QUANTUM GRAVITY, METAPHYSICS, spacetime emergence and locality

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TOPICS

- **Why quantize gravity?**
- **How to quantize gravity?**
- **A note on spacetime emergence**
- **What is the role of metaphysics?**
- **Bonus track: quantum cosmology, the measurement problem, locality**

WHY QUANTIZE GRAVITY?

What happens if we do not quantize gravity:

- Matter fields are quantized, described by some form of the Schrödinger equation, while gravity is described by classical Einstein equations:

$$i\frac{\partial}{\partial t}|\Psi\rangle = \hat{H}(\hat{\phi}, g_{\mu\nu})|\Psi\rangle\,, \qquad R_{\mu\nu} - \frac{1}{2}g_{\mu\nu}R = 8\pi G\, T_{\mu\nu}\,.$$

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- In order to make sense of $T_{\mu\nu}$ on the right-hand side, define

$$T_{\mu\nu} = \langle\Psi|\,\hat{T}_{\mu\nu}(\hat{\phi})\,|\Psi\rangle\,,$$

  then solve Einstein equations to obtain

$$g_{\mu\nu} = g_{\mu\nu}(\langle\Psi|\hat{T}|\Psi\rangle)\,,$$

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CONTRADICTION WITH THE SUPERPOSITION PRINCIPLE OF QM !!!

WHY QUANTIZE GRAVITY?

Therefore, QM does not tolerate being coupled to anything classical; all fields in nature must be quantized!

We are required to make a <u>choice</u>:

- either give up the superposition principle of QM,

- or give up the classical description of gravity, i.e. quantize it: $g_{\mu\nu} \to \hat{g}_{\mu\nu}$.

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  $\Rightarrow$ **quantum gravity zoo:** superstring theory, loop quantum gravity, spinfoam models, causal sets, causal dynamical triangulations, noncommutative geometry, asymptotic safety, entropic gravity, doubly special relativity, Hořava-Lifshitz gravity, ...

  (most of the people in the community...)

HOW TO QUANTIZE GRAVITY?

General relativity is not renormalizable.

- renormalization is a technique to keep infinities "under control",
- and the main ubiquitous source of infinities in QFT is the propagator:

$$G(x,y) \approx \frac{const}{|(x-y)^2|} \to \infty \qquad (y \to x)\,.$$

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- or give up the notion of smooth spacetime manifold, in favor of some structure which "tames away" the limit $y \to x$,

  $\Rightarrow$ **change the kinematics** of the underlying structure of spacetime.

HOW TO QUANTIZE GRAVITY?

In both cases, a plethora of <u>choices</u>:

- changing the dynamics —

theory:	**difference from GR:**
Supergravity	local super-Poincaré symmetry
Asymptotic safety	a nontrivial fixed point
R^2-gravity	renormalizable (Stelle, 1977)
$f(R)$ gravity	nonpolynomial in curvature scalar
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- changing the kinematics —

theory:	**smooth manifold substituted with:**
String theory	loop manifold
Noncommutative geometry	noncommutative manifold
Loop quantum gravity	spin networks $\times$ time
Spinfoam models	Twisted geometry manifold
Causal dynamical triangulations	piecewise-linear manifold
Causal set theory	finite set with a causal order relation

A NOTE ON SPACETIME EMERGENCE

It is a recipe to approximate the fundamental spacetime structure with a smooth manifold:

- exists in QG models which change kinematics,
- is required by the semiclassical limit of the QG model.

Classical spacetime emerges via the following scheme:

$$\begin{array}{ccc} \text{fundamental} \\ \text{structure} \end{array} \longrightarrow \begin{array}{ccc} \text{approximation} \\ \text{scheme} \end{array} \longrightarrow \begin{array}{ccc} \text{smooth} \\ \text{manifold} \end{array}$$

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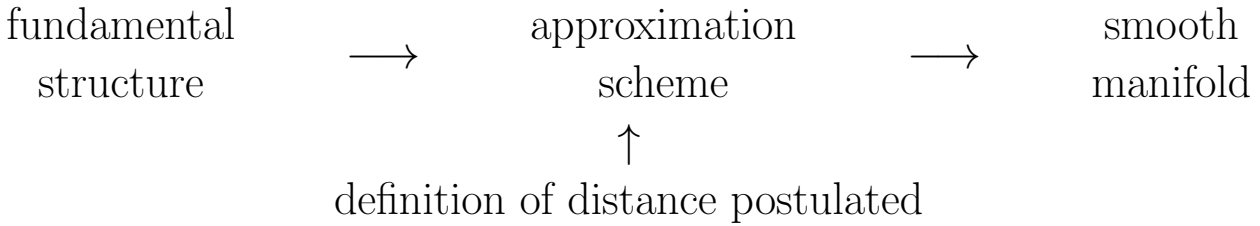

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Nothing automatic, miraculous or mystical about emergence:

SPACETIME ALWAYS EMERGES BY DESIGN !!!

ROLE OF METAPHYSICS?

Metaphysical choices all over the place:

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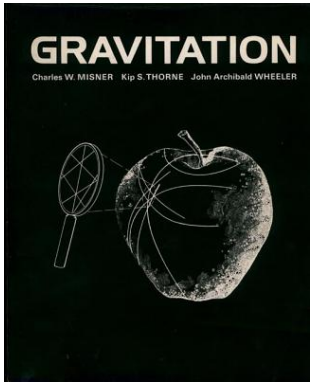
Physicists tend to disagree on the answers to these questions:

CONSTRUCTION OF THE THEORY DEPENDS ON THE SCIENTIST'S METAPHYSICAL ASSUMPTIONS ABOUT NATURE !!!

