Problem of Time

From standard quantum mechanics to quantum gravity

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Overview

Properties ascribed to time

Time is what prevents everything happening at once.

(John Wheeler)

- Some relevant aspects of what time means include the following properties

Edward Anderson. "Problem of time in quantum gravity". In: *Annalen der Physik* 524.12 (2012), pp. 757–786.

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  1. Time as an ordering: notion of present that separates future and past notions
  2. Causation: one phenomenon at an earlier time brings about another phenomenon at a later time
  3. Temporal logic: basic logic with "and then"and "at a time t"constructs

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  4. Change in time: a parameter with respect to which change is manifest
  5. Modeled by the real line
  6. Habitually taken to be monotonic

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  8. A good timefunction is globally valid
  9. Must be operationally meaningful

Edward Anderson. "Problem of time in quantum gravity". In: *Annalen der Physik* 524.12 (2012), pp. 757–786.

Fundamental problem of time

- Physical theory of time carries three fundamental problems

Stephen M Barnett and John A Vaccaro. *The Quantum Phase Operator: A Review*. Taylor & Francis, 2007.

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- Physical theory of time carries three fundamental problems
  1. Asymmetry of the "direction of time"
  2. Travelling backwards through time does not appear to be precluded by current physical theories
  3. **Lack of a consistent quantum description**

Stephen M Barnett and John A Vaccaro. *The Quantum Phase Operator: A Review*. Taylor & Francis, 2007.

Lack of a consistent quantum description

- poses a fundamental problem in quantum mechanics
- leads to a number of problems when trying to replace general relativity and quantum theory with a single framework

Edward Anderson. “Problem of time in quantum gravity”. In: *Annalen der Physik* 524.12 (2012), pp. 757–786.

Bryce S DeWitt. “Quantum theory of gravity. I. The canonical theory”. In: *Physical Review* 160.5 (1967), p. 1113.

John Archibald Wheeler and Cécile DeWitt-Morette. *Battelle rencontres: 1967 Lectures in mathematics and physics*. WA Benjamin, 1968.

Chris J Isham et al. *Quantum gravity 2: a second Oxford symposium*. Oxford University Press, USA, 1981.

KV Kuchař and CG Torre. *Conceptual Problems of Quantum Gravity ed A Ashtekar and J Stachel*. 1991.

Carlo Rovelli. *Quantum gravity*. Cambridge university press, 2004.

L Smolin. “Problem of Time Course, available in video form at http://pirsa. org”. In: *C08003* (2008).

History of the quantum time problem (QTP)

Heisenberg's uncertainty relations

There are limitations on the possible accuracy of measurements

$$\Delta x \Delta p \geq \frac{\hbar}{2} \qquad \Delta E \Delta t \geq \frac{\hbar}{2}$$

- Consequence of replacing classical numbers by operators
- Time-energy uncertainty principle is accepted as valid event though it is not deduced from the commutation relation of operators

Yakir Aharonov and David Bohm. "Time in the quantum theory and the uncertainty relation for time and energy". In: *Physical Review* 122.5 (1961), p. 1649.

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- Different types of time–energy uncertainty relation can be deduced in specific contexts (can be summarized into 8 different interpretations)
- No unique universal relation that could stand on equal footing with the position–momentum uncertainty relation

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Paul Busch. "The time–energy uncertainty relation". In: *Time in quantum mechanics*. Springer, 2008, pp. 73–105.

Heisenberg's uncertainty relations

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$$\Delta x \Delta p \geq \frac{\hbar}{2} \qquad \Delta E \Delta t \geq \frac{\hbar}{2}$$

Pauli's theorem:

- It is generally impossible to construct a self-adjoint time operator $\hat{T}$, that is canonically conjugate with the Hamiltonian
- The spectrum of the Hamiltonian must always be continuous and unbounded from below

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W. Pauli. *Handbuch der Physik*. Ed. by H. Geiger and K. Scheel. 1st. Vol. 23. Springer, 1926, pp. 1–278.

