\hat{U}_I(t,t_0)$ is also known as **Dyson Operator**. $\mathcal{T}$ is the *time ordering operator*.

$\hat{V}_I(t)$, when transformed to the *Schrödinger picture*, is the part of a Hamiltonian $\hat{H}(t) = \hat{H}_0 + \hat{V}(t)$ that contains the interaction terms and the terms with (explicit) time dependence.

Each term of the series can be represented by *Feynman diagrams*.

The Dyson series is in general (and in fact, in any interesting physical case) not a convergent **Taylor**

expansion, but at best an **asymptotic expansion**. Such an expansion is useful only in those situations in which the contribution of the initial few terms in the series to the physical quantity of interest decrease sufficiently rapidly to give a sufficiently accurate estimate of the exact answer.
In **QED**, for example, at the second order the difference from experimental data is in the order of 10^{-10}. This close agreement holds because the *coupling constant* of QED (i.e. the **fine structure constant**) is much less than 1.

Derivation

$|\Psi(t)\rangle_I$ obeys the Schwinger-Tomonaga equation, i.e.

$$i\hbar \frac{\partial}{\partial t} \left(\hat{U}_I(t,t_0)|\Psi(t_0)\rangle_I \right) = \hat{V}_I(t) \left(\hat{U}_I(t,t_0)|\Psi(t_0)\rangle_I \right)$$

which is equivalent to

$$\boxed{i\hbar \tfrac{\partial}{\partial t} \hat{U}_I(t,t_0) = \hat{V}_I(t)\hat{U}_I(t,t_0)}$$

Although this equation has the same form as the **Schrödinger equation**, it is much harder to solve than the common Schrödinger equation where the Hamiltonian is time-independent and only contains derivatives of second order.

A solution to the equations of motion of $\hat{U}_I(t,t_0)$, which is required to satisfy the boundary condition $\hat{U}_I(t_0,t_0) = \hat{1}$, is given by

$$\hat{U}_I(t,t_0) = \hat{1} - \frac{i}{\hbar} \int_{t_0}^{t} dt_1 \; \hat{V}_I(t_1)\hat{U}_I(t_1,t_0)$$

However this expression by itself is of little use as $U_I(t,t_0)$ has not been isolated. The strategy therefore is to iteratively replace $\hat{U}$ on the r.h.s. and in the end when doing calculations in concrete physical situations only consider the first few terms in the hope that higher order terms can be neglected. This turns out to work in cases where the couplings are small.
After a first substitution, we get

$$\begin{aligned} \hat{U}_I(t,t_0) &= \hat{1} - \frac{i}{\hbar} \int_{t_0}^{t} dt_1 \; \hat{V}_I(t_1) \left(\hat{1} - \frac{i}{\hbar} \int_{t_0}^{t_1} dt_2 \; \hat{V}_I(t_2)\hat{U}_I(t_2,t_0) \right) \\ &= \hat{1} - \frac{i}{\hbar} \int_{t_0}^{t} dt_1 \hat{V}_I(t_1) + \frac{(-i)^2}{\hbar^2} \int_{t_0}^{t} \int_{t_0}^{t_1} dt_1 dt_2 \hat{V}_I(t_1)\hat{V}_I(t_2)\hat{U}_I(t_2,t_0) \end{aligned}$$

and after yet another substitution

$$\hat{U}_I(t,t_0) = \hat{1} - \frac{i}{\hbar} \int_{t_0}^{t} dt_1 \hat{V}_I(t_1) + \frac{(-i)^2}{\hbar^2} \int_{t_0}^{t} \int_{t_0}^{t_1} dt_1 dt_2 \hat{V}_I(t_1)\hat{V}_I(t_2) + \frac{(-i)^3}{\hbar^3} \int_{t_0}^{t} \int_{t_0}^{t_1} \int_{t_0}^{t_2} dt_1 dt_2 dt_3 \hat{V}_I(t_1)\hat{V}_I(t_2)\hat{V}_I(t_3)\hat{U}_I(t_3,t_0)$$

For the general case it is convenient to shift the index of t and consider $\hat{U}_I(t_1,t_0)$ instead.
One then gets

$$\hat{U}_I(t_1,t_0) = \hat{1} + \sum_{n=1}^{N} \frac{(-i)^n}{\hbar^n} \int_{t_0}^{t_1} \dots \int_{t_0}^{t_n} dt_1 \dots dt_n \hat{V}_I(t_1) \dots \hat{V}_I(t_n) + \mathcal{O}(\hat{V}_I^{N+1})$$

Note, that at this stage the denominator $\hbar^n$ looks "dangerous" due to the smallness of **Planck's constant**.
This expression can be recast in a time-ordered form (for the derivation, see *time ordered product*), which is

$$\hat{U}_I(t_1,t_0) = \hat{1} + \sum_{i=1}^{N} \frac{1}{n!} \left(\frac{-i}{\hbar} \right)^n \int_{t_0}^{t_1} \dots \int_{t_0}^{t_1} dt_1 \dots dt_n \mathcal{T}(\hat{V}_I(t_1) \dots \hat{V}_I(t_n)) + \mathcal{O}(\hat{V}_I^{N+1})$$

or equivalently

$$\hat{U}_I(t_1,t_0) = \mathcal{T} \left(\hat{1} + \sum_{i=1}^{N} \frac{1}{n!} \left(\frac{-i}{\hbar} \right)^n \int_{t_0}^{t_1} \dots \int_{t_0}^{t_1} dt_1 \dots dt_n \hat{V}_I(t_1) \dots \hat{V}_I(t_n) \right) + \mathcal{O}(\hat{V}_I^{N+1})$$

Now the denominator looks better because for high enough orders the largeness of $n!$ "kills" the smallness of $\hbar$, i.e. convergence is not endangered.
It is suggestive to take (at least formally) the limit $N \to \infty$ which leaves us with a power series similar to that of the exponential function,

$$\hat{U}_I(t,t_0) = \sum_{i=0}^{\infty} \frac{1}{n!} \left(\frac{-i}{\hbar} \right)^n \int_{t_0}^{t_1} \dots \int_{t_0}^{t_1} dt_1 \dots dt_n \hat{V}_I(t_1) \dots \hat{V}_I(t_n)$$

which can be written in a more mnemonic form as

$$\hat{U}_I(t_1, t_0) = \mathcal{T} e^{-\frac{i}{\hbar}\int_{t_0}^{t_1} d\tau \hat{V}_I(\tau)}$$

But this is the Dyson series defined above.

Lectures:

- Time-Dependent Perturbation Theory local

Links:

- WIKIPEDIA - Dyson Series

Videos:

- Quantum Field Theory, Lecture 9 - P. K. Tripathy

Your comments are very much appreciated. Suggestions, questions, critique, ... ?

Eccles-Beck Model of Consciousness

John Eccles and Friedrich Beck argued that **neuron** firings are controlled by **quantum tunneling** processes at the synapses.

A personal remark

There appears to be a striking similarity between a quantum based excytosis and the functioning of a **tunnel field effect transistor**.

Papers:

- Quantum Aspects of Brain Activity and the Role of Consciousness (1992) - F. Beck, J. C. Eccles local pct. 328
- Synaptic Quantum Tunnelling in Brain Activity (2008) - F. Beck local pct. 29
- My Odyssey with Sir John Eccles (2008) - F. Beck local pct. 2

Links:

- WIKIPEDIA - Friedrich Beck
- WIKIPEDIA - Exocytosis

Videos:

- How Subtile Chemistry Evolving in the Mammalian Brain Opened it to the World of Feeling? (1992) - J. Eccles

Your comments are very much appreciated. Suggestions, questions, critique, ... ?

ELKO Spinor

ELKO Spinors ("ELKO" = German akronym for: "Eigenspinoren des Ladungs-Konjugations Operators") are eigenspinors of the *charge conjugation operator* C. According to the *Wigner classification* they are non-standard spinors and obey the unusual property $CPT^2 = -1$. (See also **CPT theorem**). Nevertheless, **field theory** of eigenspinors of the charge conjugation operator satisfying $(CPT)^2 = -1$ does not imply that it is non-local (see Streater and Wightman). If CPT is an **anti-unitary** operator, then there exists a local **quantum field theory**.

The dominant coupling of ELKO spinors to other fields is via the **Higgs mechanism** or via **gravity**. The particles associated with such a **field theory** are dark and therefore it is natural to apply them to the **dark matter** and **dark energy** problem. Consequently, they are also called **Dark Spinors**.

ELKO Spinor spinors were introduced in [1] and [2].

Papers:

- [1] Spin Half Fermions with Mass Dimension One: Theory, Phenomenology, and Dark Matter (2004) - D. V. Ahluwalia-Khalilova, D. Grumiller local pct. 81
- [2] Dark Matter: A Spin One Half Fermion Field with Mass Dimension one? (2005) - D. V. Ahluwalia-Khalilova, D. Grumiller local pct. 73
- Where are ELKO Spinor Fields in Lounesto Spinor Field Classification? (2005) - R. da Rocha, W. A. Rodrigues Jr. local pct. 57
- Dark Spinor Inflation - Theory Primer and Dynamics (2008) - C. G. Böhmer local pct. 41
- The most General Cosmological Dynamics for ELKO Matter Fields (2011) - L. Fabbri local pct. 10
- Dark Spinor Driven Inflation (2010) - S. Shankaranarayanan local pct. 8
- Dark Spinors (2010) - C. B. Böhmer, J. Burnett local pct. 6

Presentations:

- Dark Energy and Spinors (2010) - J. Burnett local
- Dark Spinor Inflation - Theory Primer and Dynamics (2007) - C. G. Böhmer local

Links

- Website Christian G. Böhmer

Your comments are very much appreciated. Suggestions, questions, critique, ... ?

Fermionic Path Integral

The **Fermionic Path Integral** is given by

$$Z = \int \mathcal{D}[\bar{\mathbf{\Psi}}]\mathcal{D}[\mathbf{\Psi}]e^{iS[\bar{\mathbf{\Psi}},\mathbf{\Psi}]}$$

where

$$S[\bar{\mathbf{\Psi}},\mathbf{\Psi}] = \int \mathrm{d}^4x\bar{\mathbf{\Psi}}(i\overset{\leftrightarrow}{\partial\!\!\!/} - m)\mathbf{\Psi}$$

is the action of the **Dirac field**. $\mathbf{\Psi}$ and $\bar{\mathbf{\Psi}}$ are complex **Grassmann variables** in this case.

See also:

- **Berezin calculus**

Papers:

- Grassmann Calculus, Pseudoclassical Mechanics, and Geometric Algebra (1993) - C. Doran, A. Lasenby, S. Gull local pct. 32 - With a suggestion for a (Euclidean) path integral in **Clifford geometric algebra**.
- Time Evolution in Fermion Path Integrals (1982) - P. Hoyer local pct. 8

Videos:

- Quantum Field Theory II - Lecture 6 (2009) - F. David

Your comments are very much appreciated. Suggestions, questions, critique, ... ?

Generalized Uncertainty Principle

It was shown that at the **Planck scale** the usual **momentum-position uncertainty relation** acquires a (high-energy) correction term, leading to

$$\Delta x \equiv \Delta x_0 + \Delta x_1 \approx \frac{\hbar}{\Delta p} + \text{const.}\, \ell_P^2 \, \frac{\Delta p}{\hbar} = \Delta x_0 + \text{const.}\, \ell_P^2 \, \Delta x_0^{-1}$$

with a constant, presumably of the order of 1.

This result can be derived in different ways, e. g. by means of

- **string theory**,
- **black hole** physics,
- and simple estimates based on Newtonian gravity and **quantum mechanics**.

Papers:

- On Gravity and the Uncertainty Principle (1999) - R. J. Adler, D. I. Santiago local pct. 223

Your comments are very much appreciated. Suggestions, questions, critique, ... ?

Gleason's Theorem (Quantum Mechanics)

Papers:

- Measures on the Closed Subspaces of a Hilbert Space (1970) - A. M. Gleason local pct. 1044

Theses:

- Gleason's Theorem (2006) - H. Granström local tct. 1

Lectures:

- Lecture Notes for Physics 229: Quantum Information and Computation (1998) - J. Preskill local

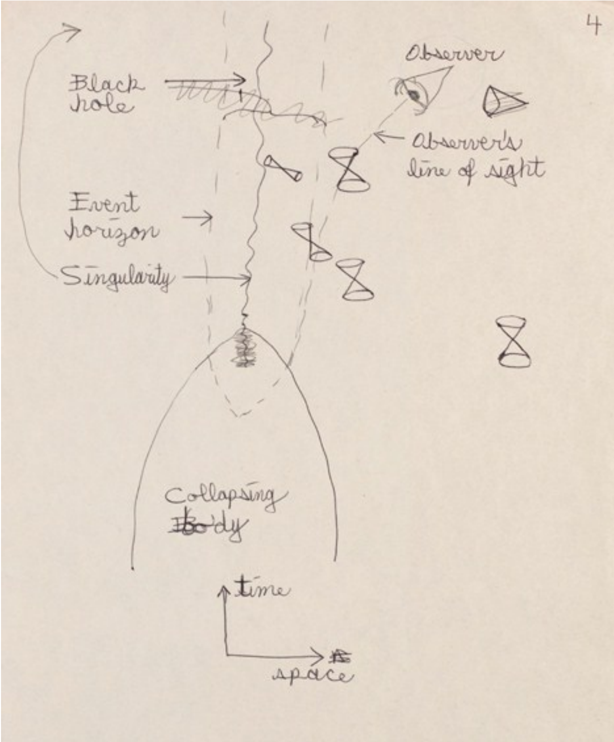
Links:

- WIKIPEDIA - Gleason's Theorem

Your comments are very much appreciated. Suggestions, questions, critique, ... ?

Hawking Radiation

> Black Hole evaporation is one of the most puzzling features of gravity and quantum theory. The derivation by Hawking is nonsense, in that it uses features of the theory in regimes where we know the theory is wrong. Analog models of gravity have given us a clue that despite the shaky derivation, the effect is almost certainly right.
> - Bill Unruh [1] -



Theromodynamics

A (Schwarzschild-) **black hole** of mass M may be viewed as a thermodynamic system having temperature T and **entropy** S, where

$$S \propto M^2$$

and

$$T = \frac{\hbar c^3}{8\pi G k}\,\frac{1}{M}$$

Thus

$$S \propto \frac{1}{T^2}$$

As $S \propto 2MdM$, inserting the second equation, leads to $dM \propto TdS$ which is in accordance with the standard thermodynamic relation $dM = TdS$.

Black hole information loss paradox

If one assumes that the black hole can be described by **quantum mechanics** and initially is in a **pure state**, as it thermally radiates, it evolves into a mixed state, which contains much less information about the black hole system, as compared to its initial state.
This transition from a pure to a mixed state is not allowed in quantum mechanics, because it leads to a breakdown of the central sacred quantum principle: quantum complex linear superposition or quantum coherence. According to quantum mechanics, purity is eternal ! The problem is known as information loss paradox.

The shortcomings of Hawking's semi-classical calculations are that they take into account only the quantum properties of matter, but do not probe the suspected quantum structure of spacetime itself.

Critique

See [2], [3].