ROLE OF METAPHYSICS?

An illustrative example — two textbooks on general relativity:



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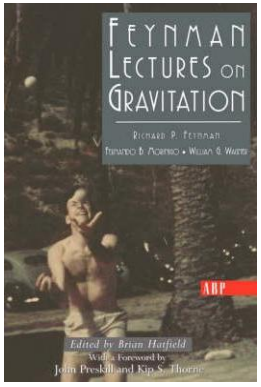

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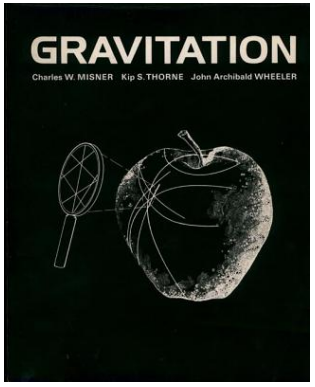

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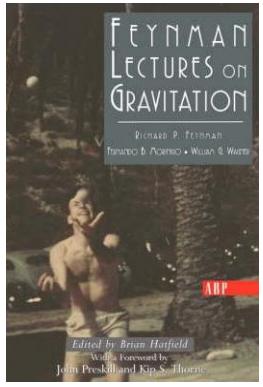

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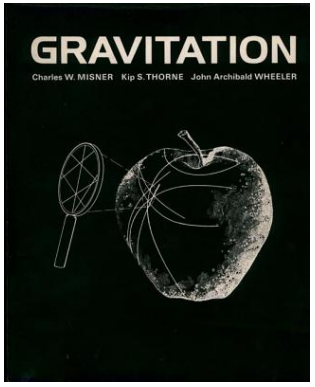

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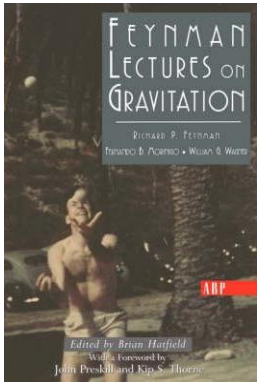

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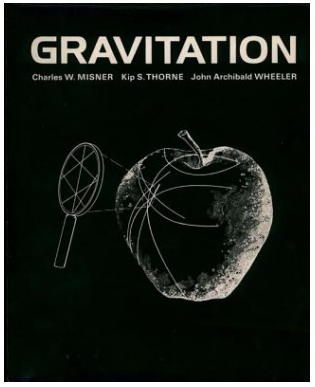

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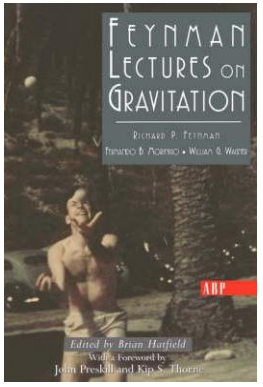

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SAME PHYSICS, DIFFERENT METAPHYSICS !!!

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Another illustrative example:

- the question: **what classical theory best describes current human knowledge regarding gravity?**

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Yet another example:

- the question: **what geometric object best describes the motion of planets?**
- one answer: **Heliocentric ellipses!**
- another answer: **Geocentric epicycles!**

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The contingency of QG models:

- **the properties of every QG model are contingent on prior education and prejudices of its author (!!!)**

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  - order in which one reads books and takes physics courses;
  - choice of the thesis supervisor;
  - geographical location ("east coast" vs. "west coast" universities in US);
  - religious beliefs;

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  - religious beliefs;
- **some physicists tend to present themselves as "agnostic about metaphysics", but nobody really is!**

STUDYING AND CLASSIFYING THESE PREJUDICES IS A FERTILE GROUND FOR PHILOSOPHY AND SOCIOLOGY OF SCIENCE

THE MEASUREMENT PROBLEM IN QM

Interaction between the system and the environment:

$$|\Psi_{\text{initial}}\rangle = \frac{1}{\sqrt{2}}\Big(|\uparrow\rangle + |\downarrow\rangle\Big) \otimes |\text{Rest of the Universe}\rangle$$

$$\downarrow \quad \text{linear evolution and decoherence}$$

$$|\Psi_{\text{final}}\rangle = \frac{1}{\sqrt{2}}\Big(|\uparrow\rangle \otimes |U\uparrow\rangle + |\downarrow\rangle \otimes |U\downarrow\rangle\Big)\,.$$

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But we never observe $|U+\rangle$ and $|U-\rangle$!! Why?

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Naive responses:

- "You have made a mistake in the calculation somewhere."
- "You do not understand QM properly."
- "This problem has been resolved in QM."
- "This problem has been resolved in QG."
- "So what?"

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~~**Naive responses**~~

Serious responses:

- the full "wavefunction of the Universe" does not exist;
- the Universe is not an isolated system;
- the mechanism for determining the einselection basis will be based on locality;

Again, the properties of the theory depend on the metaphysical assumptions of the author!

THE MEASUREMENT PROBLEM IN QM

Relation to gravity:

- the solution to the **measurement problem in QM** (as proposed by MWI) is based on
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- the notion of **locality**, which is based on
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THE INFLUENCE OF METAPHYSICS "REACHES BEYOND" JUST PURE QUANTUM GRAVITY...

THANK YOU!