Non-parametric aspect of time

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- Tunneling time: time it takes to emerge on the other side of a potential barrier
- Escape time: time it takes to escape the potential well

Interference in time

Lindner experiment

The double slit is realized in the time-energy domain where the role of the slits is played by windows in time of attosecond duration.

- Nonrelativistic Schrodinger theory cannot be used to predict interference phenomena in time
- Implies the existence of a time observable

F. Lindner et al. "Attosecond Double-Slit Experiment". In: *Phys. Rev. Lett.* 95 (4 July 2005), p. 040401.

Lawrence P Horwitz. "Quantum interference in time". In: *Foundations of Physics* 37.4-5 (2007), pp. 734–746.

Time as a quantum observable

E. A. Galapon and P. C. M. Flores. "Time and particles". In: *In preparation* ().

Time as a quantum observable

Weak form of the quantum time problem

Is the result of any measurement of time involving a quantum object, such as time of arrival (TOA) and tunneling time of a quantum particle, describable in terms of a resolution of the identity?

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Time as a quantum observable

Weak form of the quantum time problem

Is the result of any measurement of time involving a quantum object, such as time of arrival (TOA) and tunneling time of a quantum particle, describable in terms of a resolution of the identity?

Strong form of the quantum time problem

Is every time measurement distribution derivable from a time operator? Or does time measurement distribution has an underlying ideal distribution generated from a time operator?

E. A. Galapon and P. C. M. Flores. "Time and particles". In: *In preparation* ().

Perspectives on the QTP

The weak and strong forms of the quantum time problem are not equivalent.
$\Rightarrow$ How is time treated in quantum mechanics?.

Eric A Galapon, Roland F Caballar, and Ricardo T Bahague Jr. "Confined quantum time of arrivals". In: *Physical review letters* 93.18 (2004), p. 180406.

V Delgado and JG Muga. "Arrival time in quantum mechanics". In: *Physical Review A* 56.5 (1997), p. 3425.

Norbert Grot, Carlo Rovelli, and Ranjeet S Tate. "Time of arrival in quantum mechanics". In: *Physical Review A* 54.6 (1996), p. 4676.

Paul Busch; Marian Grabowski; Pekka Lahti. *Operational quantum physics*. Lecture notes in physics., New series m„ Monographs ;, m31. Springer, 2001.

Marco Toller. "Localization of events in space-time". In: *Physical Review A* 59.2 (1999), p. 960.

Riccardo Giannitrapani. "Positive-operator-valued time observable in quantum mechanics". In: *International Journal of Theoretical Physics* 36.7 (1997), pp. 1575–1584.

Harald Atmanspacher and Anton Amann. "Positive-operator-valued measures and projection-valued measures of noncommutative time operators". In: *International Journal of Theoretical Physics* 37.2 (1998), pp. 629–650.

1. Accept Pauli's theorem

It is not a property of a system in the same way as spin and mass are properties of a system. As such time is not a dynamical observable of a given system and not subject to the laws of quantum measurement theory. In particular, no time operator exists in the same way that a position or a momentum operator exists.

E. A. Galapon and P. C. M. Flores. "Time and particles". In: *In preparation* ().

Asher Peres. "Measurement of time by quantum clocks". In: *American Journal of Physics* 48.7 (1980), pp. 552–557.

Yakir Aharonov, Peter G Bergmann, and Joel L Lebowitz. "Time symmetry in the quantum process of measurement". In: *Physical Review* 134.6B (1964), B1410.

Yakir Aharonov and Lev Vaidman. "The two-state vector formalism: an updated review". In: *Time in quantum mechanics.* Springer, 2008, pp. 399–447.

An extensive review is subject for future work

2. Disprove Pauli's theorem

It must be represented by an operator in the system Hilbert space and the distribution of measurement is dictated by the resolution of the identity provided by the operator. It is not only that time is an operator but that it has the additional property of being canonically conjugate with the system Hamiltonian such that it evolves in step with the parametric time, i.e. time observables are time operators.

E. A. Galapon and P. C. M. Flores. "Time and particles". In: *In preparation* ().

An extensive review is subject for future work

3. Bypass Pauli's theorem

In this view, it is possible that the aspect of time under consideration is represented by an operator but not necessarily conjugate to the Hamiltonian. Or that time measurement must always be taken in context with other systems such as a measuring instrument.

