0. SETUP

ESQUISSE D'UN PROGRAMME

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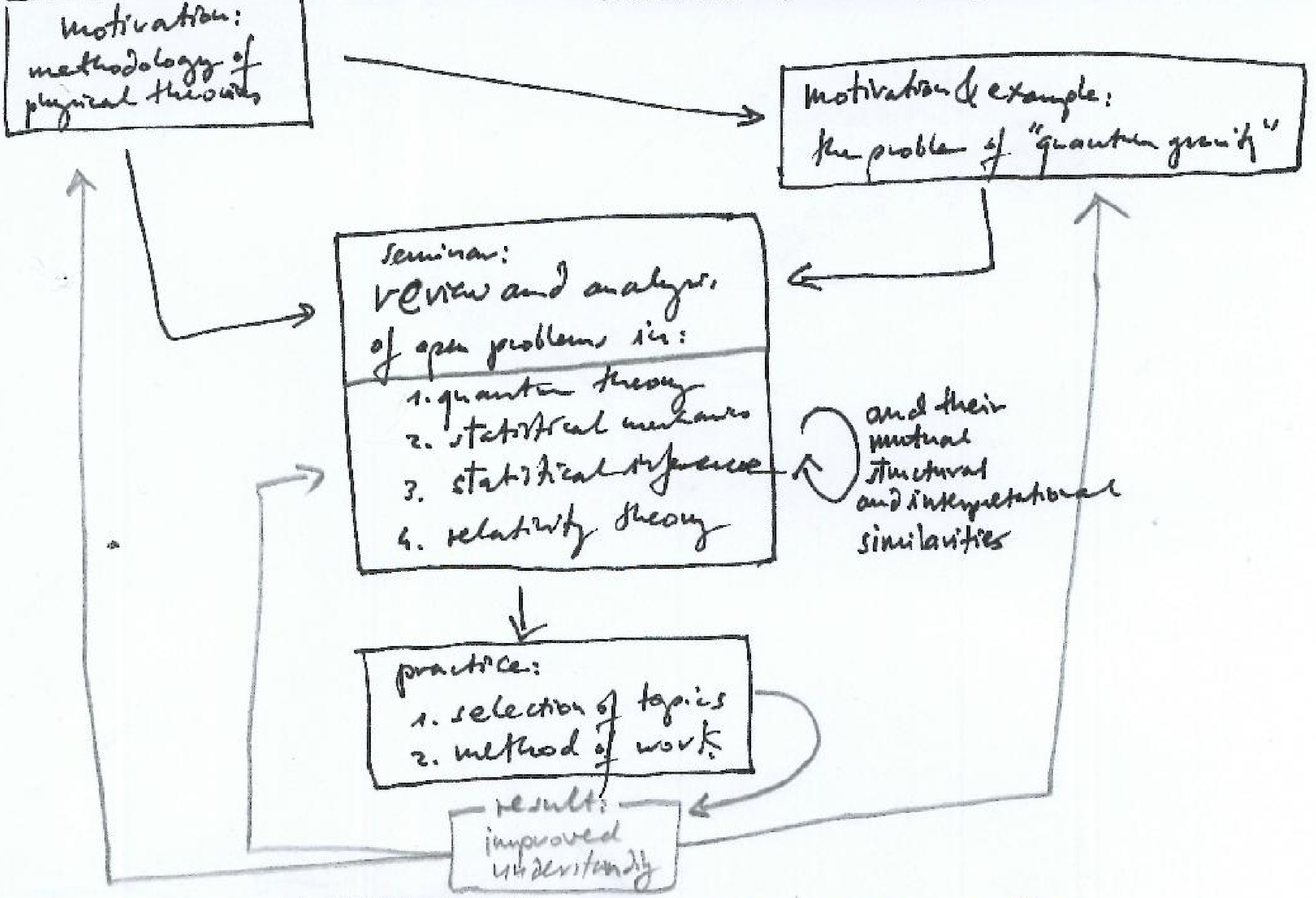

... or the SKETCH OF THE PROGRAMME FOR THE UNDERGROUND SEMINAR ON OPEN PROBLEMS IN FOUNDATIONS OF MODERN PHYSICAL THEORIES.