See also:

- **Analogue gravity**

Papers:

- Particle Creation by Black Holes (1975) - S. W. Hawking local pct. 7475
- Hawking Radiation as Tunneling (2001) - M. K. Parikh, F. Wilczek local pct. 1198
- Particle Production and Complex Path Analysis (1998) - K. Srinivasan, T. Padmanabhan local pct. 389
- Black Hole Radiation in the Presence of a Short Distance Cutoff (1993) - T. Jacobson local pct. 181 - A critical account of Hawking's derivation.
- Hawking Radiation of Apparent Horizon in a FRW Universe (2009) - R.-G. Cai, L.-M. Cao, Y.-P. Hu local pct. 142
- Hawking Radiation from Ultrashort Laser Pulse Filaments (2010) - F. Belgiorno, S.L. Cacciatori, M. Clerici, V. Gorini, G. Ortenzi, L. Rizzi, E. Rubino, V.G. Sala, D. Faccio local pct. 130
- Towards the Observation of Hawking Radiation in Bose--Einstein Condensates (2001) - C. Barceló, S. Liberati, M. Visser local pct. 86
- Observer Dependent Horizon Temperatures: a Coordinate-Free Formulation of Hawking Radiation as Tunneling (2008) - S. Stotyn, K. Schleich, D. Witt local pct. 20
- [2] On the Existence of Black Hole Evaporation Yet Again (2006) - V. A. Belinski local pct. 17
- [3] The Time Factor in the Semi-classical Approach to the Hawking Radiation (2009) - M. Pizzi local pct. 3

Theses:

- Hawking Radiation (2008) - D. K. Brattan local

Links:

- WIKIPEDIA - Hawking Radiation
- [1] Where do the particles come from? - B. Unruh

Videos:

- Introduction to Hawking Radiation (2014) - G. Mandal
- Hawkings Derivation of Black-hole Entropy and Hawking Radiation (2013) - G. Mandal
- Emergence/Analogy and Hawking Radiation (2011) - B. Unruh
- WHY PRE-HAWKING RADIAITION NEVER BECOMES THERMAL (2011) - E. Greenwood
- Experimental Detection of Stimulated Hawking Thermal Radiation from Analog White Holes (2010) - B. Unruh

Your comments are very much appreciated. Suggestions, questions, critique, ... ?

Heisenberg Cut

See also:

- **Schrödinger's Cat**
- **Wigner's friend**
- **Collapse of the wavefunction**
- **Born rule**
- *Projection postulates*

Papers:

- On a Model of Quantum Mechanics and the Mind (2014) - J. A. de Barros local pct. 0

Links:

- WIKIPEDIA - Heisenberg Cut

Your comments are very much appreciated. Suggestions, questions, critique, ... ?

Interaction Picture

The **Interaction Picture** (a.k.a. **Dirac Picture**) is an intermediate representation between the *Schrödinger picture* and the *Heisenberg picture*. In this picture both operators and **state vectors** are time-dependent. The interaction picture is particularly useful in problems involving time dependent external forces or potentials acting on a system. It also provides a route to the whole apparatus of **quantum field theory** and *Feynman diagrams*. This approach to field theory was pioneered by **Dyson** in the the 1950's.

Given a Hamiltonian in the Schrödinger picture of the form

$$\hat{H}(t) = \hat{H}_0 + \hat{V}(t)$$

where $\hat{H}_0$ is time-independent and it is assumed that for it alone the exact solutions (eigenvectors and eigenvalues) are known. $\hat{V}(t)$ describes some interaction which can be time dependent. The goal is to find solutions for $\hat{H}(t)$.

A **state** in the interaction picture is defined by

$$|\psi(t)\rangle_I = e^{\frac{i}{\hbar}\hat{H}_0(t-t_0)}|\psi(t)\rangle = U_0^{-1}(t,t_0)|\psi(t)\rangle$$

where $|\psi(t)\rangle$ is a state in the Schrödinger picture and $U_0^{-1}(t,t')$ is a *time evolution operator*. t_0 is an arbitrary, fixed reference time whereas t is variable. For convenienvce t_0 is often taken to be 0.
An operator in the interaction picture is defined by

$$\hat{O}_I(t) = e^{\frac{i}{\hbar}\hat{H}_0(t-t_0)}\hat{O}(t)e^{-\frac{i}{\hbar}\hat{H}_0(t-t_0)} = U_0^{-1}(t,t_0)\hat{O}U_0(t,t_0)$$

where $\hat{O}(t)$ is an operator in the Schrödinger picture. Note that the time dependence of $\hat{O}(t)$ can only be an explicit one, as by definition an operator in the Schrödinger picture has no implicit time dependence. Explicit time dependence occurs for instance if an external, time-varying electric field is applied to the system.

Taking the partial derivative of a state in the interaction picture in respect to time leads to

$$i\hbar\frac{\partial}{\partial t}|\psi(t)\rangle_I = (i\hbar)\frac{i}{\hbar}\hat{H}_0 e^{\frac{i}{\hbar}\hat{H}_0(t-t_0)}|\psi(t)\rangle + (i\hbar)e^{\frac{i}{\hbar}\hat{H}_0(t-t_0)}\frac{\partial}{\partial t}|\psi(t)\rangle$$

Substituting the **Schrödinger equation**

$$i\hbar\frac{\partial}{\partial t}|\psi(t)\rangle = \left(\hat{H}_0 + \hat{V}(t)\right)|\psi(t)\rangle$$

one gets

$$i\hbar\frac{\partial}{\partial t}|\psi(t)\rangle_I = e^{\frac{i}{\hbar}\hat{H}_0(t-t_0)}\hat{V}(t)|\psi(t)\rangle$$

as two terms containing $\hat{H}_0$ cancel.

Inserting $1 = e^{-\frac{i}{\hbar}\hat{H}_0(t-t_0)}e^{\frac{i}{\hbar}\hat{H}_0(t-t_0)}$ results in

$$i\hbar\frac{\partial}{\partial t}|\psi(t)\rangle_I = e^{\frac{i}{\hbar}\hat{H}_0(t-t_0)}\hat{V}(t)\left(e^{-\frac{i}{\hbar}\hat{H}_0(t-t_0)}e^{\frac{i}{\hbar}\hat{H}_0(t-t_0)}\right)|\psi(t)\rangle$$

Assuming that the operators are associative, we can shift the brackets according to

$$i\hbar\frac{\partial}{\partial t}|\psi(t)\rangle_I = \left(e^{\frac{i}{\hbar}\hat{H}_0(t-t_0)}\hat{V}(t)e^{-\frac{i}{\hbar}\hat{H}_0(t-t_0)}\right)\left(e^{\frac{i}{\hbar}\hat{H}_0(t-t_0)}|\psi(t)\rangle\right)$$

(What if they are **not associative** ?)
Using the definitions of an operator and a state in the interaction picture from above this can be expressed as

$$\boxed{i\hbar\frac{\partial}{\partial t}|\psi(t)\rangle_I = \hat{V}_I(t)|\psi(t)\rangle_I}$$

This equation is also known as **Schwinger-Tomonaga Equation** which is the analogue of the Schrödinger equation in the interaction picture.
If V_I were constant, its solution would be of the same form as that of the Schrödinger equation, i.e.

$$|\psi(t)\rangle_I = \hat{U}_I(t,t')|\psi(t')\rangle_I$$

with $U_I(t,t') = e^{-\frac{i}{\hbar}\hat{V}_I(t-t')}$.
However for a time dependent interaction the solution is more complicated, given by the **Dyson operator**

$$\hat{U}_I(t,t_0) = \mathcal{T}e^{-\frac{i}{\hbar}\int_{t_0}^{t}\hat{V}_I(t')dt'}$$

For the time evolution of $\hat{H}_I(t)$ we get

$$\begin{aligned} i\hbar \frac{d}{dt}\hat{H}_I(t) &= i\hbar \frac{d}{dt}\left(e^{\frac{i}{\hbar}\hat{H}_0 t}\hat{H}(t)e^{-\frac{i}{\hbar}\hat{H}_0 t}\right) \\ &= -\hat{H}_0 H_I + H_I \hat{H}_0 + e^{\frac{i}{\hbar}\hat{H}_0 t}\frac{\partial}{\partial t}\hat{V}(t)e^{-\frac{i}{\hbar}\hat{H}_0 t} \end{aligned}$$

as $\frac{d}{dt}\hat{H}(t) = \frac{\partial}{\partial t}\hat{H}(t)$ in the Schrödinger picture (only explicit time dependence is allowed, as already mentioned).
Hence the time evolution of the Hamiltonian in the interaction picture is given by the following Heisenberg-like equation, with the total Hamiltonian replaced by H_0

$$\boxed{i\hbar \frac{d}{dt}\hat{H}_I(t) = \left[\hat{H}_I(t), \hat{H}_0\right] + i\hbar \frac{\partial \hat{V}(t)}{\partial t}\bigg|_I}$$

Links:

- WIKIPEDIA - Interaction Picture

Videos:

- Quantum Field Theory, Lecture 8 - P. K. Tripathy

Your comments are very much appreciated. Suggestions, questions, critique, ... ?

Interpretation of Quantum Mechanics

"There was a time when the newspapers said that only twelve men understood the theory of relativity. I do not believe that there ever was such a time. ... On the other hand, I think it is safe to say that no one understands quantum mechanics. ... Do not keep saying to yourself, if you can possibly avoid it, 'But how can it be like that?' because you will get 'down the drain' into a blind alley from which nobody has yet escaped. Nobody knows how it can be like that."

R. P. Feynman
The Character of Physical Law
(1967a, p. 129)

A personal remark

The Copenhagen interpretation can be seen as the minimalistic (consensus) interpretation of **quantum mechanics**. As far as we know it applies to any laboratory experiment. But it may well fail when it comes to the whole of the cosmos (**quantum cosmology**) where the observer needs to be included in the quantum mechanical system.

See also:

- **Many worlds interpretation**
- *Consistent histories*
- **QBism**
- **Philosophical aspects of quantum field theory**

Papers:

- Do we Really Understand Quantum Mechanics? Strange Correlations, Paradoxes and Theorems. (2011) - F. Laloë local pct. 205
- Quantum Mechanics and Reality (1970) - B. S. DeWitt local pct. 57

- A Snapshot of Foundational Attitudes Toward Quantum Mechanics (2013) - M. Schlosshauer, J. Kofler, A. Zeilinger local pct. 14
- Why Quantum Theory is Possibly Wrong (2010) - H. Lyre local pct. 3

Links:

- WIKIPEDIA - Interpretation of Quantum Mechanics
- Foundations of Quantum Mechanics and Relativity Theory - W. M. de Muynck

Videos:

- World Science Festival - Measure For Measure: Quantum Physics and Reality (2014)
- The Copenhagen Interpretation

Your comments are very much appreciated. Suggestions, questions, critique, ... ?

Light Cone Quantization

Papers:

- Quantum Chromodynamics and Other Field Theories on the Light Cone (1997) - S. Brodsky, H.-C. Pauli, S. Pinsky local pct. 1045

See also:

- **Light cone coordinates**

Your comments are very much appreciated. Suggestions, questions, critique, ... ?

Loop Quantum Gravity

One drawback of **Loop Quantum Gravity** is that it has not been shown to reproduce **General Relativity** in the classical limit.

See also:

- **Spin foam**

Papers:

- Lectures on Loop Quantum Gravity (2002) - T. Thiemann local pct. 245
- Loop Quantum Gravity: An Inside View (2006) - T. Thiemann local pct. 73
- Gravity and the Quantum (2004) - A. Ashtekar local pct. 71
- Critical Overview of Loops and Foams (2010) - S. Alexandrov, P. Roche local pct. 25

Magazines:

- Following the Bouncing Universe (2008) - M. Bojowald local mct. 15

Videos:

- Pentahedral Volume, Chaos, and Quantum Gravity (2012) - H. Haggard
- Recent Advances in Loop Quantum Cosmology (2011) - A. Ashtekar
- Loop Quantum Gravity (2008) - C. Rovelli
- Quantum Spin Dynamics in Loop Quantum Gravity
- Lectures on Loop Quantum Gravity (2007) - T. Thiemann 1 2|videos/*QCS-180x144*.avi]

Your comments are very much appreciated. Suggestions, questions, critique, ... ?

Many Worlds Interpretation

> The church of the large Hilbert space elevates the linearity of the Schrödinger equation to a religious belief.
> - [1] -

Links:

- WIKIPEDIA - Many-Worlds Interpretation

Videos:

- Anthony Leggett on the Many Worlds Interpretation (2011)
- [1] Are there Quantum Effects Coming from Outside Space-Time ? Nonlocality, Free Will & No-many-worlds (2010) - N. Gisin
- Everett@50 (2007)

Your comments are very much appreciated. Suggestions, questions, critique, ... ?

No-cloning Theorem

Links:

- WIKIPEDIA - No-Cloning-Theorem

Your comments are very much appreciated. Suggestions, questions, critique, ... ?

Nonlinear Quantum Mechanics

> The linearity of quantum mechanics, expressed in the "superposition principle" is anomalous. Linearity is a common feature of physical theories, but in all other known cases it is an approximation. The range over which linearity holds may be extensive, but is always limited: Maxwell's equations break down for very intense fields (when pair creation is important) and the linearity of space-time itself is a weak-field approximation.
> - T. W. B. Kibble [1] -

Papers:

- Generalized Quantum Mechanics (1974) - B. Mielnik local pct. 164
- [1] Relativistic Models of Nonlinear Quantum Mechanics (1978) - T. W. B. Kibble local pct. 118
- On (Non)Linear Quantum Mechanics (1997) - P. Nattermann local pct. 3

Your comments are very much appreciated. Suggestions, questions, critique, ... ?

Normal Order

A product of *creation and annihilation operators* is said to be **Normal Ordered** (or **Wick Ordered**) if all creation operators are to the left of all annihilation operators.
I.e. it is of the form

$$\hat{a}_1^\dagger \hat{a}_2^\dagger \cdots \hat{a}_i^\dagger \hat{a}_{i+1} \hat{a}_{i+2} \cdots \hat{a}_n$$

The process of putting a product into normal order is called **Normal Ordering** (or **Wick Ordering**).
Given a set of creation and annihilation operators $S = \{\hat{a}_1^\dagger, \hat{a}_2^\dagger, \cdots \hat{a}_i^\dagger, \hat{a}_{i+1}, \hat{a}_{i+2}, \cdots \hat{a}_n\}$ and a product of elements in an arbitrary order, denoted $P(S)$, normal ordering is indicated by colons and given by

$$: P(S) := \sigma \hat{a}_1^\dagger \hat{a}_2^\dagger \cdots \hat{a}_i^\dagger \hat{a}_{i+1} \hat{a}_{i+2} \cdots \hat{a}_n$$

where σ is always $+1$ for bosons and $(-1)^n$ for fermions where n counts the number of transpositions of operators.

Examples

Bosons

$$:\hat{a}\hat{a}^\dagger\hat{a}\hat{a}^\dagger: = \hat{a}^\dagger\hat{a}^\dagger\hat{a}\hat{a}$$

Note, that normal ordering is not linear. For example,

$$\hat{a}^\dagger\hat{a} =:\hat{a}\hat{a}^\dagger: =:1+\hat{a}^\dagger\hat{a}: \neq :1: + :\hat{a}\hat{a}^\dagger:= 1+\hat{a}^\dagger\hat{a}$$

where we have used the **CCR** in the second step.

Fermions

$$:\hat{a}\hat{a}^\dagger:= (-1)\hat{a}^\dagger\hat{a}$$

The normal order of any more complicated cases gives zero because there will be at least one creation or annihilation operator appearing twice.

Links:

- WIKIPEDIA - Normal Order

Your comments are very much appreciated. Suggestions, questions, critique, ... ?

Octonionic Hilbert Space

See also:

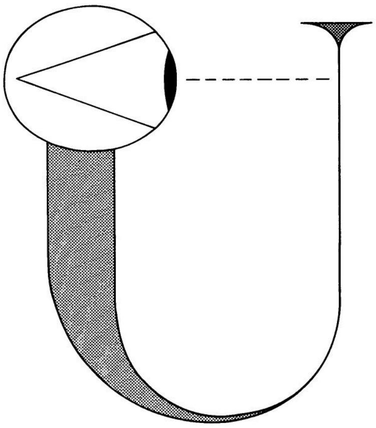
- **Octonionic physics**
- **Cayley-Dickson quantum mechanics**
- **Polyvector Fourier Transform**
- *Polyvector path integral*

Papers:

- On a Hilbert Space with Nonassociative Scalars (1962) - H. H. Goldstine, L. P. Horwitz local pct. 20
- Octonionic Interpretation of the Multiquark States in the Dual String Picture (1979) - P. Żenczykowski local pct. 0

Your comments are very much appreciated. Suggestions, questions, critique, ... ?