E. A. Galapon and P. C. M. Flores. "Time and particles". In: *In preparation* ().

Gordon R Allcock. "The time of arrival in quantum mechanics I. Formal considerations". In: *Annals of physics* 53.2 (1969), pp. 253–285.

Gordon R Allcock. "The time of arrival in quantum mechanics II. The individual measurement". In: *Annals of Physics* 53.2 (1969), pp. 286–310.

GR Allcock. "The time of arrival in quantum mechanics III. The measurement ensemble". In: *Annals of Physics* 53.2 (1969), pp. 311–348.

An extensive review is subject for future work

4. Time is multifaceted.

It has several aspects so that it is not expected that the same treatment applies to them all. This view accommodates the possibility that time can be a parameter labeling the system, a dynamical observable, and a measurable quantity but not necessarily represented by a time operator.

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- quantum time
- coordinate time
- time of arrival
- Wheeler-DeWitt time
- Leibniz time
- time and memory

E. A. Galapon and P. C. M. Flores. “Time and particles”. In: *In preparation* ().

An extensive review is subject for future work

Space and time on equal footing

The wavefunctions $\psi(x, t)$ is a square-integrable function over spatial variables parametrized by an external time t.

- The probability that an event will take place at (x, t) in a frame S should be equal to the probability that the same event will happen at (x', t') in a frame S'

Lawrence P Horwitz. *Relativistic quantum mechanics*. Vol. 180. Springer, 2015, pp. 1–7.

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- t' is no longer a parameter because it is dependent on both x and t
- The transformed function loses its interpretation as the description of a state because Hilbert spaces associated with different times are distinct

Lawrence P Horwitz. *Relativistic quantum mechanics*. Vol. 180. Springer, 2015, pp. 1–7.

Relativistic canonical commutation relations

Covariant commutation relation

We should expect that the Heisenberg uncertainty relations can be written in a compact form

$$[\hat{x}^{\mu}, \hat{p}^{\nu}] = -i\hbar g^{\mu\nu}$$

where, $g^{\mu\nu} = \mathrm{diag}(1, -1, -1, -1)$.

- The time operator is supposed to be the x^0 component of the 4-position operator $\hat{x}^{\mu}$.
- The Hamiltonian is supposed to be the p^0 component of the 4-momentum operator $\hat{p}^{\nu}$.

Hrvoje Nikolić. "Time in relativistic and nonrelativistic quantum mechanics". In: *International Journal of Quantum Information* 7.03 (2009), pp. 595–602.

Localization problem

Consists of finding the operator representative of the 4-position and/or its eigenstates.

- Such an operator should be able to simultaneously answer when and where a particle is
- Solutions of the Klein-Gordon and Dirac equations cannot provide a well-defined local probability distribution

Andrés J Kálnay. "The localization problem". In: *Problems in the Foundations of Physics*. Springer, 1971, pp. 93–110.

Juan León. "Time-of-arrival formalism for the relativistic particle". In: *Journal of Physics A: Mathematical and General* 30.13 (1997), p. 4791.

Lawrence P Horwitz. *Relativistic quantum mechanics*. Vol. 180. Springer, 2015, pp. 1–7.

Theodore Duddell Newton and Eugene P Wigner. "Localized states for elementary systems". In: *Reviews of Modern Physics* 21.3 (1949), p. 400.

Covariant canonical commutation relations

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where, $g^{\mu\nu} = \mathrm{diag}(1, -1, -1, -1)$.

- Consider a transformation to a primed frame moving with velocity v in the x-direction
- Low-energy: (ignore QED corrections)
  - What happens to the transformation connecting the operators in the two frames?
  - Are the commutators invariant?

Frank R Tangherlini. "Canonical commutation relations and special relativity". In: *Physica Scripta* 77.6 (2008), p. 065008.

What if time is still an external parameter?

N-particle system

Consider a system composed of N particles, and let the coordinates of each particle be $r_1, r_2, \ldots, r_N$. The probability amplitude of the system is $|\psi(t, r_1, \ldots, r_n)|^2$.