—draft version—

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17.02.2011.
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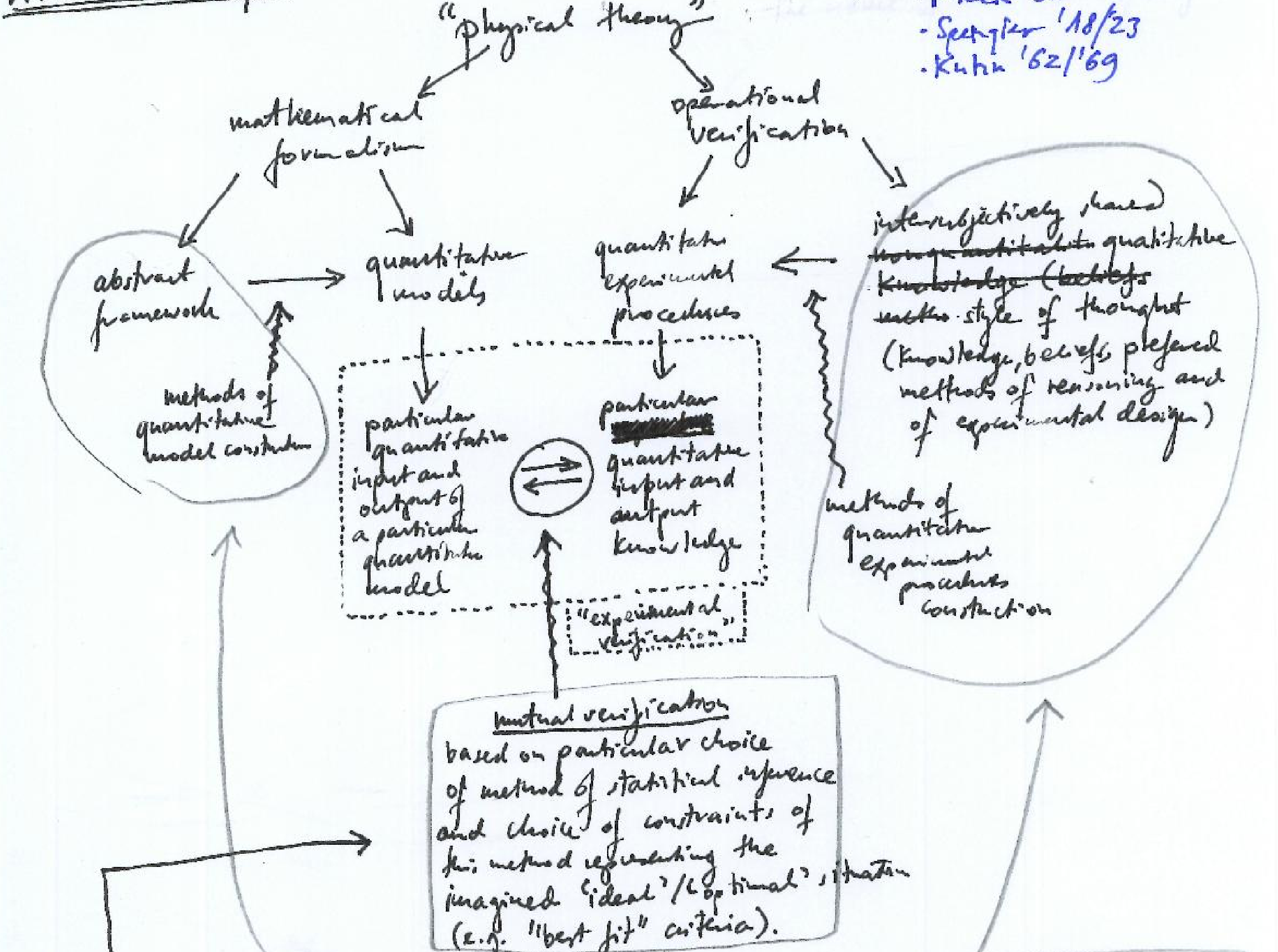
Contents

Beware! It is about going around and around of the walls of Jericho!

I. METHODOLOGY

Primary lectures:
- Fleck '35
- Spengler '18/23
- Kuhn '62/'69



mutual verification based on particular choice of method of statistical inference and choice of constraints of this method representing the imagined "ideal"/"optimal" situation (e.g. "best fit" criteria).

These components are NEVER subjected to "experimental verification". They are subjected to CHANGES which do not follow deductively from (= are not implied by) any particular mutual verifications between quantitative models and quantitative experimental procedures.

« Interpretation of a "physical theory" » is a meta-theoretic tool that is used as a source of selection of particular forms of these components, and the source of changes of these forms. Interpretation is never "experimentally verified". It can be always saved as "valid" by adaptation of the operational verification through change of intersubjective style of thought (in particular: the change of additional hypothesis, as in Duhem–Quine thesis) or by the change of abstract framework ("a discovery of a new deep structure that confirms the tale"), or by reinterpretation of the "mutual verification" details*.

* (e.g. "discovery of a new subtle but crucial effect, previously ignored")

Note that:

- every practical use of a mathematical formalism for prediction/retrodiction of the quantitative "results of experiment" requires some definite operational & intersubjective description of the elements of the formalism.
- every such use allows many different "interpretations"
- in the above context: "interpretations" of physical theories are irrelevant for practical verification of quantitative models ~~(in their~~ (apart from the operational components of these "interpretations")
- so, while "interpretations" are meta-theoretical, may vary, are experimentally inaccessible, and have always some arbitrary components (that are meta-physical = non-operational), the operational rules have to be (intersubjectively) definite.