Participatory Anthropic Principle



The **Participatory Anthropic Principle** (a.k.a. **Participatory Universe**) which is due to **Wheeler** and based on the **Copenhagen interpretation of quantum mechanics** says that our universe was in a quantum superposition until the first observer "brought it into existence" through a **state reduction**.

Links:

- Participatory Anthropic Principle (PAP)

Your comments are very much appreciated. Suggestions, questions, critique, ... ?

Particle Number Operator

Links:

- WIKIPEDIA - Particle Number Operator

Your comments are very much appreciated. Suggestions, questions, critique, ... ?

Polyvector Canonical Quantization

> The career of a young theoretical physicist consists of treating the harmonic oscillator in ever-increasing levels of abstraction.
> - Sidney Coleman -

The idea of **Canonical Polyvector Quantization** is to lift a non-linear field theory to **polyvector space**, casting it to a quasi-linear formulation. This should allow for applying the classical tools of canonical field quantization.
Therefore on the level of polyvector geometry a quantized polyvector field can be seen as represented by states of a collection of **harmonic polyvector oscillators** which in fact can be (highly) **anharmonic oscillators** on the level of conventional field theory.

Seen more generally, due to the linearity of the description in a polyvecor tangent space, one can expect the axioms of **quantum mechanics** to go through. Therefore it should be possible to lift all the "tools of trade" of **(relativistic) quantum field theory** in a flat spacetime background to polyvector space, also based on a "flat" background.

Agenda

- One would expect a generalization of the canonical anti-commutation relations of the Dirac creation and anihilation field operators, which depend on the algebra of the respective polyvector space. That is, instead of quantizing the classical **Dirac equation** one starts out canonically quantizing the **polyvector Dirac equation**.

- One can check the formalism by calculating the **vacuum** energy. New terms should show up (which are due to nonlinearities in the classical setting) and if one is lucky enough they counter the "ugly" and infamous leading term derived via classial quantum field theory. (That is the hope is to fix the **cosmological constant** problem this way).

Examples

- **Canonical polyvector Klein-Gordon field quantization**

See also:

- *Polyvector propagator*
- *Polyvector quantization*

Papers:

- Dirac's Field Operator Ψ - H. T. Cho, A. Diek, R. Kantowski local pct. 0

Lectures:

- Quantum Field Theory I (2012) - U. Haisch local

Videos:

- Quantum Field Theory (2009) - D. Tong

Your comments are very much appreciated. Suggestions, questions, critique, ... ?

QBism

See also:

- **Interpretation of quantum mechanics**

Papers:

- Quantum Probabilities as Bayesian Probabilities (2001) - C. M. Caves, C. A. Fuchs, R. Schack local pct. 207

Links:

- WIKIPEDIA - Quantum Bayesianism
- Physics: QBism Puts the Scientist Back into Science (2014) - N. D. Mermin lct. 1

Your comments are very much appreciated. Suggestions, questions, critique, ... ?

Quantization

> Quantization is not a science, quantization is an art.
> - Ludwig Faddeev -

> Already from first principles one encounters difficulties. Given that the classical description of a system is an approximation to its quantum description, obtained in a macroscopic limit (when $\hbar \to 0$), one expects that some information is lost in the limit. So quantization should somehow have to compensate for this. But how can a given quantization procedure select, from amongst the myriad of quantum theories all of which have the same classical limit, the physically correct one?
> - Mark J. Gotay -

The following is a (surely incomplete) list of known "recipes" that allow one to get from a classical symmetry to a quantized one. Note, that there are no first principles that would allow one to go from the classical to the quantum world in a straightforward manner, as **Quantization** means a generalization which implies that further information is required which is a priori unknown. (See also: **Correspondence principle**).

Canonical quantization

The canonical quantization problem in physics consists of a commutative algebra of functions equipped with a **Poisson bracket** and the search for a **noncommutative algebra** with **commutators** reproducing this to lowest order in a deformation parameter.
It is well known that actually the converse problem is more well posed: Given a noncommutative algebra which is a flat deformation one may recover its semiclassical structure and Poisson bracket of which it is a quantization.
Either way, Poisson brackets are the semiclassical data for associative noncommutative algebras.

Deformation quantization

(Moyal-)Fedosov Quantization

Weyl quantization

Group quantization

Path integral quantization

Stochastic quantization

Chaotic quantization

Faddeev-Popov quantization

BRST quantization

Light cone quantization

Wick quantization

Covariant Quantization

First Quantization

Second Quantization

> This was the work of many theorists during the period 1928–1934, including Jordan, Wigner, Heisenberg, Pauli, Weisskopf, Furry, and Oppenheimer. Although this is often talked about as second quantization, I would like to urge that this description should be banned from physics, because a quantum field is not a quantized wave function.
> - S. Weinberg -

Antibracket formalism

Polyvector quantization

(... my own initiative)

Personal remark

What is quantization ?

My answer is this: It is the (appropriate) twisting of a **cochain**. Or put it differently, it is "fixing the **cohomology**".

Papers:

- Quantisierung als Eigenwertproblem (1926) - E. Schrödinger local pct. 2190
- General Concept of Quantization (1975) - F. A. Berezin local pct. 679

Your comments are very much appreciated. Suggestions, questions, critique, ... ?

Quantized Time

In respect to a putative theory of **quantum gravity** the question arises if both **time** and space need to be **quantized** - or merely space, leaving time classical.

See also:

- **Time operator**

Links:

- WIKIPEDIA - Chronon

Books:

- The Physical Basis of the Direction of Time (2007) - H. D. Zeh bct. 609

Your comments are very much appreciated. Suggestions, questions, critique, ... ?

Quantum Anharmonic Oscillator

The **Quantum Anharmonic Oscillator** serves as a toy model for a $1+0$-dimensional **quantum field theory** (QFT), i.e. a QFT in one spacial point. As one is dealing with one oscillator only instead of infinitesimally many as in a higher dimensional QFTs, the treatment is purely **quantum mechanical**. As a consequence, the quantum anharmonic oscillator demonstrates the applicability of *Feynman diagrams* in a merely quantum mechanical situation.

See also:

- **Anharmonic Oscillator**

Papers:

- Everything You Always Wanted To Know About The Cosmological Constant Problem (But Were Afraid To Ask) (2012) - J. Martin local pct. 68
- The General Structure of Eigenvalues in Nonlinear Oscillators (2000) - A. D. Speliotopoulos local pct. 18
- Feynman Diagrams in Quantum Mechanics - T. G. Abbott local pct. 0

Theses:

- The Approach to Classical Chaos in an Anharmonic Quantum Oscillator (1995) - J. P. Zibin local tct. 2

Videos:

- Dynamics of Oscillators and the Anharmonic Oscillator (2009) - J. Binney

Your comments are very much appreciated. Suggestions, questions, critique, ... ?

Quantum Biology

It has been documented [1],[2],[3] that light-absorbing molecules in some photosynthetic proteins capture and transfer energy according to **quantum-mechanical** probability laws instead of classical laws at temperatures as high as ambient temperature. This contrasts with the long-held view that long-range quantum coherence between molecules cannot be sustained in complex biological systems, even at low temperatures.

Papers:

- [1] Evidence for Wavelike Energy Transfer through Quantum Coherence in Photosynthetic Systems (2007) - G. S. Engel, T. R. Calhoun, E. L. Read, T.-K. Ahn, T. Mančal, Y.-C. Cheng, R. E. Blankenship, G. R. Fleming local pct. 1097
- [2] Coherently Wired Light-harvesting in Photosynthetic Marine Algae at Ambient Temperature (2010) - E. Collini, C. Y. Wong, K. E. Wilk, P. M. G. Curmi, P. Brumer, G. D. Scholes local pct. 548
- [3] Coherence Dynamics in Photosynthesis: Protein Protection of Excitonic Coherence (2007) - H. Lee, Y.-C. Cheng, G. R. Fleming local pct. 533
- Long-lived Quantum Coherence in Photosynthetic Complexes at Physiological Temperature (2010) - G. Panitchayangkoon, D. Hayes, K. A. Fransted, J. R. Caram, E. Harel, J. Wen, R. E. Blankenship, G. S. Engel local pct. 319
- Proton Tunneling in DNA and its Biological Implications (1963) - P.-O. Löwdin local pct. 316
- Quantum Biology on the Edge of Quantum Chaos (2012) - G. Vattay and S. Kauman, S. Niiranen local pct. 3

Links:

- WIKIPEDIA - Quantum Biology
- Spectrumdirect - Mit allen Quantenmitteln - Nichttriviale Quanteneffekte in Biologischen Systemen (2010) - M. Pollmann
- Quantum Effects Help Cells Capture Light, but the Details are Obscure (2013)

Videos:

- Quantum Biology? (2013) - J. Tuszynski
- Seth Lloyd on Quantum Life
- Quantum Life: How Physics Can Revolutionise Biology - J. Al-Khalili

Audios:

- Quantum Coherence in Biology: Facts, Fiction and Challenges (2011) - A. Olaya-Castro

Your comments are very much appreciated. Suggestions, questions, critique, ... ?

Quantum Brain Dynamics

> In any material in condensed matter physics any particular information is carried by certain ordered patterns maintained by certain long range correlations mediated by massless quanta. It looked to me that this is the only way to memorize some information; memory is a printed pattern of order supported by long range correlations ...
> - Hiroomi Umezawa -

Quantum Brain Dynamics is a model of the **brain** based on **quantum field theory**. It is also known as **Many-body Model of the Brain** or simply **"Quantum Model of the Brain"**.

The model was put forward by Umezawa and Ricciardi in 1967 and has since been developed further by Stuart, Takahashi, Umezawa, Jibu, Yasue, Pribram, Vitiello and others.

Memory in this model is "a printed pattern of order supported by long range correlations". The most revolutionary feature is the existence of a **quantized** field, consisting of **Nambu-Goldstone bosons** resulting from **spontaneous symmetry breaking** (or *pseudo-Goldstone bosons* when considering a system of finite size).

In its original version the model had the problem of "overprinting", meaning that the memory capacity is extremely small: any successive memory printing overwrites the previously recorded memory. A solution was suggested by Vitiello in 1995, extending the model to **dissipative** dynamics (e.g. known as **Dissipative Many-body Model of the Brain** or **Dissipative Brain Model**), which relies on two facts:
One is that the brain is a system permanently coupled with the environment (an open or dissipative system). The other one is a crucial property of quantum field theory, i.e. the existence of infinitely many states of minimal energy, the so called vacuum states or ground states, these being **unitarily inequivalent**. On each of these vacua there can be built a full set (a space) of other states of nonzero energy. One thus has infinitely many state spaces, which, in technical words, are called **representations** of the canonical commutation relations.

The dissipative version of the model is the one that will be considered in the following.

The **neuron** and the glia cells and other physiological units are not quantum objects in the dissipative many-body model of the brain. This distinguishes this model from all other quantum approaches to brain, mind and behavior. Moreover, the dissipative model describes the brain, not mental states. Also in this respect this model differs from those approaches where brain and mind are treated as if they were a priori identical.

Concrete realisations

TODO

Some personal remarks

In my opinion brain models based on quantum field theory offer an extraordinarily fascinating and conceptually powerful and convincing approach to explainig the brain (and maybe even **consciousness**). Such models also have a good chance to be tested experimentally (which has already been done in parts - yet interpreting the complex data is difficult and ambiguous).

The most interesting aspect is that, as a consequence of using quantum field theory instead of **quantum mechanics** only, classical (thermodynamical/physiological) **time** naturally arises as acts of memory storage or retrieval are related to changes of the state space. (This also implies a change of **entropy**). Therefore such models seem to be superior to conventional quantum mechanical approaches, purely based on *unitary* time evolution (see also **quantum consciousness**). They may also help to resolve **Schrödinger's cat paradox** and related paradoxes, as memory acts classically rendering reality objective.

Papers:

- Dissipation and Memory Capacity in the Quantum Brain Model (1995) - G. Vitiello local pct. 208
- Quantum Noise, Entanglement and Chaos in the Quantum Field Theory of Mind/brain States (2003) - E.

Pessa, G. Vitiello local pct. 53
- Formation and Life-time of Memory Domains in the Dissipative Quantum Model of Brain - E. Alfinito, G. Vitiello local pct. 49
- Dissipation and Spontaneous Symmetry Breaking in Brain Dynamics (2008) - W. J. Freeman, G. Vitiello local pct. 47
- The Dissipative Brain (2004) - G. Vitiello local pct. 38
- Coherent States, Fractals and Brain Waves (2009) - G. Vitiello local pct. 29
- Dissipation of 'Dark Energy' by Cortex in Knowledge Retrieval - A. Capolupo, W. J. Freeman, G. Vitiello local pct. 11
- Modeling Quantum Mechanical Observers via Neural-Glial Networks (2012) - E. Konishi local pct. 4
- The Dissipative Brain and Non-Equilibrium Thermodynamics (2011) - W. J. Freeman, G. Vitiello local pct. 3
- The Model of the Theory of the Quantum Brain Dynamics can be cast on the Heisenberg Spin Hamiltonian (2008) - T. Ohsaku local pct. 1
- Fractals as Macroscopic Manifestation of Squeezed Coherent States and Brain Dynamics (2012) - G. Vitiello local pct. 0

Theses:

- Oscillations in the Brain: A Dynamic Memory Model (2002) - M. van Vugt local

Links:

- WIKIPEDIA - Quantum Brain Dynamics

Videos:

- Relations between Many-Body Physics and Nonlinear Brain Dynamics (2007) - G. Vitiello - Short version.
- Relations between Many-body Physics and Nonlinear Brain Dynamics (2007) - G. Vitiello - Long version. Excellent talks !
- The Coming Revolution in Wave Biology: An Interview with Dr. Luc Montagnier (2011)

Google books:

- Quantum Brain Dynamics and Consciousness: An Introduction (1995) - M. Jibu, K. Yasue bct. 266

Your comments are very much appreciated. Suggestions, questions, critique, ... ?

Quantum Cognition

Quantum Cognition is an emerging field that uses mathematical principles of **quantum theory** to help formalize and understand cognitive systems and processes.

Contrary to **quantum consciousness** quantum cognition does not rely on the hypothesis that some physical processes in the **brain** related with cognition and **consciousness** require a quantum physical description.

Papers:

- Overextension of Conjunctive Concepts: Evidence for a Unitary Model of Concept Typicality and Class Inclusion (1988) - J. A. Hampton local pct. 245
- A Quantum Theoretical Explanation for Probability Judgment Errors (2011) - J. R. Busemeyer, E. M. Pothos, R. Franco, J. S. Trueblood local pct. 177
- Quantum Structure in Cognition (2009) - D. Aerts local pct. 155
- Applications of Quantum Statistics in Psychological Studies of Decision Processes (1997) - D. Aerts, S. Aerts
- local pct. 155
- Disjunction of Natural Concepts (1988) - J. A. Hampton local pct. 103
- Mental States Follow Quantum Mechanics During Perception and Cognition of Ambiguous Figures. (2009) - E. Conte, A. Y. Khrennikov, O. Todarello, A. Federici, L. Mendolicchio, J. P. Zbilut local pct. 99
- Empirical Comparison of Markov and Quantum Models of Decision Making (2009) - J. R. Busemeyer, Z. Wang, A. Lambert-Mogilian local pct. 86
- Can Quantum Probability Provide a New Direction for Cognitive Modeling? (2013) - E. M. Pothos, J. R. Busemeyer local pct. 40
- Experimental Evidence for Quantum Structure in Cognition (2008) - D. Aerts, S. Aerts, L. Gabora local pct. 34
- Quantum Structure in Cognition: Fundamentals and Applications (2011) - D. Aerts, L. Gabora, S. Sozzo, T. Veloz local pct. 5

Links:

- WIKIPEDIA - Quantum Cognition
- Quantum Minds: Why we Think like Quarks (2011) - M. Buchanan

Videos:

- The Quantum Challenge in Concept Theory and Natural Language Processing (2013) - S. Sozzo slides local
- A Quantum Probability Approach to Decision Making (2013) - J. Trueblood
- Quantum Minds: Why We Think Like Quarks

Your comments are very much appreciated. Suggestions, questions, critique, ... ?