- Contradiction with the relativity of simultaneity
- In another reference system, all particles in the system would no longer share a common time coordinate
- The original Hamiltonian would no longer correspond to the total energy

ZY Wang, B Chen, and CD Xiong. "Time in quantum mechanics and quantum field theory". In: *Journal of Physics A: Mathematical and General* 36.18 (2003), p. 5135.

Sin-Itiro Tomonaga – Nobel Lecture. NobelPrize.org. Nobel Media AB 2020. Tue. 20 Oct 2020. <https://www.nobelprize.org/prizes/physics/1965/tomonaga/lecture/>

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Many-time theory:

- Separate time coordinate for every particle
- Can compute probability that particle 1 is at r_1 at time t_1, etc.
- Space coordinates can be taken as dynamic variables while the time coordinate cannot

Paul Adrien Maurice Dirac. "Relativistic quantum mechanics". In: *Proceedings of the Royal Society of London* 136.829 (1932), pp. 453–464.

Felix Bloch and Arnold Nordsieck. "Note on the radiation field of the electron". In: *Physical Review* 52.2 (1937), p. 54.

Recap of QFT:

- In standard quantum mechanics, position is an operator while time is a parameter
- We are now presented with two options:
  1. promote time to an operator
  2. demote position to a parameter

Recap of QFT:

$\Rightarrow$ **operators:** $\hat{x}, \hat{p} \longrightarrow \hat{\Psi}(x,t), \hat{\Pi}(x,t)$
$\Rightarrow$ **canonical commutation relations:**

$$[\hat{x}, \hat{p}] = i\hbar \longrightarrow \left[\hat{\Psi}(x,t), \hat{\Pi}(x',t)\right] = i\hbar\delta(x - x')$$

$\Rightarrow$ **are there no problems regarding time in QFT?**
the time-energy uncertainty manifests itself as the phase-number uncertainty

Number-phase uncertainty

Phase operator

The existence of a Hermitian phase operator $\hat{\phi}$ was first postulated by Dirac in his description of the quantized electromagnetic field.

- The creation and annihilation operators were factored in the following form

$$\hat{a} = \exp\left(i\hat{\phi}\right)\sqrt{\hat{N}} \qquad \hat{a}^{\dagger} = \sqrt{\hat{N}}\exp\left(-i\hat{\phi}\right)$$

- It follows that $\left[\hat{N}, \hat{\phi}\right] = i\hbar$

DT Pegg and SM Barnett. “Unitary phase operator in quantum mechanics”. In: *EPL (Europhysics Letters)* 6.6 (1988), p. 483.

Paul Adrien Maurice Dirac. “The quantum theory of the emission and absorption of radiation”. In: *Proceedings of the Royal Society of London. Series A, Containing Papers of a Mathematical and Physical Character* 114.767 (1927), pp. 243–265.

Number-phase uncertainty

Phase operator

The existence of a Hermitian phase operator $\hat{\phi}$ was first postulated by Dirac in his description of the quantized electromagnetic field.

- The approach has two problems:
  1. The operator $\exp\left(i\hat{\phi}\right)$ is not unitary
  2. The number operator has a spectrum bounded below

  $\Rightarrow$ these are the same problems encountered by the time operator which led Pauli to the conclusion of the non-existence of a time operator

DT Pegg and SM Barnett. “Unitary phase operator in quantum mechanics”. In: *EPL (Europhysics Letters)* 6.6 (1988), p. 483.

Christopher Gerry, Peter Knight, and Peter L Knight. *Introductory quantum optics*. Cambridge university press, 2005.

Super many time theory

An extension of Dirac's many time theory to quantum field theory was done by Tomonaga

$\Rightarrow$ was able to show that infinities in the field theory of the electron and electromagnetic fields, and quantum electrodynamics can be regarded as a correction to the mass and energy of electrons

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S. Tomonaga. "On a Relativistically Invariant Formulation of the Quantum Theory of Wave Fields". In: *Progress of Theoretical Physics* 1 (2 Feb. 1949).