Quantum Conformal Gravity

The idea is to **quantize conformal gravity** instead of **General Relativity** assuming that the former is the correct theory at short distances and the latter arises at large distances due to quantum corrections.

This approach to **quantum gravity** is motivated by analogy with **QCD** where at high energies or in the $\hbar \to 0$ limit one has **scale invariance**.

See also:

- **Conformal invariance hypothesis**
- **Dimensional transmutation**
- **Is quantum gravity trivial ?**

Papers:

- Conjecture on the Physical Implications of the Scale Anomaly (2005) - C. T. Hill local pct. 4
- Conformal Gravity with Fluctuation-Induced Einstein Behavior at Long Distances (2014) - H. Kleinert local pct. 0

Journals:

- Einstein Gravity Emerging from Quantum Weyl Gravity (1983) - A. Zee jct. 48

Your comments are very much appreciated. Suggestions, questions, critique, ... ?

Quantum Consciousness

Theories of **Quantum Consciousness** purport that in order to explain **consciousness**, **quantum mechanics** is essential, i.e. a mere classical description is not enough.

So far no unambiguous experimental evidence for the existence of relevant quantum effects in the context of **brain** function and consciousness could be established and quantum mechanics is not part of conventional neurobiology.

Quantum consciousness has to be distinguished from **quantum cognition** which merely posits that certain mental processes find a convenient description in terms of a quantum-like formalism, though not excluding the possibility that they are rooted in quantum mechanics.

Models of quantum consciousness

- **Orch-OR model**,
- **Eccles-Beck model of consciousness** (which is regarded as the most concrete model of quantum consciousness [1]),
- **quantum brain dynamics**,
- and many more ... (e.g. [2],[3])

See also:

- **Hard problem of consciousness**
- **Is consciousness fundamental?**
- **David Bohm**

Papers:

- The Importance of Quantum Decoherence in Brain Processes (1999) - M. Tegmark local pct. 540
- Theory of Brain Function, Quantum Mechanics and Superstrings (1995) - D. Nanopoulos local pct. 43
- Quantum Dissipation and Information: A Route to Consciousness Modeling (2007 - G. Vitiello local pct. 34
- [2] Quantum Models of Consciousness (2008) - A. Vannini local pct. 29
- A Non-Critical String (Liouville) Approach to Brain Microtubules: State Vector Reduction, Memory Coding and Capacity (1995) - N. E. Mavromatos, D. V. Nanopoulos local pct. 23
- Macroscopic Quantum Effects in Biophysics and Consciousness (2007) - D. Raković, M. Dugić, M. M. Cirkovic local pct. 13
- A Quantum Theory of Consciousness (2008) - S. Gao local pct. 11
- Quantum Logic of the Unconscious and Schizophrenia (2012) - P. Zizzi, M. Pregnolato local pct. 3
- Quantum Processes, Space-time Representation and Brain Dynamics (2003) - S. Roy, M. Kafatos local pct. 1

Links:

- WIKIPEDIA - Quantum Mind

- PHYSORG: Study Rules Out Fröhlich Condensates in Quantum Consciousness Model
- [1] Stanford Encyclopedia of Philosophy - Quantum Approaches to Consciousness
- NeuroQuantologie - An Interdisciplinary Journal of Neuroscience and Quantum Physics
- [3] Quantum Physics in Consciousness Studies - D. K. F. Meijer, S. Raggett

Videos:

- Does an Explanation of Higher Brain Function require References to Quantum Mechanics (2008) - H. Neven

Google books:

- Rethinking Neural Networks: Quantum Fields and Biological Data (1993) - K. H. Pribram bct. 121

Your comments are very much appreciated. Suggestions, questions, critique, ... ?

Quantum Cosmology

> What is the probability that the universe is probabilistic ?
> **- Markus' wisdom -**

See also:

- **Wheeler-DeWitt equation**
- **Wavefunction of the universe**

Papers:

- Predictions from Quantum Cosmology (1995) - A. Vilenkin local pct. 276
- An Introduction to Quantum Cosmology (2003) - D. L. Wiltshire local pct. 70
- Unitary and Non-Unitary Evolution in Quantum Cosmology (1999) - S. Massar, R. Parentani local pct. 5
- Tomography of Quantum States of the Universe and Cosmological Dynamics (2006) - C. Stornaiolo local pct. 3
- Quantum Cosmology for the XXIst Century: A Debate (2010) - M. Bojowald local pct. 0

Links:

- YAHOO ANSWERS - Is it possible that there was only probability before the Big Bang?

Videos:

- Beyond the Big Bang in Loop Quantum Cosmology (2008) - P. Singh

Your comments are very much appreciated. Suggestions, questions, critique, ... ?

Quantum Damped Harmonic Oscillator

The **Quantum Damped Harmonic Oscillator** (**QDHO**) or **Damped Quantum Harmonic Oscillator** (**DQHO**) represents the simplest *dissipative system* and is therefore of particular interest.

Its **quantization** is not an easy task and various approaches have been devised, but not one of them seems to be a final version which does not contain weak points.

One way to study the quantization of the QDHO is by doubling the **phase-space** degrees of freedom. The *doubled degrees of freedom* play the role of the bath degrees of freedom.

See also:

- **Quantum harmonic oscillator**

Papers:

- Classical and Quantum Mechanics of the Damped Harmonic Oscillator (1981) - H. Dekker local pct. 550
- Quantum Mechanics of the Damped Harmonic Oscillator (2002) - M. Blasone, P. Jizba local pct. 20
- Quantum Theory of the Harmonic Oscillator in Nonconservative Systems (2002) - C.-I. Um, K.-H. Yeon local pct. 11

Your comments are very much appreciated. Suggestions, questions, critique, ... ?

Quantum Darwinism

Documents:

- Quantum Darwinism (2008) - A. Ananthaswamy local

Links:

- New Evidence for Quantum Darwinism found in Quantum Dots (2010) - L. Zyga
- WIKIPEDIA - Quantum Darwinism

Videos:

- Quantum Darwinism - W. H. Zurek

Your comments are very much appreciated. Suggestions, questions, critique, ... ?

Quantum Entanglement

> When two systems, of which we know the states by their respective representatives, enter into temporary physical interaction due to known forces between them, and when after a time of mutual influence the systems separate again, then they can no longer be described in the same way as before, viz. by endowing each of them with a representative of its own. I would not call that one but rather the characteristic trait of quantum mechanics, the one that enforces its entire departure from classical lines of thought.
> - **Erwin Schrödinger** [1] -

> What I think is novel is that Einstein gave us a way of switching off the rest of the world outside the light cone. You could say that yes the rest of the world is going to have an effect, but that effect will not arrive before light could propagate. So, that was a way of dividing the world into bits which are relevant, and bits which could not be relevant. And that we don't have any more.
> - John S. Bell [2] -

Given two **pure states** $|\Psi_A\rangle$ and $|\Psi_B\rangle$ with respective **Hilbert spaces** $\mathcal{H}_A$ and $\mathcal{H}_B$, the Hilbert space of the **Composite System** (bipartite system in this case) is the tensor product

$$\mathcal{H}_{A\otimes B} = \mathcal{H}_A \otimes \mathcal{H}_B$$

The most general pure state in $\mathcal{H}_{A\otimes B}$ is given by a linear combination of the form

$$\Psi_{A\otimes B} = \sum_{i_A, i_B} c_{i_A i_B} |i_A\rangle |i_B\rangle$$

where $c_{i_A i_B}$ are coefficients and $|i_A\rangle$, $|i_B\rangle$ are a complete set of basis elements in $\mathcal{H}_A$ and $\mathcal{H}_B$ respectively.

On the other hand one has the special case

$$\Psi_{A\otimes B} = |\Psi_A\rangle|\Psi_B\rangle = \left(\sum_{i_A} |i_A\rangle\right) \left(\sum_{i_B} |i_B\rangle\right)$$

where $c_{i_A i_B} = a_{i_A} b_{i_B}$.
States that can be written this way are called **separable states**.

States that are not separable, that is $c_{i_A i_B} \neq a_{i_A} b_{i_B}$, are known as **Entangled States**. Although the composite system is in a pure state, it is impossible to attribute to either system A or system B a definite pure state. Another way to say this is that while the **von Neumann entropy** of the whole state is zero (as it is for any pure state), the entropy of the subsystems is greater than zero.

An example is a **Bell State** which is defined as a maximally entangled quantum state of two **qubits**.

The construction straightforwardly generalizes to *n-particle (multipartite, n-partite) states*.

Entanglement measures

Entanglement measures of two- and three **qubit** systems are well understood.
Yet for higher dimensional systems these are still a matter of research, including the challenging topic of multi-qubit systems.
One measure of entanglement is *entanglement entropy*.

A Gedankenexperiment

Suppose we are in a flat spacetime background and start entangling states $|\Psi_i\rangle$. For simplicity we assume that each one has the same mass $m \geq m_{min}$ and $m \ll m_P$ with m_{min} the **minimal mass** and m_P the **Planck mass**.
Thus for N entangled states the resulting state is

$$|\Psi\rangle = \sum_{i_1,\ldots,i_N} c_{i_1\ldots i_N} |\Psi_{i_1}\rangle |\Psi_{i_2}\rangle \ldots |\Psi_{i_N}\rangle$$

Let's assume that its mass is $M \approx Nm$. (E.g. for a *Cooper pair* this is justified).

As long as $M << m_p$ there seems to be no problem and supposedly (conventional) **quantum mechanics** applies.
However upon reaching m_p the entangled state more and more curves the spacetime background, possibly rendering the whole setting non-linear. The question then is, can unitarity "survive" under these circumstances ? If not, quantum mechanics needs an amendment and the usual argument that for a Planck mass object the **Schwarzschild radius** "meets" the uncertainty relation (see **Compton wavelength**) can not be upheld, as one can no longer take the usual **uncertainty relations** for granted. (That is to say that it is not clear weather the **unification** of quantum mechanics and relativity is to happen around the Planck energy scale. It seems plausible, that as soon as non-linearities become relevant, unification has to "kick in").
If nevertheless a black hole forms, which is a **quantum black hole** in this case, the entangled states get hidden behind the black hole horizon and one is facing known problems, such as the **information paradox**.

Contrary to the formation of a typical large **black hole** in astrophysics, which is more of a classical process, here the procedure for its creation is purely quantum mechanical due to the *entanglement process* being so. It therefore seems important, in particular as long as black holes are not generally understood, to really distinguish between a (pure) quantum black hole and a semiclassical black hole, i.e. a (large) classical black hole with quantum effects around it. (A *black hole remnant* after **evaporation** of a large black hole maybe being the former).

See also:

- **3-qubit state**
- *4-qubit state*
- *Quantum entanglement process*
- **Quantum teleporation**

Papers:

- [1] Discussion of Probability Relations between Separated Systems (1935) - E. Schrödinger local pct. 1499
- On Multi-Particle Entanglement (1997) - N. Linden, S. Popescu local pct. 208
- Geometry of Entangled States, Bloch Spheres and Hopf Fibrations (2001) - R. Mosseri, R. Dandolof local pct. 111
- Thinking Outside the Box: The Essence and Implications of Quantum (2006) - H. Hu, M. Wu local pct. 36
- Theoretical and Experimental Evidence of Macroscopic Entanglement Between Human Brain Activity and Photon Emissions: Implications for Quantum Consciousness and Future Applications (2010) - M. A.

Persinger, C. F. Lavallee local pct. 25
- Neutrino Oscillations through Entanglement (2011) - T. E. Smidt local pct. 0

Documents:

- [2] Indeterminism and Nonlocality (1990) - J. S. Bell local

Presentations:

- Multipartite Entangled States in Particle Mixing (2008) local

Links:

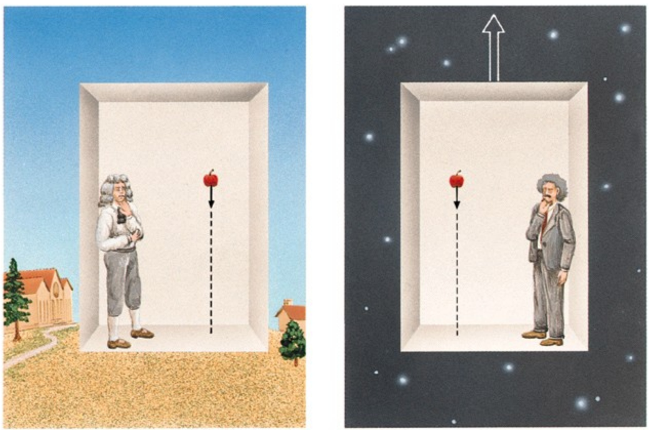
- WIKIPEDIA - Quantum Entanglement
- WIKIPEDIA - Bell State
- Quantum Effects Brought to Light (2011) - Z. Merali

Videos:

- Prof. Anton Zeilinger Speaks on Quantum Physics at UCT (2011)
- Quantum Entanglements (2006) - L. Susskind - Note that Susskind is known for his "black hole war" with **Stephen Hawking** where entanglement plays an eminent role.
- Leonard Susskind - The Black Hole War
- Quantum Information, Entanglement and Nonlocality (2007) - J. Walgate

Your comments are very much appreciated. Suggestions, questions, critique, ... ?

Quantum Equivalence Principle



*This is a **Draft** !*

What could be the underlying principle of a theory of **quantum gravity**, presupposing that such a theory exists ?
I suggest a **quantization** of the **equivalence principle** of **General Relativity** (GR), which I will call **Quantum Equivalence Principle** (**QEP**).

The usual approach when going from a classical **field theory** to a **quantum field theory** is to quantize the field. So it appears natural to do the same when it comes to **gravity**.

But which mathematical entity represents the **gravitational field** ? Is it the **metric**, the *connection* or something else ? Nobody really seems to know. GR suggests that it is the metric, but with it one runs into problems, e.g. with **renormalisaibility**. Should one go beyond GR and include **torsion** or higher curvature terms, for instance, to get a reasonable theory or even consider more fundamental entities such as **strings**, **branes**, **spin networks**, etc. ?

Whatever the right way to quantize gravity is, there is one thing that seems to be reasonable to require from a theory of quantum gravity because it has proved to be fruitful both in general relativity and in **quantum mechanics**, which is **operationalism**. That is for any physical entity there should in principle be a way to devise an experiment to measure it. In general relativity this boils down to setting up clocks and sending light from here to there (something **Einstein** was very concerned with). In quantum mechanics this means that one has to find appropriate observables, given an experimental setup. I.e. concerning this fundamental principle, quantum mechanics and GR are already on the same footing.

Furthermore, we try to be conservative in that we stick to general relativity because this is the most fundamental theory of gravity we have experimental evidence for at the moment.
But general relativity, i.e. the description of a gravitational field, is equivalent to a description of a "field" of accelerations (without the gravitational field), as it is based on the equivalence principle. I.e. we can trade gravitation with acceleration before the act of quantization.
Therefore, if we were to consider a theory of quantum gravity where we give up the equivalence principle, we would at the same time "throw general relativity of the window", which is not what we want to do here.

Thus it is forced upon us to consider a quantization of acceleration. Due to the equivalence principle this is equivalent to the quantization of the gravitational field.
We therefore make the following claim:

Quantum equivalence principle

Any two observer which are accelerated relative to one another can only determine this acceleration up to a *minimal acceleration*, a_0.
(Note that this principle includes a relativity- and an **uncertainty principle**).

For every such observer one can locally define a **quantum vacuum** allowing one to do standard **quantum field theory**. Although both observer may perceive their vacuum state (particle content) in the same way, a given observer must in principle be able to detect a relative difference when comparing her vacuum with that of the other observer (relativity principle for accelerations), e.g. by measuring **Unruh quanta**. This is comparable to the relativity of time in **special relativity** where time dilations are only manifest when comparing two reference frames.
However, if the relative acceleration is smaller than a_0 the vacua should be indistinguishable and therefore for all practical purposes they can be declared to be one and the same. This is where the operational aspect alluded to above comes into play (and philosophy is given a cold shoulder). We will henceforward call any two such mutually distinguishable reference frames **Quantum Rest Frames** (**QRFs**).

An objection to the principle could be that one can have smaller relative accelerations for macroscopic bodies than the one given by a_0.
But here the situation is analogous to the one for an ideal gas in a container, moving at a small constant speed. Although individual particles can be related to reference frames having large velocities relative to one another, what counts when it comes to calculating the velocity of the container is their average velocity.
In case of the QEP this means that for macroscopic bodies having a minute acceleration relative to one another, accelerations of elementary particles must considerably cancel when doing an average over them. Usually, aside from gravity, the other forces of nature have to be taken into account, acting among the constituents whose action is far stronger at short distances than the one of gravity, leading to steady changes of the QRFs of individual particles. (In fact any classical macroscopic body exhibits some degree of elasticity, leaving individual particles some "wiggle room").
Thus to have a pristine situation one had to consider a generic quantum state. Very promising in respect to testing the QEP in the lab appear to be macroscopic wavefunctions, as given a force acting on them, the resulting acceleration would be particularly small.

Some open questions concerning the QEP:

- It seems that there is a distinguished QRF, given by the the **3K cosmic background**. Is such a rest frame fundamental in nature or merely an environmental effect (see also **Mach's principle**) ? Under **quantum gravity from dark energy** arguments are given that from the perspective of an observer it is fundamental and intimately related to its *apparent horizon*. (In fact this is the most troubling point to me at the moment concerning the viability of the QEP).
- Do QRFs define *superselection* sectors, i.e. does the superposition principle merely hold for states that belong to one and the same vacuum ?
- Is a transition between QRFs given by **quantum tunneling** ?
- Is **Schrödinger's cat** dead, alive or in a lasting superposition of both states? There is an interesting twist to the problem in this setting: Consider one observer who sees an Unruh quantum hitting the trigger that leads to the killing of the cat which the other observer doesn't see. I.e. it may then well be that the cat is dead for the one observer whereas it is alive for the another one, it's merely a matter of perspective (see also **complementarity principle**). But in this case the **Wigner's friend** argument would not apply if the two observer belong to different superselection sectors.
- If we speak of a quantum of acceleration, we should be able to find a quantum mechanical *acceleration operator*. What is it ?

As a last remark, it is not clear to the author if the resulting theory has anything to do with the notion of a theory of quantum gravity considered by others. Most approaches aim at a UV completion of gravity. Here, the theory definitely makes statements about IR aspects of gravity (e.g. on cosmic scales) but it is less obvious if it can also make predictions about the UV and if problems there remain. Although there is a slight and preliminary hint that gravity in the UV is "trivial", i.e. that nothing is to be found there, as the IR physics in principle allows one to saturate the *Bekenstein bound*, leaving no (considerable) amount of information for some "fancy" things in the UV :-). This could also mean that the **Planck scale** and quantum gravity are just not related, which is commonly thought to be the case.
I therefore can well imagine that the "failure" of conventional approaches to quantum gravity for so long have quite a simple explanation, it is yet another way of "chasing shadows" - hopefully time will tell (within our lifetimes) if this is so or not. See also: **Is there really a theory of quantum gravity ?**.

See also:

- **External field effect**

Links:

- Physics from the Edge - M. McCulloch

Your comments are very much appreciated. Suggestions, questions, critique, ... ?

Quantum Field Cellular Automaton

The idea is that any **tunneling** between two **unitarily inequivalent vacua** of a **quantum field theory** defines an elementary "time step" of a **cellular automaton**, which in this case will be called a **Quantum Field Cellular Automaton** (**QFCA**).

Your comments are very much appreciated. Suggestions, questions, critique, ... ?

Quantum Field Computer

It's hard to have an idea and somebody didn't have it before. This is what happened to me with the **Quantum Field Computer** (**QFC**), although it seems I have a bit of a different take on the subject. More details can be found under **unitary inequivalence**.
Quantum field computing, which is computing with the "continuum" rather than digital computing, I suspect to be the ultimate computing paradigm, way superior to any form of classical or **quantum computing**. I think it should allow to proof the **Church-Turing Hypothesis** to be wrong. In its full fledged form it must involve all the forces of nature, in particular **gravity**. (An implementation though requires a better understanding of **quantum gravity**). Moreover it should allow for answering the question as to how to construct real **AI** and solve the **"hard problem" of consciousness** in philosophy, paving the way to building "conscious machines". If the conscious mind involves computations based on **quantum field theory**, there had to be elements of **non-computability**, something which has already been suspected by some people (e.g. **Roger Penrose**).
For a good understanding of the subject, it would be crucial to know how to build a quantum field computer "from scratch". At the moment I do not have a good idea how to do this.

If the human **brain** is a quantum field computer, then it must have an uncountably infinite number of states. If one divides this number by the number of atoms in the brain (which is finite), one is left with an uncountably infinite number of states. The consequence is that elementary particles must already be conscious and are the building blocks of "higher" forms of consciousness. Again, not really a new idea. Thus an elementary particle is a small cosmos all by its own, having an incredible computational capacity, by far exceeding that of any classical computer. Therefore, emulating such a system on a classical computer will never be possible. The best one can do is to approximate it to a certain degree.

Some postulates

A QFC ...

- is non-**deterministic**. Although it may be constrained to a certain degree, leading to *superselection rules*. Thus in a way any quantum field computer has generic **free will**.
- can emulate biological systems (**quantum field biology**).
- can simulate a **Hilbert hotel**. A rearrangement in the hotel can be interpreted as an elementary operation of a QFC. (An example would be a "global shift operation", letting all people go to rooms with even numbers). The point is that any operation is global, i.e. it does not involve the propagation of a signal limited by the speed of light. An idea is that this "update" of Hilbert's hotel is a *quantum tunneling* process between inequivalent quantum vacua. I.e. the paradigm of a QFC would be very much that of an **infinite cellular automaton** with Hilbert's hotel being a nice illustrative example. The crucial difference between a Turing machine and a QFC is that the former only can do local changes (on the Turing strip), i.e. a finite number of bits are flipped at a time, whereas the latter is bound to do an infinite number of changes of states per time step otherwise there is no transition to a new vacuum.
- never "crashes" - it just can't do so by definition. Concerning nature, what has been very intriguing to me is that if it is doing a huge computation (some even believe it's a **simulation**) based on a "digital" algorithm, why does it "never" crash ("never", for all practical purposes) ? But if the fundamental building blocks of nature are quantum fields - which is state of the art of our understanding - then an explanation is at hand. (See also [1] for more details).

Questions

- What is the smallest QFC possible ? The answer could come from biology and "living" systems.
- Can we find a generic QFT effect we "cannot put on a conventional machine". (There are some hints of such effects, e.g. *chiral fermions* in **lattice field theory**).

... etc. pp. - an awful lot remains to be understood !

See also:

- **Quantum field cellular automaton**
- **Quantum field biology**
- **Digital physics**
- **Is nature infinite ?**

Papers:

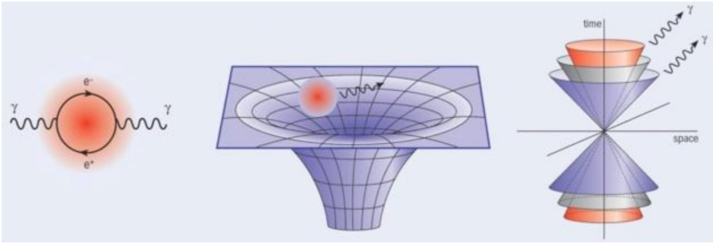
- P/NP, and the Quantum Field Computer (1998) - M. H. Freedman local pct. 115
- Quantum Algorithms for Quantum Field Theories (2011) - S. P. Jordan, K. S. M. Lee, J. Preskill local pct. 49
- [1] The Dissipative Brain (2004) - G. Vitiello local pct. 36
- The Unity between Quantum Field Computation, Real Computation, and Quantum Computation (2001) - A. C. Manoharan local pct. 3
- Beyond Quantum Computation and Towards Quantum Field Computation (2003) - A. C. Manoharan local pct. 0
- QFT + NP = P Quantum Field Theory (QFT): A Possible Way of Solving NP-Complete Problems in Polynomial Time (1996) - A. Beltran, V. Kreinovich, L. Longpré local pct. 0

Your comments are very much appreciated. Suggestions, questions, critique, ... ?

Quantum Field Theory in Curved Spacetime

The subject of **Quantum Field Theory in Curved Spacetime** is the study of the behavior of quantum fields propagating in a classical **gravitational field**. It is used to analyze phenomena where the quantum nature of fields and the effects of gravitation are both important, but where the **quantum nature of gravity** itself is assumed not to play a crucial role, so that gravitation can be described by a classical, curved spacetime, as in the framework of **general relativity**. Its two applications of greatest interest are to phenomena occurring in the very early universe and to phenomena occurring in the vicinity of **black holes**. Despite its classical treatment of gravity, quantum field theory in curved spacetime has provided some of the deepest insights into the nature of quantum gravity so far (e.g. the **Hawking effect**).

Contrary to the standard treatments of quantum field theory in flat spacetime which rely heavily on **Poincaré symmetry** (usually entering the analysis implicitly via plane-wave expansions) and the interpretation of the theory primarily in terms of a notion of "particles", neither Poincaré (or other) symmetry nor a useful notion of "particles" exists in a general, curved spacetime, so a number of the familiar tools and concepts of field theory must be "unlearned" in order to have a clear grasp of quantum field theory in curved spacetime.



One of the technical problems one is facing when doing quantum field theory in a curved background is that there exist **unitarily inequivalent Hilbert space** constructions of free quantum fields in spacetimes with a noncompact *Cauchy surface* and (in the absence of symmetries of the spacetime) none appears "preferred". That is, there is no "preferred" choice of a **vacuum state** and an unambiguous notion of "particles" doesn't exist.
For a free field in Minkowski spacetime, the notion of "particles" and "vacuum" is intimately tied to the notion of "positive frequency solutions", which, in turn relies on the existence of a time translation symmetry. These notions of a (unique) "vacuum state" and "particles" can be straightforwardly generalized to (globally) stationary curved spacetimes, but not to general curved spacetimes. For a free field on a general curved spacetime, one has the general notion of a quasi-free Hadamard state (i.e., vacuum) and a corresponding notion of "particles". However, these notions are highly non-unique - and indeed, for spacetimes with a non-compact Cauchy surface different choices of quasi-free Hadamard states give rise, in general, to unitarily inequivalent Hilbert space constructions of the theory.

The difficulties that arise from the existence of unitarily inequivalent Hilbert space constructions of quantum field theory in curved spacetime can be overcome by formulating the theory via the **algebraic framework**, where the relevant physics is encoded by the algebra of local field observables and where one does not have to specify a choice of state (or representation) to formulate the theory. The algebraic approach also fits in very well with the viewpoint naturally arising in quantum field theory in curved spacetime that the fundamental observables in QFT are the local quantum fields themselves.

For linear fields in curved spacetime, a fully satisfactory, mathematically rigorous theory can be constructed.

See also:

- *Klein-Gordon Field in curved spacetime*

Papers:

- Quantum Field Theory in Curved Spacetime (1975) - B. S. DeWitt local pct. 1134
- On Quantum Field Theory in Gravitational Background (1984) - R. Haag, H. Narnhofer, U. Stein local pct. 154
- Quantization of Scalar Fields in Curved Background and Quantum Algebras (2001) - A. Iorio, G. Lambiase, G. Vitiello local pct. 16
- Quantum Fields in Nonstatic Background: A Histories Perspective (1999) - C. Anastopoulos local pct. 13
- Quantum Field Theory on Curved Backgrounds (2013) -- A Primer M. Benini, C. Dappiaggi, T.-P. Hack local pct. 13

Presentations:

- Quantum Field Theory on Curved Spacetime - Y. Ahmed local

Links:

- WIKIPEDIA - Quantum Field Theory in Curved Spacetime

Videos:

- Axiomatic Quantum Field Theory in Curved Spacetime (2009) - R. M. Wald transparencies local
- The Locally Covariant Approach to Quantum Field Theory in Curved Spacetimes (2008) - C. J. Fewster
- Quantum Field Theory in Curved Spacetime (2007) - R. Wald

Books:

- Quantum Fields in Curved Space (1986) - N. D. Birrell, P. C. W. Davies bct. 6105
- Quantum Field Theory in Curved Spacetime and Black Hole Thermodynamics (1994) - R. M. Wald bct. 1259 - My favourite book in the subject.

Your comments are very much appreciated. Suggestions, questions, critique, ... ?

Quantum Graphity

Papers:

- Quantum Graphity (2006) - T. Konopka, F. Markopoulou, L. Smolin local pct. 48
- A Quantum Bose-Hubbard Model with Evolving Graph as Toy Model for Emergent Spacetime (2009) - A. Hamma, F. Markopoulou, S. Lloyd, F. Caravelli, S. Severini, K. Markström local pct. 31
- Domain Structures in Quantum Graphity (2012) - J. Q. Quach, C.-H. Su, A. M. Martin, A. D. Greentree local pct. 5

Links:

- WIKIPEDIA - Fotini Markopoulou-Kalamara
- PHYSORG - Big Bang Theory Challenged by Big Chill (2012)
- Melbourne Researchers Rewrite Big-Bang-Theory (2012)

Your comments are very much appreciated. Suggestions, questions, critique, ... ?

Quantum Hall Effect

Papers:

- A Four Dimensional Generalization of the Quantum Hall Effect (2001) - S.-C. Zhang, J. Hu local pct. 226

Links:

- WIKIPEDIA - Fractional Quantum Hall Effect

Your comments are very much appreciated. Suggestions, questions, critique, ... ?

Quantum Harmonic Oscillator

> Ashamingly, the only quantum fields that we fully understand to date in four dimensions are free quantum fields on four-dimensional Minkowski space. Formulated more provocatively: In four dimensions we only understand an (infinite) collection of uncoupled harmonic oscillators on Minkowski space !
> - T. Thiemann -

The **Quantum Harmonic Oscillator** may be regarded as one of the most important and paradigmatic concepts in all of physics. It is one of the few quantum-mechanical systems for which a simple, exact solution is known. It often serves as a first approximation and toy model for complicated systems.

For details, see:

- **Bosonic quantum harmonic oscillator**
- *Fermionic quantum harmonic oscillator*
- *Supersymmetric quantum harmonic oscillator*
- *Adelic quantum harmonic oscillator*

See also:

- **Quantum anharmonic oscillator**
- **Quantum damped harmonic oscillator**

Your comments are very much appreciated. Suggestions, questions, critique, ... ?

Quantum Information

See also:

- **Qubit**

Papers:

- Black Holes, Qubits and Octonions (2008) - L. Borsten, D. Dahanayake, M. J. Duff, H. Ebrahim, W. Rubens local pct. 50
- Unitary Reflection Groups for Quantum Fault Tolerance - M. Planat, M. Kibler pct. 3
- A Survey of Finite Algebraic Geometrical Structures Underlying Mutually Unbiased Quantum Measurements (2004) - M. Planat, H. C. Rosu, S. Perrine pct. 24

Your comments are very much appreciated. Suggestions, questions, critique, ... ?

Quantum Mechanics Explained

Having thought about the **anthropic principle** and the meaning of life and **consciousness** in this context, I came up with the following explanation of **quantum mechanics** which is quite convincing to me.