Sin-itiro Kanesawa Suteo; Tomonaga. "On a Relativistically Invariant Formulation of the Quantum Theory of Wave Fields. IV *". In: *Progress of Theoretical Physics* 3 (1 Jan. 1950).

S.-i. Kanesawa S.; Tomonaga. "On a Relativistically Invariant Formulation of the Quantum Theory of Wave Fields. V: Case of Interacting Electromagnetic and Meson Fields". In: *Progress of Theoretical Physics* 3 (1 Mar. 1948).

Sin-Itiro Tomonaga – Nobel Lecture. NobelPrize.org. Nobel Media AB 2020. Tue. 20 Oct 2020. <https://www.nobelprize.org/prizes/physics/1965/tomonaga/lecture/>

See: University of Tsubaka, Bibliography: Dr. Sin-Itiro Tomonaga `https://bit.ly/2JyRzwg`

Frozen time

Wheeler-DeWitt equation

Physical states are annihilated by the Hamiltonian of the theory

$$\hat{H}\Psi[g_{ik}, \phi] = 0$$

where, $\hat{H}$ is a constraint quadratic in momenta conjugate to g_{ik}.

$\Rightarrow$ The wave function of the Universe is in an eigenstate of its Hamiltonian.
$\Rightarrow$ Hamiltonian does not generate time translations of the physical states with respect to an external time.

Bryce S DeWitt. "Quantum theory of gravity. I. The canonical theory". In: *Physical Review* 160.5 (1967), p. 1113.

Edward Anderson. "Problem of time in quantum gravity". In: *Annalen der Physik* 524.12 (2012), pp. 757–786.

Page and Wootters mechanicsm

Consider an ancillary system in addition to the system S of interest. Could we then have a setup in which the global system is time independent, yet system S is time dependent and obeys the Schrödinger equation?

- Use a clock as the ancillary system, and correlate its initial state with the initial state of S

Don N Page and William K Wootters. "Evolution without evolution: Dynamics described by stationary observables". In: *Physical Review D* 27.12 (1983), p. 2885.

Alexander RH Smith and Mehdi Ahmadi. "Quantizing time: Interacting clocks and systems". In: *Quantum* 3 (2019), p. 160.

Other facets of the problem of time

- it has become more common to suggest that the problem of time is the Frozen Formalism Problem.

Edward Anderson. "Problem of time in quantum gravity". In: *Annalen der Physik* 524.12 (2012), pp. 757–786.

KV Kuchař and CG Torre. *Conceptual Problems of Quantum Gravity ed A Ashtekar and J Stachel*. 1991.

Chris J Isham. "Canonical quantum gravity and the problem of time". In: *Integrable systems, quantum groups, and quantum field theories*. Springer, 1993, pp. 157–287.

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- it has become more common to suggest that the problem of time is the Frozen Formalism Problem.
- A more long-standing point of view is that the POT contains a number of further facets.

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- These facets interfere with each other

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- These facets interfere with each other
- All arise from a common cause: the mismatch of the notions of time in GR and Quantum Theory

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Other facets of the problem of time

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Foliation dependence problem

How observers operationally determine the foliation for the physics that they experience

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Constraint closure problem

Closure of a classical Poisson bracket algebroid does not entail closure of the corresponding quantum commutator algebroid

Other facets of the problem of time

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Global problem of time

Time functions may not be globally defined in space and/or time.

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Multiple Choice Problem

Different choices of time variable may give inequivalent quantum theories, e.g. making different choices of sets of variables to quantize may give inequivalent quantum theories.

Other facets of the problem of time

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Problem of beables/observables

Involves construction of a sufficient set of beables for the physics of one's model, which are then involved in the model's notion of evolution.