Firstly, let's assume that quantum mechanics is the fundamental description of all of physical reality.
To make things simpler we use a toy model, namely the H-atom with discrete energy levels. Quantum mechanics tells us that to determine the **state** of the atom, we (the observers) have to do a measurement because without the measurement the electron is not localized, possibly being in a superposition of states (actually in a mixed state without any prior knowledge).
We now apply this toy model to the whole of reality be it the **multiverse** or whatever. In **string theory** this would be **"the landscape"** with finitely many vacua, but it could also be infinite like in **inflationary models**. (We'll use the word multiverse in the following as a placeholder for the maximally possible consistent state space).
The subtle point is that the atom has infinitely many energy levels but once we do a measurement we only see one realized. Applied to the multiverse we interpret this in that our visible universe is such a realization (that we observe) whereas the whole of the multiverse is the set of all possible states. But there is one crucial difference between our toy model and the multiverse. In the former the observer is outside the system whereas in the latter he/she is within. (This seems to be the key point when it comes to the problems with the **interpretation of quantum mechanics**).

Suppose that reality is in a superposition of all possible universes (or even an ensemble, a mixed state). If it would contain no observer, it could not be *projected into one particular state*. (We would have quantum mechanics without the **Born "rule"**, which nevertheless would be a consistent framework). But obviously this is not so due to the very existence of our conscious selves and the fact that we do measurements, rendering the multiverse "classical" through a conscious act ("collapse" of the ensemble to a pure state). Let's take a subset of those states of the multiverse that are consistent with life. In our toy model we could take two energy levels and allow the external observer only to look at these two energy levels. This way we impose a *superselection rule*. In the multiverse this superselection rule is implicit, as any possible observer is so. Once we have measured that an electron is one of the two allowed energy states, we have reduced the non-actual ensemble to an actual pure state. But due to quantum mechanics this pure state will continue to *unitarily* evolve, i.e. the orbital corresponding with the energy level evolves in time. Moreover due to **quantum uncertainty** the electron could **tunnel** to any other energy level (the probability depending on the energetic separation between the energy levels), in which case the pure state becomes mixed again, the longer we wait, the higher the probability for this to happen. So in the limit $t \to \infty$ we have completely lost track and sight of where the electron could be and we have the perfectly mixed state corresponding with our H-atom. Now back to our multiverse. Let's do a measurement. This at least boils down to projecting (Born rule) our multiverse into the set of states of universes compatible with life. It might still be in a slightly impure state because we may not have knowledge of exactly which life friendly state we are in, but nevertheless we most probably have reduced the state space enormously. As is the case in our atom model, after the measurement the universe will evolve unitarily but it will also possibly tunnel to other universes of the multiverse. (Other **unitarily inequivalent** vacua). If it just evolved unitarily no further measurement could take place, no conscious act would happen, as these acts are completely identical, indistinguishable. If it tunnels to a universe outside of the set of life compatible states no measurement will be possible either and there is no conscious act. (This may concern most of the states of the multiverse and it is not far fetched to assume that there are infinitesimally many of them - as is the case for the H-atom).
But if our system tunnels to another life friendly state or becomes a mixed state containing at least one state consistent with life (the former being a special case of the latter) then a conscious act again is possible. Upon a conscious act, the life incompatible states are projected out no matter what they are. As unitary evolution alone does not lead to a sequence of conscious acts, we need a change of the state, corresponding to a quantum jump from one energy level to another - consistent with our superselection rule (i.e. life/consciousness) - leading (*Noether's theorem*) to a breaking of *time reversal invariance*. (One could also say that a conscious act induces a slight **symmetry breaking** in our physical universe). This leads to a flow of classical **time** which corresponds to a trajectory in the space of life consistent states and moreover a

change in **entropy**.

What remains to be understood is why we do not experience random jumps within the state space of states consistent with life. Having a look at the H-atom the explanation is at hand: Given the electron is measured to be in a state corresponding with a certain energy. If we assume that the time span between two consecutive conscious acts is smaller than between many of them, then due to the uncertainty relation the energy uncertainty will be larger in the latter case and the probability that a state is further away from the initial state is larger. (In case of the string landscape this means that the compactification of our observed universe only changes slightly between two conscious acts of observers, i.e. a change in the fundamental physical parameters should not be observable to be consistent with observations).
What about the fact that there is not just one observer but many in our universe ? In the most simple case we could decompose our set of life consistent universes into disjoint sets of life consistent universes each one concerning a specific observer. Thus given an observer the situation described above applies to the respective subset. In this case all conscious acts are strictly sequential. But one could also imagine that the subsets overlap such that conscious acts can be "simultaneous" (whatever that means).
It may also be required that there is a "drift" within the set of life friendly states taking into account that the universe evolves towards more intelligence. As the time between two (human) conscious acts is about $1/50\mathrm{s}$ we could ask what the related energy uncertainty is. It turns out that this is the **Planck energy** (indicating that this is the right energy to get tunneling from one vacuum of the multiverse to another one going). One could be afraid that our current universe tunnels far away from its current state in the next step. This may be so. But this tends to be a life unfriendly state and no conscious act will take place there and until that happens the next time no observer will experience time. But still, it could return to a conscious universe quite different from the one we see. Yet quantum mechanics saves the day. The fact that quantum effects are so small (determined by the smallness of **ħ**) and the fact that the energy for the quantum jump is virtual (we have just "borrowed" it and must "give it back") guarantees that after a few conscious acts we must be "back to normal". Thus in fact it is imaginable that once in a while we have freaky conscious acts, totally unrelated to reality, but this seems to be unlikely and the more different from our usually experienced world they are, the less likely they are. (This situation is contrary to the one for **Boltzmann brains** thus avoiding this paradox and related ones).

So given two states of the multiverse one that is life friendly and one that is not, what makes them so substantially different ? In other words if we sort through the 10^{500} vacua of the string landscape, how could we know if a vacuum corresponds with consciousness or not ? I.e. we have to know what exactly our superselection rule is. Or at least, what is the measure of life consistent states in the multiverse.
This seems to be a hard question. What does it mean for a state to be able to do a self-collapse, to project back onto itself ? Probably this requires a proper understanding what exactly the difference between dead and lively matter is.
Although the answer is not clear, nevertheless let's make an attempt to come up with one: First of all, life involves great complexity. Let's assume that this is a necessary condition for life and consciousness. A biological system evolves through many many states and the changes in energy are moderate or small only. If we go back to our atom model, we would like to have a superselection rule which only allows for moderate or small jumps of energy. (Actually the smallness of Planck's constant helps us here and the question is if it could be different in other branches of the landscape - I leave this question to string theoreticians). That is the life friendly subset of states of the multiverse comprises those that have a certain typical mutual energetic separation such that there is enough fine graining needed for energetically small enough changes in our world and with it in its biological subsystems. Seen this way any state of the multiverse is potentially conscious, but for most the sequence of conscious acts does not correspond to a robust classical realization of a biological matter system as the matter part is fluctuating considerably. (Imagine a world with a very large Planck's constant = quantum effects are dominant). Pictorially speaking an ape would have a thought and the next thought would be in the form of a mouse. Maybe life is close to an *attractor* where states are close to each other and therefore with high probability it stays in its vicinity. Physically speaking this may be a *critical point* for which it is well known that complexity arises. (See also *is reality a critical phenomenon ?* and **the ultimate principle of physical reality**). *(What is the density of states at a critical point).*

Is there the possibility of the recurrence of a conscious act of an individuum in this scenario (*reincarnation*) ? First of all, in our atom model be have to assume that the background stays the same, i.e. the H-atom will always be the H-atom and creation and annihilation of particles does not take place. This is a simplification and in case of a relativistic treatment it is not true. So at least we have to include **quantum field theory** to find an answer. But QFT doesn't change the rules of the game of quantum mechanics so one expects the same results in principle, the state space just gets larger when also quantizing the fields. Moreover, physically enlarging the system is not a problem either. It just means that we were ignorant, only considering one H-atom in a H gas for instance.
The real trouble arises when infinities enter the game (see also **is nature infinite ?**) which is suggested when applying quantum field theory (introducing an infinite number of degrees of freedom). Yet it is not clear if they play a fundamental in physics. If a subspace of life compatible universes is infinite but the number of states making me and you possible finite, then when drifting away from them, it gets exceedingly unlikely to

return to them or the set containing them. Mathematically speaking, their measure is 0 and therefore the probability for a return is also 0. But, calculating with infinities is a dangerous and ambiguous thing (e.g. see **Hilbert's hotel** and **measure of the multiverse**) and it is not clear what to make out of that, maybe it's really just a mathematical **idealization**. In fact, if string theory is right and there are "only" 10^{500} vacua this at least suggests that the number of all possible conscious acts is countable and will repeat. (The "string landscape" saves the **soul**).

Coming back to the anthropic principle, how is it to be seen in this scenario ?
The strong anthropic principle just means that the multiverse must contain conscious states (states that can project onto themselves) which given the fact that we are around renders this principle a triviality. The weak anthropic principle says that states that are not consistent with life consistent are observed.

Having said all that, is there a punchline ? Yes,
Consciousness = superselection rule for physical reality. The rest is a theoretical state which cannot be observed.

Miscellanea

- The multiverse can be understood as the most general mathematically consistent partition sum (*partition of 1*). At this level physics is only a mathematical reality (**Platonic realm**). We cannot observe the whole of this state space as most of it is incompatible with life. It exists only on paper because no one can ever be there. Nevertheless, the whole state space may be relevant in the theory in regards to consistency to subspaces that can be observed. This life consistent subspace recruits physical reality which is what is observed and thus is conscious (or at least contains life).

- Conscious also selects the laws in that it selects the phase. E.g. an unbroken phase having a certain symmetry may be incompatible with life as it is too uniform and the latter requires complexity. Therefore for instance certain **gauge symmetries** are preferred by life. So besides the **parameters**, one also expects the laws to be **fine tuned**. E.g. replacing $U(1) \times SU(2) \times SU(3)$ by another gauge symmetry may be incompatible with life or at least it could be in the space of life consistent states so far away from our state that we will never see it. (This sheds light on the fact that laws are the same everywhere around us). In other words, our physical body just cannot make it there without being totally disintegrated - or medically dead in between. If a "reassembled" body can continue its original identity is not clear. This would boil down to reincarnation. It depends on what defines a subset of the state space of the multiverse of me and you. It seems that what defines the boundaries between different conscious selves is rather space than time. But what to make out of that ?

- If one could make the case that life requires **GR** (maybe because of the $1/r^2$ force-law) then due to the **singularity theorems** it would follow that life would have to find itself in a universe (spacetime bubble) with an initial "singularity" (a **Big Bang**).

- So how do we find out the laws of nature, a **TOE** (i.e. theses things that descent from mathematical to physical reality). The answer is, look for what is compatible with life.

- Why the **second law** ? The answer is quite simple: Because of the highly spectacular initial conditions (**low entropy**) in the Big Bang. Yet their origin is still a big riddle.

- Which kind of matter is conscious, which is not ? An ordinary molecule like a benzole ring or a protein are both unconscious as they evolve unitarily only. (That is chemistry organic as well as anorganic is the science of dead matter in the first place). It seems that a macromolecule having the mass of around one Planck mass is the threshold to life and "self-awareness" for the time uncertainty of such a molecule is less than the *Planck time* and it is therefore no longer confined to a certain physical vacuum.

- Concerning the **Wheeler-deWitt equation**, because unitary evolution cannot be detected by observers and has not the same meaning as in a local system where the observer is external, it at least requires field quantization (see *third quantization*) such that vacuum transitions are possible. (Local system, not including the observer = unitary time evolution = 1st quantization. Whole cosmos, including the observer + local system = quantum field = 3rd quantization).

- Why does the world around us appear so robust, immutable, classical ? (Why is it that a stone feels hard and "real" when banged on ones head and experience is so authentical ?) Actually this need not to be so in general, rather it necessary appears so only from the perspective of a usual, classical (non freaky) conscious observer (for which quantum mechanical fluctuations are decent).

- The time we perceive (i.e. thermodynamic or non-unitary/complex time) is defined by a sequence of conscious states. I.e. time is fundamentally "attached" to life. For all we know, a fundamental time step is given by the Planck time. A striking thing is that if one counts the number of such time steps since the Big Bang and multiplies it with one Planck mass one roughly gets the mass of the universe. As we assume that any transition from one vacuum state to another involves life, there have been 10^{60} experiences of lively systems since the Big Bang all in all (which in a way have brought about the current universe).

- The claim is that consciousness or life must always have been around, since the Big Bang to "keep the universe on going" (evolving in classical time). There remains the explanatory gap, what exactly life is in each step that induces the "collapse of the state of the universe", in particular in the early universe. The most straighforward explanation seems to be that our cosmos was initiated by intelligence (see **creating a universe** and **cosmic creation and God**) and there is a continuity in the sequence of lively universes. (This also avoids the bizarre situation one faces in the **participatory model of the universe** where one has to wait for a state reduction until the first observer appears on the scene).

- There are some similarities with other models/explanations of quantum mechanics, e.g. Wheeler's participatory universe, **Langan's CMTU model**, Page's sensible quantum mechanics, **quantum darwinism**, etc. Surprisingly I was not able to find this scenario described in literature so far. Actually it can be seen as yet another interpretation of quantum mechanics. What comes closest to this interpretation are the Von Neumann interpretation of quantum mechanics, Wheeler's participatory universe and Penrose's model of objective state reduction. I am therefore tempted to coin a new name for this interpretation and hence (preliminarily) call it the **Sentient Reality Interpretation of Quantum Mechanics** (**SRI**). Key features are an objective collapse (or better state reduction) and, very importantly, this reduction is global, also involving regions that are spacelike in respect to us (all else wouldn't make sense as any two observers have different *apparent horizons* with nonoverlapping spacelike regions).

- This view of quantum mechanics is reminiscent of a **cellular automaton** with a global time. Each change of the quantum vacuum of the universe corresponds with a global update of the automaton. Moreover if we split up the automaton algorithms into those that "get stuck", i.e. end up in a loop, and those that don't and show complexity and "interesting", unpredictable behaviour, the latter correspond with our physical reality containing the sentient observers. (Based on this analogy the states that don't correspond with physical reality can be interpreted as being those that are "unitarily stuck" in one vacuum, unable to tunnel). The analogy may also suggest that the universe is a **simulation** but the objection to this is that right from the outset we have to consider the most general mathematically consistent state space. Presupposing that no designer is required for the Platonic mathematical world, i.e. that mathematics just is and taking into account that no **designer** is required to bring physical reality into existence, sentient beings do it all by themselves, self-referentially (via "boot strapping of reality" if you like), no designer is needed at all. (Yet this does not preclude the possibility that there is intelligence that designed the spacetime bubble we live in which we call our universe).

- Open questions: Is there just one physical reality and is it connected ? How to include relativity in the description ? Does one have to add it or does it naturally come out of the framework ? A more concrete realisation of the model (the model of **quantum brain dynamics** seems be interesting in this respect and to point in the right direction).

See also:

- *When time stands still*

Your comments are very much appreciated. Suggestions, questions, critique, ... ?

Quantum Neuronal Network

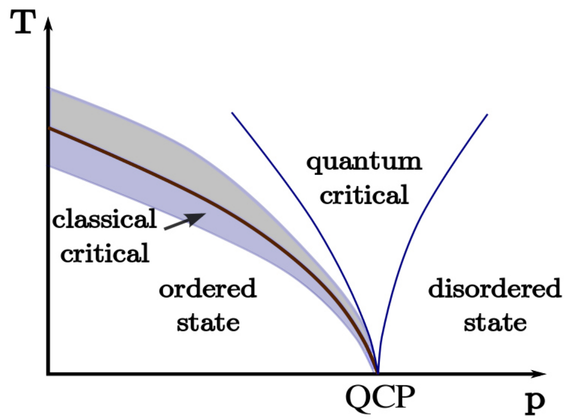
It is an open question what advantages a **Quantum Neural Network** (**QNN**) would have over a classical network. It has been shown that QNNs should have roughly the same computational power as classical networks. Other results have shown that QNNs may work best with some classical components as well as quantum components.
Quantum searches can be proven to be faster than comparable classical searches.

Papers:

- Quantum Neural Networks (2000) - A. A. Ezhov, D. Ventura local pct. 50
- Training a Quantum Neuronal Network (2003) - B. Ricks , D. Ventura local pct. 11

Your comments are very much appreciated. Suggestions, questions, critique, ... ?

Quantum Phase Transition



A **Quantum Phase Transition** (**QPT**) is a quantum **critical phenomenon** which, contrary to a classical **phase transition**, takes place at a zero (absolute) temperature ($T = 0\,\mathrm{K}$), known as **Quantum** *Critical Point* (**QCP**). QPTs are continuous **phase transitions**, where quantum-mechanical phase coherence exists even for the long-wavelength fluctuations that control the transition.

Quantum-critical states are among the most complicated **quantum states** ever studied, and describing them efficiently is an important goal of theoretical studies of quantum criticality. In almost all cases, one cannot even explicitly write down the critical wavefunction; instead, one must usually resort to tools from **quantum field theory** or from numerical simulations to extract the subtle quantum correlations between the constituents.

The quantum-critical state at $g = g_c$ is defined by the ground-state wavefunction, so, strictly speaking, it is present only when the temperature T is at absolute zero. Thus, from an experimental perspective, it may seem that a continuous quantum phase transition, and its exotic **entangled** critical point, is an abstract theoretical idea of little practical interest. However, the influence of the critical point extends over a wide regime in the $T > 0$ phase diagram. That regime of quantum criticality is the key to explaining wide variety of experiments.

Close to $g = g_c$ the ground-state wavefunction has the entangled critical form at lengths smaller than ξ; at longer lengths, the wavefunchon has the noncritical product form. At finite temperatures, the system has another characteristic length: $\hbar c/k_B T$, the characteristic *de Broglie wavelength* of the excitations at the quantum critical point g_c (e.g. c is the spin-wave velocity). When $\xi < \hbar c/k_B T$ (the regions denoted by "quantum critical" in the figure), the wavefunction assumes the product form at a length scale shorter than that at which thermal effects are manifested. So thermal fluctuations excite the noncritical wave and particle states.

The novel quantum-critical region emerges in the opposite limit, when $hc/k_B T < \xi$. Since ξ diverges as $|g - g_c|$ vanishes, the region has a characteristic fan shape. Remarkably, and somewhat paradoxically, the importance of quantum criticality increases with increasing T, far beyond the isolated quantum critical point at $T = 0$. (Yet, once the thermal energy is too large all the arguments here break down; the phase diagram in the figure applies only when T remains smaller enough). Because the de Broglie wavelength is shorter than ξ, thermal fluctuations act directly on the quantum-critical entangled state. Thus one needs a theory of the excitations of the complex critical state and the manner in which they interact with each other.

Critical phenomena in general are associated with the cooperative fluctuations of a large number of microscopic degrees of freedom. However, when the critical point is pushed down to $T = 0$, the divergent length scale is the result of quantum fluctuations, demanded by **Heisenberg's uncertainty principle**, rather than thermal fluctuations.

Understanding **universal behavior** near **Quantum Critical Points** has been a major goal of **condensed matter** physics for at least thirty years.
Most of the important concepts in QPTs arise from the 1-dimensional *Ising model*. And results of this model are believed to be exact.
Some quantum critical points can be understood via mapping to standard classical critical points in one higher dimension, but many of the most experimentally relevant quantum critical points do not seem to fall into this category. Furthermore, even quantum critical points that can be studied using the quantum-

to-classical mapping have important universal features such as frequency-temperature scaling that do not appear at finite-temperature critical points. Quantum phase transitions are responsible for very unusual behavior that cannot be described within traditional theoretical frameworks. In fact, certain aspects of QPTs have been shown to be different from their classical counterparts.

The transition temperature is driven to zero through the application of pressure, chemical doping or magnetic fields. There are a number of materials (such as $CeNi_2Ge_2$) where this occurs serendipitously. More frequently a material has to be tuned to a quantum critical point. Most commonly this is done by taking a system with a second-order phase transition which occurs at finite temperature and tuning it. Tuning a system unavoidably introduces disorder in the material. Disorder can strongly affect QPTs because quantum fluctuations are very sensitive to geometrical constraints.

Examples

- Condensation of bosonic fluids such as **Bose-Einstein condensates**.
- *Superfluid* transition in liquid helium.
- Transitions in **quantum Hall systems**.
- Localization in Si-MOSFETs (metal oxide silicon field-effect transistors).
- **Superconductor**-insulator transition in two-dimensional systems.

Just an idea

As the universe is a very cold place (meaning that the *temperature of the vacuum* is very low), could it be that (part of) its expansion (**inflation**, acceleration due to **dark energy**) is driven by a quantum phase transition ?

Papers:

- Quantum Phase Transition from a Superfluid to a Mott Insulator in a Gas of Ultracold Atoms (2002) - M. Greiner, O. Mandel, T. Esslinger, T. W. Hänsch, I. Bloch local pct. 4310
- Scaling of Entanglement Close to a Quantum Phase Transition (2002) - A. Osterloh, L. Amico, G. Falci, R. Fazio local pct. 1137
- 'Deconfined' Quantum Critical Points (2003) - T. Senthil, A. Vishwanath, L. Balents, S. Sachdev, M. P. A. Fisher local pct. 622
- Quantum Phase Transitions (2003) - M. Vojt local pct. 261
- Quantum Criticality (2005) - P. Coleman, A. J. Schofield local pct. 237
- Chaos and the Quantum Phase Transition in the Dicke Model (2003) - C. Emary, T. Brandes local pct. 235
- Quantum Criticality (2011) - S. Sachdev, B. Keimer local pct. 64 - A highly recommended reading.
- Quantum Phase Transitions and the Breakdown of Classical General Relativity (2001) - G. Chapline, E. Hohlfeld, R. B. Laughlin, D. I. Santiago local pct. 67
- Quantum-critical Relativistic Magnetotransport in Graphene (2008) - M. Müller, L. Fritz, S. Sachdev local pct. 46
- Criticality and Entanglement in Random Quantum Systems (2009) - G. Refael, J. E. Moore local pct. 27
- Cosmological Inflation as a Quantum Phase Transition (1995) - M. Morikawa local pct. 26
- Pressure-Induced Magnetic Quantum Phase Transition in KCuCl (2007) - K. Goto, M. Fujisawa, A. Oosawa, T. Osakabe, K. Kakurai, Y. Uwatoko, H. Tanaka local pct. 1
- Dissipative Quantum Phase Transition in a Quantum Dot (2006) - L. Borda, G. Zarand, D. Goldhaber-Gordon local pct. 1
- Theory of Quantum Critical Phenomenon in Topological Insulator - (3+1)D Quantum Electrodynamics in Solids (2012) - H. Isobe, N. Nagaosa local pct. 0
- Quantum Phase Transition (2002) - G. Zhu local pct. 0

Links:

- WIKIPEDIA - Quantum Phase Transition
- WIKIPEDIA - Quantum Critical Point
- Website Subir Sachdev

Videos:

- Where is the QCP in the Cuprates? (2009) - S. Sachdev

Your comments are very much appreciated. Suggestions, questions, critique, ... ?

Quantum State

> When our knowledge of a system is incomplete, we say that the system is in an impure state, and correspondingly we sometimes refer to a regular state $|\Psi\rangle$ as a pure state. This terminology is unfortunate because a system in an 'impure state' is in a perfectly good quantum state; the problem is that we are uncertain what state it is in - it is our knowledge of the system that's impure, not the system's state.
> - James Binney, David Skinner -

In **quantum mechanics** one distinguishes between a

Pure State, which can be described by a single **ket vector** and a

Mixed State, which is a statistical ensemble of pure states, but cannot be expressed by ket vectors only. Instead, it is described by its associated **density matrix**, which in fact can describe both mixed and pure states, treating them on the same footing.

A criterion for the purity of a quantum state is the **Von Neumann entropy**, which is 0 for a pure state and strictly positive for a mixed state.

There is considerable freedom in choosing the association between the physical states of a system and the corresponding state vectors in **Hilbert space**. It can be shown, however, that all physical phenomena in quantum mechanics can be described by restricting the state vectors to unit **rays**. (A unit ray is the set of all vectors that have unit norm and are related by a phase).

Transformations from one physical state to another are described by operators that act within Hilbert space. **Wigner's theorem** says that these operators can be chosen to be either *unitary* operators or **anti-unitary** operators.

See also:

- **Separable state**

Papers:

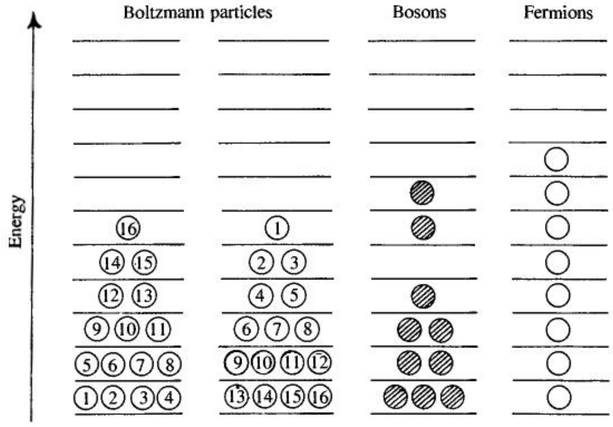
- On the Reality of the Quantum State (2012) - M. F. Pusey, J. Barrett, T. Rudolph local pct. 35

Links:

- WIKIPEDIA - Quantum State

Your comments are very much appreciated. Suggestions, questions, critique, ... ?

Quantum Statistical Mechanics



See also:

- **Bose-Einstein statistics**
- **Fermi-Dirac statistics**

Papers:

- On the Equilibrium States in Quantum Satistical Mechanics (1967) - R. Haag, N. M. Hugenholtz, M. Winnink local pct. 601
- Taking Thermodynamics Too Seriously (2001) - C. Callender local pct. 63

Links:

- WIKIEDIA - Quantum Statistical Mechanics

Your comments are very much appreciated. Suggestions, questions, critique, ... ?

Quantum Statistics

Papers:

- On the Equilibrium States in Quantum Satistical Mechanics (1967) - R. Haag, N. M. Hugenholtz, M. Winnink local pct. 572

Your comments are very much appreciated. Suggestions, questions, critique, ... ?

Quantum Teleportation

Papers:

- Teleporting an Unknown Quantum State via Dual Classical and Einstein-Podolsky-Rosen Channels (1993) - C. H. Bennett, G. Brassard, C. Crepeau, R. Jozsa, A. Peres, W. K. Wootters local pct. 9356
- Quantum Teleportation between Remote Atomic-ensemble Quantum Memories (2012) - X.-H. Bao, X.-F. Xu, C.-M. Li, Z.-S. Yuan, C.-Y. Lu, J.-W. Pan local pct. 10
- Energy-Entanglement Relation for Quantum Energy Teleportation (2010) - M. Hotta local pct. 3
- Quantum Energy Teleportation without Limit of Distance (2014) - M. Hotta, J. Matsumoto, G. Yusa local pct. 0

Links:

- WIKIPEDIA - Quantum Teleportation
- Physicist Discovers How to Teleport Energy (2010)

Your comments are very much appreciated. Suggestions, questions, critique, ... ?

Quantum Tunneling

> Sidney Coleman has taught us that a semiclassical description of quantum tunneling is given by the bounce solution of euclidean field equations (that is, of the field equations with t changed to $-it$).
> - **Alexander Vilenkin** -

See also:

- *Macrosopic quantum tunneling*

Papers:

- Creation of Universes from Nothing (1984) - A. Vilenkin local pct. 451 - "...the universe is created by quantum tunneling from literally nothing. ... This scenario does not require any changes in the fundamental equations of physics; it only gives a new interpretation to a well-known cosmological solution. ... The instanton can be interpreted as describing the tunneling to **de Sitter space** from nothing." - So in fact what **Vilenkin** means is not really nothing - thus no need to get too philosophical here - but a Euclidean domain of spacetime exhibiting **solitonic** behaviour. In other words, if spacetime is described by means of a manifold having two signatures, "nothing" is just the piece of the manifold with the one signature (a.k.a. "false vacuum"). Yet time changes its role (interpretation) upon **crossing from Lorentzian to the Euclidean signature**. (Thus, a bit of philosophy may nevertheless be in place). ERGO: "NOTHING" = EUCLIDEAN SPACE = **QFT** = SOLITON in this case.
- Macroscopic Quantum Tunneling of a Bose-Einstein Condensate with Attractive Interaction (1998) - M. Ueda, A. J. Leggett local pct. 144
- Complex-time path-integral formalism for Quantum Tunneling (1994) - H. Aoyama, T. Harano local pct. 9

Your comments are very much appreciated. Suggestions, questions, critique, ... ?

Quaternionic Quantum Mechanics

> It seems fair to say that ... the structure of the current quaternionic models for quantum theories is not (yet) rich enough to accomodate dreams that extend beyond the complex Hilbert space formalism.
> - S. L. Adler [1] -

Papers:

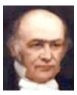
- Quaternionic Quantum Field Theory (1986) - S. L. Adler local pct. 48 - With quaternionic Lagrangians, Hamiltonians and **path integrals** ! - prl. 10
- A Relativistic Quaternionic Wave Equation (2006) - C. Schwartz local pct. 9 pct. 48
- [1] A Rejoinder on Quaternionic Projective Representations (1997) - S. L. Adler, G. G. Emch local pct. 7
- Quaternionic Quantum Mechanics and Noncommutative Dynamics (1996) - S. L. Adler local pct. 7

Theses:

- Non-Commutative Methods in Quantum Mechanics (1997) - A. C. Millard local tct. 4

Google books:

- Quantum Mechanics of Fundamental Systems (1988) - C. Teitelboim bct. 55



Your comments are very much appreciated. Suggestions, questions, critique, ... ?

Qubit

A **Qubit** is a 2-state quantum system.

See also:

- **3-qubit state**
- *4-qubit state*

Papers:

- The Geometry of a Qubit (2007) - M. Ozols local pct. 0

Your comments are very much appreciated. Suggestions, questions, critique, ... ?

Ray

In **quantum mechanics** a **Ray** is a set of normalized vectors (i.e. $\langle\Psi|\Psi\rangle = 1$) with Ψ and Ψ' belonging to the same ray if $\Psi' = \lambda\Psi$ for any $\lambda \in \mathbb{C}$ with $|\lambda| = 1$.

Your comments are very much appreciated. Suggestions, questions, critique, ... ?

Relational Quantum Mechanics

Relational Quantum Mechanics (**RQM**) is an interpretation of quantum mechanics which treats the state of a quantum system as being observer-dependent.

Papers:

- Relational Quantum Mechanics (1997) - C. Rovelli local pct. 241

Links:

- WIKIPEDIA - Relational Quantum Mechanics

Your comments are very much appreciated. Suggestions, questions, critique, ... ?

Relativistic Quantum Information

> Studying relativistic quantum information is the closest we can get to Star Trek.
> - [1] -

In the field of **Relativistic Quantum Information** (**RQI**) a main goal is to find suitable ways to store and process information using quantum systems in relativistic settings. The vantage point of these investigations is that the world is fundamentally both quantum and relativistic.

Some questions in RQI theory:

- Can one perfectly **teleport** a **quantum state** between two observer moving at relativistic speeds relative to one another? Or observer accelerating relative to one another?
- Does anything change if quantum teleportation takes place in the presence of a **gravitational field** such as the earth's or the one of a **black hole** ?
- Does gravity have effects on **entanglement** or other quantum properties ?
- Can quantum information say anything about the **information loss paradox** in black holes ?

Although relativistic **quantum field theory** and non-relativistic quantum information theory are well established fields, exploring the connection between the two was only begun recently.