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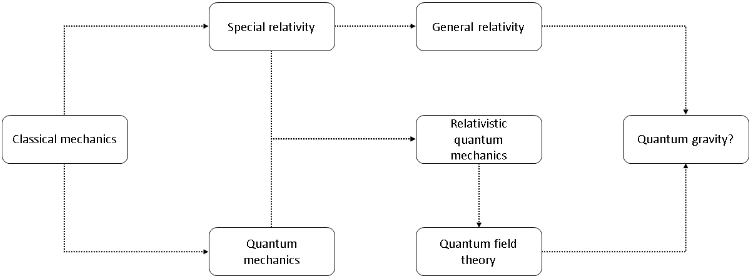
Spacetime reconstruction problem

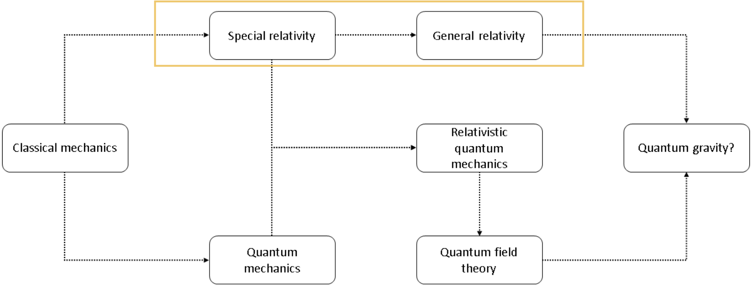
Quantum fluctuations are too numerous to be embedded within a single spacetime

Summary



- Quantum gravity aims to unify the empirically successful theories of general relativity and quantum field theory
- Incompatible notions of time

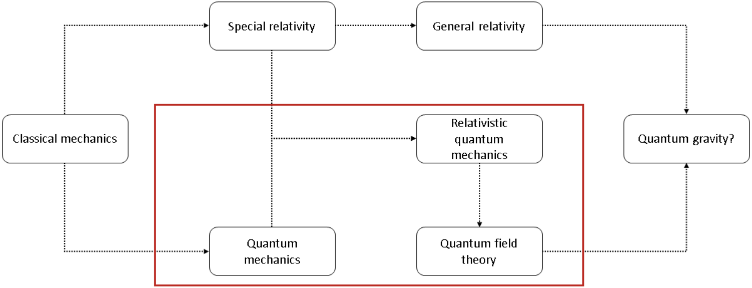
Summary



Time in relativity is dynamical:

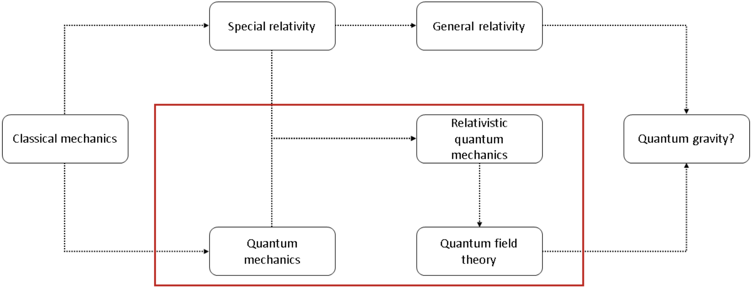
- SR treats time and space as components of a 4-vector
- Time in GR is influenced by the geometry of spacetime

Summary



- Quantum mechanics treats time as an external parameter which governs the evolution of the system
- Quantization schemes lack any fundamental notion of time

Summary



- How should the notion of time be reintroduced?
- Is time a fundamental concept or is it purely phenomenological?

Summary

- lack of a consistent quantum description of time has far reaching consequences
- the problem is a very broad subject and a rich history

Thank You

A derivation of the time-energy uncertainty relation by Bohr

Let Δt, Δx be the extension of a wavepacket in time and space, respectively. Furthermore, let $\Delta\nu$ and $\Delta\sigma$ be the frequency and number widths.
"In the most favorable case"

$$\Delta t \Delta\nu = \Delta x \Delta\sigma = 1$$

$$\Delta t \Delta \left(\frac{E}{h}\right) = \Delta x \Delta \left(\frac{p}{h}\right) = 1$$

$$\Delta t \Delta E = \Delta x \Delta p = h$$

N Bohr. *The quantum postulate and the recent development of atomic energy, talk at the Como Conference 1927, published in Nature (Supplement), 121, 580-590 (1928); reprinted in Atomic Theory and the Description of Nature*. 1934.