Papers:

- Quantum Communication in Rindler Spacetime (2011) - K. Brádler, P. Hayden, P. Panangad local pct. 13

Links:

- [1] Facebook - Relativistic Quantum Information

Videos:

- Perimeter Institute - Relativistic Quantum Information (2012)
- Quantum Information Processing in Spacetime - I. Fuentes - A good introduction to the field. -

Your comments are very much appreciated. Suggestions, questions, critique, ... ?

Schwinger-Keldysh Formalism

The **Schwinger-Keldysh Formalism**, or **Close-time-path Formalism** is a real-time formulation of **finite temperature field theory**.
It uses a closed path in the *complex-time* plane such that the contour goes along the real axis and then back.
From this procedure an effective doubling of the degrees of freedom emerges, such that the **Green functions** are represented by 2×2 matrices.

The technique applies to equlibrium as well as **non-equilibrium systems**.
It has been used for problems in *statistical physics* and **condensed matter theory** such as

- spin systems,
- **superconductivity**,
- lasers,
- **tunneling** and secondary emission,
- plasmas,
- transport processes,
- **symmetry breaking**.

Papers:

- Equilibrium and Nonequilibrium Formalisms Made Unified (1985) - K Chou, Z Su, B Hao, L Yu local pct. 766
- Schwinger-Keldysh Propagators from AdS/CFT Correspondence (2003) - C. P. Herzog, D. Thanh Son local pct. 239

Your comments are very much appreciated. Suggestions, questions, critique, ... ?

Separable State

Separable States are **quantum states** without **quantum entanglement**.

Links:

- WIKIPEDIA - Separable State
- WIKIPEDIA - Product State

Videos:

- Quantum Mechanics Lecture 16 (2010) - J. Binney

Your comments are very much appreciated. Suggestions, questions, critique, ... ?

Statistical Operator

The **Statistical Operator** or **Density Operator** $\hat{\rho}$ allows for the description of a **quantum system** being in a **pure** as well as in a mixed state.

Given a set of pure states $|\Psi_i\rangle$, it can be defined according to

$$\hat{\rho} \equiv \sum_i p_i \, |\Psi_i\rangle \, \langle\Psi_i|$$

where p_i denotes the probability of the system being in the state Ψ_i. $|\Psi_i\rangle \, \langle\Psi_i|$ is the *projection operator* onto the respective state.

Properties

- $\hat{\rho}$ is **hermitesch**.
- Its time evolution is given by the **von Neumann equation**.

Links:

- WIKIPEDIA - Dichtematrix

Your comments are very much appreciated. Suggestions, questions, critique, ... ?

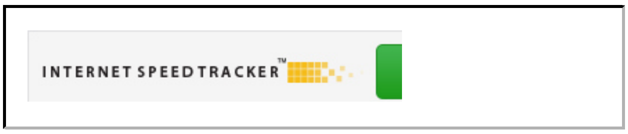
Strangeness

Strangeness is one of the *flavour* quantum numbers of quarks.

Links:

- WIKIPEDIA - Strangeness

Videos:



Your comments are very much appreciated. Suggestions, questions, critique, ... ?

Supersymmetric Quantum Mechanics

> Whether it is just simply a theoretical musing or it is actually realized in nature is not clear, since no single experimental evidence of SUSY has been found so far. But as an upshot of the work carried out in this field, powerful mathematical tools and tantalizing insights has been obtained. In particular, SUSY QM was initially developed as a toy model for testing the breaking of supersymmetry.
> - Adolfo del Campo [1] -

See also:

- **Supersymmetry**
- **Quantum mechanics**

Papers:

- Supersymmetry and Quantum Mechanics (1994) - F. Cooper, A. Khare local pct. 1333
- Supersymmetry in Quantum Mechanics (1985) - R. W. Haymaker, A. R. P. Rau local pct. 131
- [1] Supersymmetric Quantum Mechanics SUSY QM (2005) - A. del Campo local pct. 0

Links:

- WIKIPEDIA - Supersymmetric Quantum Mechanics

Your comments are very much appreciated. Suggestions, questions, critique, ... ?

Time Operator

See also:

- **Time operator**

Papers:

- Principles of Discrete Time Mechanics: I. Particle Systems (1997) - G. Jaroszkiewicz, K. Norton local pct. 48
- Principles of Discrete Time Mechanics: IV. The Dirac Equation, Particles and Oscillons (1997) - K. Norton, G. Jaroszkiewicz local pct. 7

Your comments are very much appreciated. Suggestions, questions, critique, ... ?

Transition Amplitude

The **Transition Amplitude** $T_{i \to f}$ between an initial **state** $|i\rangle$ and a final state $|f\rangle$ is given by

$$T_{i \to f} = \langle f | i \rangle$$

Note, that $T_{i \to f} \in \mathbb{C}$.
The probability of a transition, which is what can be measured, is the the square of modulus, $|T_{i \to f}|^2 \in \mathbb{R}$.

Papers:

- Transition Probabilities and Measurement - Statistics of Postselected Ensembles (2003) - T. Fritz local pct. 0

Lectures:

- Quantum Field Theory I (2006) - C. Wetterich local

Your comments are very much appreciated. Suggestions, questions, critique, ... ?

Unitary Inequivalence

> ... the analogue of the Stone-von Neumann uniqueness theorem for infinitely many degrees of freedom is false; indeed, in that case, there is an enormously infinite number of unitarily inequivalent representations of the CCR in the Weyl form and, therefore, also of the original CCR. This fact was only slowly and painfully realized, because physicists choose to ignore the restriction in the hypothesis of the Stone-von Neumann uniqueness theorem.
> - Stephen J. Summers -

> Perhaps the single most important problem in the foundations of QFT is the problem of inequivalent representations.
> - David John Baker -

Unitary Inequivalence occurs in systems having an **infinite number of degrees of freedom**.
There are uncountably infinitely many **Unitarily Inequivalent Irreducible Representations** (**URIs**) of the CCRs (see **Heisenberg algebra**) in this case and the choice of proper representation is crucial in any physical application.
It has become clear from rigorous study of concrete models in **constructive quantum field theory** that bosonic systems with identical kinematics but physically distinct dynamics (i.e. when considering forces) require inequivalent representations of the CCRs. Roughly speaking, the kinematical aspects determine the choice of Heisenberg algebra, whereas the dynamics fix the choice of the representation of the given Heisenberg algebra in which to make the relevant, perturbation-free computations. (It is also believed - and proven in a number of indicative special cases - that perturbation series in one representation provide divergent and at best asymptotic approximations to the physically relevant quantities in another, unitarily inequivalent representation).

Different kinds of infinities

A representation of the CCRs can be realized in terms of *creation- and annihilation operators* (satisfying certain (anti-)commutation relations). A (diagonalized) state in this representation is given by

$$|n_0, n_1, \ldots, n_k, \ldots \ldots\rangle$$

where $k \in \mathbb{N}$ and $n_k \in \mathbb{N}$ for bosons and $n_k \in \{0, 1\}$ for fermions. k denotes the degrees of freedom alluded to above.
The set of all states will be denoted Γ.

Therefore, the overall number of possible states has **cardinality** $\aleph_0^{\aleph_0} = \aleph_1$ for bosons and $2^{\aleph_0} = \aleph_1$ for fermions. In any case, the cardinality is that of the **continuum**, $\aleph_1$, i.e. the number of states is uncountably infinite. (See also: **Cantor's diagonal argument**).
Since the number of states is non-denumerable, a **separable Hilbert space** cannot be constructed from Γ

and the **Stone-Von Neumann theorem** does not hold. This is where the fundamental difference of **quantum mechanics** and **quantum field theory** lies ! (Actually Q.M. is contained in QFT and the latter is the much broader framework).

Contrary to this, for systems with a finite number of degrees of freedom $k \equiv k_0 < \infty$, the overall number of possible states is $\aleph_0^{k_0} = \aleph_0$ for bosons and even less for fermions. A crucial difference !

Let Γ_0 be the set which contains only a finite number of particles, $\left\{|n_0, n_1, \ldots, n_k, \ldots\ldots\rangle : \sum_{k=0}^{\infty} n_k < \infty\right\}$. (Note, that the number of degrees of freedom is still infinite).
This set of vectors contains the **vacuum** state which has no particles: $|0, 0, 0, \ldots\rangle$ and it spans a Hilbert space in the **Fock space** representation. Its number of basis vectors is countable infinite as the number of degrees of freedom is so.
This is the Hilbert space containing the "bare", "undressed" vacuum. Any other unitarily inequivalent space has an infinite number of particles as seen from this distinguished space.
The reason is this: Applying a finite sequence of creation or annihilation operations to a state will lead to a state that is still within the original Hilbert space.
The application of an infinite sequence of such operations can only annihilate a finite number of already excited states, leaving an infinite number of creation and annihilation operations. If not only a finite number of them are not mutually generating and annihilating particles, one must have an infinite number of particle creations.

On the set $\{\bar{\Gamma}_0\}$ (the complement of $\{\Gamma_0\}$) an equivalence relation can be defined such that each equivalence class $[\bar{\Gamma}_0]$ contains all sequences that differ only in a finite number of places. The set of these equivalence classes $\{[\bar{\Gamma}_0]\}$ is non-denumerable. The vectors corresponding to the sequences in an equivalence class can be used as the basis to construct a Hilbert space. Thus, by defining the creation and annihilation operators on these Hilbert spaces one can build a continuum of UIRs of the CCRs (or CARs = Canonical anticommutation relations) from $\{[\bar{\Gamma}_0]\}$ that are unitarily inequivalent to the Fock representation and among each other.

The non-Fock representations of $\{\bar{\Gamma}_0\}$ are also sometimes called **Myriotic Representations**, describing a quantized field that has creation and annihilation operators satisfying specified commutation rules, but no vacuum state.

Another way to explain the reason that there are an uncountable number of UIRs is that there are an uncountable number of ways of choosing a countable subset from an uncountable set.

Not surprisingly, unitary inequivalence has a deep implications for the **philosophy of physics**, in particular that of quantum field theory.

Flat spacetime

There is a distinguished Hilbert space, namely the one which contains the zero particle state. Does this correspond with a flat spacetime ? What speaks for this is that it is the Hilbert space that high energy physicists like to use, who usually don't care about **gravity** and curvature. One uses this space for the "in-" and "out-states" assuming that the incoming and outgoing particles come from and go to a Minkowski vacuum. (Yet given the known global geometry of spacetime, this can at best be a very good approximation - which in fact it is, as is demonstrated by innumerous (scattering) experiments in high energy physics). The states involving the interactions are encoded by the **S-matrix**. Due to **Haag's theorem** these must "live" in another Hilbert space which presumably then is unitarily inequivalent to the one of the in- and out states. That is to say that one could think of forces, bringing in the dynamics, as introducing as key element, non-unitarity, resulting in virtual particles, "dressed" physical values, infinities, etc. This situation can be brought under control by parameterizing the *coupling constants* and carrying out **renormalization**. Does this mean that following the **renormalization group** flow means "running" through unitarily inequivalent Hilbert spaces (= "running of the coupling constants") ?
Also, in this scenario there seems to be no hope for constructing a theory of **quantum gravity** in a single Hilbert space. (Interestingly it has been shown (Stelle, 1977) that gravity in fact is renormalizable, if one dispenses with unitarity).
To be consequent, one had to include gravity in the S-matrix, but then the usual procedure doesn't go through because there are no free in- and out states any more. Rather, the whole universe had to serve as the object to be scattered at - quite of an oddity though. (Here it may be good advice to ask condensed matter physicists, who face similar situations in the laboratory, e.g. **phase transitions**).
Another picture that arises is that in the conventional approach the in- and out states at "unitary infinity", which are the ones that are measured, are **"collapsed" states** which correspond with particles, whereas the states in between, described by the S-matrix, are virtual particles, those are the particles involving forces/dynamics, etc. An interesting question that arises is this: It seems that short range forces are less problematic than long range ones, as if one goes far enough away from the spot of interactions the former

are negligible for all practical purposes. This is why gravity may pose a problem. But then, why is quantum electrodynamics so successful ? (Yet, in fact, it is known that there are also problems with this theory in very high orders, where presumably it breaks down).

Some further thoughts

As QFT is based on the continuum whereas an ordinary computer (also a **quantum computer**, as it can be mapped to a Turing machine) is based on a sequence of no more than a countably infinite number of calculation steps (thereby facing the **halting problem**), the issue of **noncomputability** of the **conscious brain** (e.g. advocated by **Roger Penrose**) comes to mind.
If consciousness really encompasses unitarily inequivalent vacua, then it would easily outperform any Turing machine. (In fact modelling the brain by means of QFT seems to be feasible - see **quantum brain dynamics**). If this were so, to achieve true **AI** one had to harness QFT.
This would also imply that **quantum consciousness**, merely based on quantum mechanics, does not work. It therefore may be interesting to think about how to built a computer based on QFT, a **quantum field computer**.

Unitary inequivalence may also be related to a **gravitationally induced state reduction** in the context of consciousness (e.g. "**Orch-OR reduction**").

... to be continued ...

Papers:

- Representations of the Anticommutation Relations (1954) - L. Gårding, A. Wightman local pct. 101
- Representations of the Commutation Relations (1954) - L. Gårding, A. Wightman local pct. 83
- Clifford Geometric Parameterization of Inequivalent Vacua (1997) - B. Fauser local pct. 21
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- Unitarily Inequivalent Representations in Algebraic Quantum Theory (2005) - FM Kronz, T. A Lupher local pct. 9
- Goldstone Theorem, Hugenholtz-Pines Theorem and Ward-Takahashi Relation in Finite Volume Bose-Einstein Condensed Gases (2005) - H. Enomoto, M. Okumura, Y. Yamanaka local pct. 6
- On Representations of Finite Type (1998) - R. V. Kadison local pct. 1
- How to Construct Unitarily Inequivalent Representations in Quantum Field Theory - T. Lupher local pct. 0
- Quantum Phase Transition, Dissipation, and Measurement (2009) - S. Chakravarty local pct. 0

Theses:

- The Philosophical Significance of Unitarily Inequivalent Representations in Quantum Field Theory (2008) - T. A. Lupher local tct. 2 trl. 10
- Quantum Field Theory and Phase Transitions - Symmetry Breaking and Unitary Inequivalence (2010) - D. Sánchez de la Peña local

Links:

- Website of Tracy Lupher

Your comments are very much appreciated. Suggestions, questions, critique, ... ?

Von Neumann Equation

The **Von Neumann Equation** which is the quantum analogue of the *Liouville equation* is given by

$$\dot{\rho} = -\frac{i}{\hbar}[H, \rho]$$

where H is the Hamilton operator.

Your comments are very much appreciated. Suggestions, questions, critique, ... ?

Weak Measurement

Papers:

- How the Result of a Measurement of a Component of the Spin of a Spin- ½ Particle Can Turn Out to be 100 (1988) - Y. Aharonov, D. Z. Albert, L. Vaidman local pct. 923

Links:

- WIKIPEDIA - Weak Measurement

Videos:

- Weak Values: Their Meaning and Uses in Quantum Foundation (2013) - H. M. Wiseman

Your comments are very much appreciated. Suggestions, questions, critique, ... ?

Wigner's Friend

See also:

- **Schrödinger's cat**
- **Heisenberg cut**
- **Collapse of the wavefunction**

Links:

- WIKIPEDIA - Wigner's Friend

Videos:

- Die Quantenmechanische Bedeutung des Begriffes Realität (1982) - E. Wigner - Wigner explains Wigner's friend.

Your comments are very much appreciated. Suggestions, questions, critique, ... ?

Wigner's Theorem

Wigner's (Unitary-Antiunitary) Theorem states that every **ray** transformation on a **Hilbert space** H which preserves the transition probabilities can be lifted to a (linear) unitary or a (conjugate-linear) antiunitary operator on H.

Papers:

- A Note on Wigner's Theorem on Symmetry Operations (1964) - V. Bargmann local pct. 190

Links:

- WIKIPEDIA - Wigner's Theorem
- WIKIPEDIA - Antiunitary Operator

Your comments are very much appreciated. Suggestions, questions, critique, ... ?