This means that

- one should always strictly divide the provided semantics of the given mathematical framework into:
  - operational justification of the abstract elements of the formalism
  - operational justification of the quantitative model construction methods
  - operational justification of the choice of the particular method (and criteria) of "experimental verification"
  - the rest of interpretation, which is irrelevant, and can be always changed to something else

II. PRINCIPAL CASE STUDY

Primary literature
- Isham '93/'95
- Rovelli's book
- no really good reference for overall perspective.

Quantum gravity

↓

"a theory that in appropriate limit reduces to quantum theory and gravity theory"

COMPONENTS:

- what is "quantum theory"?
- what is "gravity theory"?

(problems with the definitions of mathematical formalism and/or operational verifications of each theory on its own)

TASK:

- should one "quantise gravity", "gravitate quantum" or "~~transgress~~ transcend the boundaries"? (= how to unify math. formalism?)

non-linear tensorial lagrangean field theory on differential manifold $\underset{?}{\overset{?}{\rightleftarrows}}$ linear operator hamiltonian theory on Hilbert space

?! ? ⇅ QG ⇅ ? ?!

- how to unify operational verification methods? (seems to cry out loud for the "new interpretation")

CONSTRAINTS:

- what is definitively known about QG? (see below)
- some unsuccessful approaches:
  - * Wheeler-deWitt
  - * superstring theory
  - * loop quantum gravity
  - * noncommutative geometry

- what is definitively known about QG?

1. general relativity ⟷ thermodynamics link:
   - * Beckenstein, Hawking, Unruh, Israel, Wald: the geometry of black holes in GR shares the same formal relations as the rules of thermostatics.
   - * Jacobson: Einstein GR equations from thermodynamic equation of state on differential geometric manifold.
2. statistical mechanics ⟷ quantum theory link:
   - * Wick rotation (Osterwalder-Schrader, Bilu-Fröhlich theorems) turns euclidean statistical mechanical probability distributions into lorentzian quantum mechanical ones
   - * every faithful or KMS algebraic state on a C^*-algebra generates a unique Hilbert space equipped with a unique 1-parameter group of unitary automorphisms (quantum dynamics). Moreover, it is a direct generalisation of maximum entropy Gibbs state
3. quantum theory ⟷ general relativity link:
   - * Bisognano-Wichmann, Sewell: the precise form of Fulling-Unruh effect requires to use KMS state
   - * Haag isomorphism between the lattice of bounded regions of Minkowski spacetime and the subalgebras of the von Neumann algebra of the vacuum state of qft.

+ Fredenhagen et al functional assignment of a category of von Neumann algebras to a category of globally hyperbolic spacetimes.

It is worth to observe that the existing approaches to "quantum gravity" have failed due to the same 2 reasons which is the source of foundational problems in all 4 theories under consideration:

1. the problem of lack of unique general method of quantitative model construction that corresponds directly to the quantitative results and control parameters of the experimental procedures

loops: "lack of semiclassical state" problem
strings: "landscape problem"
ncg: the arbitrariness of the choice of nc algebra problem (see discussion on Alain Connes' blog about the failure of his nc model for Standard Model)

2. the problem of lack of unique method of quantitative construction of temporal behaviour of the model that corresponds directly to the temporal changes of quantitative results and control parameters of the experimental procedures.

loops: "hamiltonian constraint problem"
strings: contained in "landscape problem and in the use of q.f.t.-like ad hoc perturbative techniques
WdW: $H\Psi=0$

In the highly simplified versions, these problems exist under the name of "the measurement problem" and "the problem of time". The complete recognition of the above form of these problems is blocked by the pre-assumed (implicitly and non-consciously assumed) ontological interpretation of the framework under consideration.

Fortunately, we do not need to choose any particular interpretation (as discussed previously), especially if it is a priori constraining our understanding. We care only about the operational criteria of meaning of quantitative properties of quantitative models.

The above two problems have their own detailed instances in each of 4 theories. We will discuss them in what follows. But...

Before we follow, reconsider the structure: QG → CONSTRAINTS

→ WHAT IS KNOWN TO HOLD (A)

→ REASONS OF FAILURE OF "FAILED" APPROACHES (B)

In both cases we are lead to reconsideration of GR, SM and QT.

In case (A), we are lead to search for the mutual connections between these theories as well as the structural similarities between these theories.

In case (B), we are lead to search for the structural similarities of the problems of these theories. In both cases (A) and (B) we learn about QG in passing.

#549

<u>1867 – 1902</u>
equilibrium statistical mechanics
↓
problems!
↓
<u>1940's +</u>
<u>non-equilibrium statistical mechanics</u>
lacking fixed abstract framework
lacking fixed intersubjectively shared assumptions

<u>1925 – 1932</u>
quantum mechanics
↓
problems!
↓
<u>1940's +</u>
<u>quantum theory</u>
lacking fixed abstract framework
lacking fixed intersubjectively shared assumptions

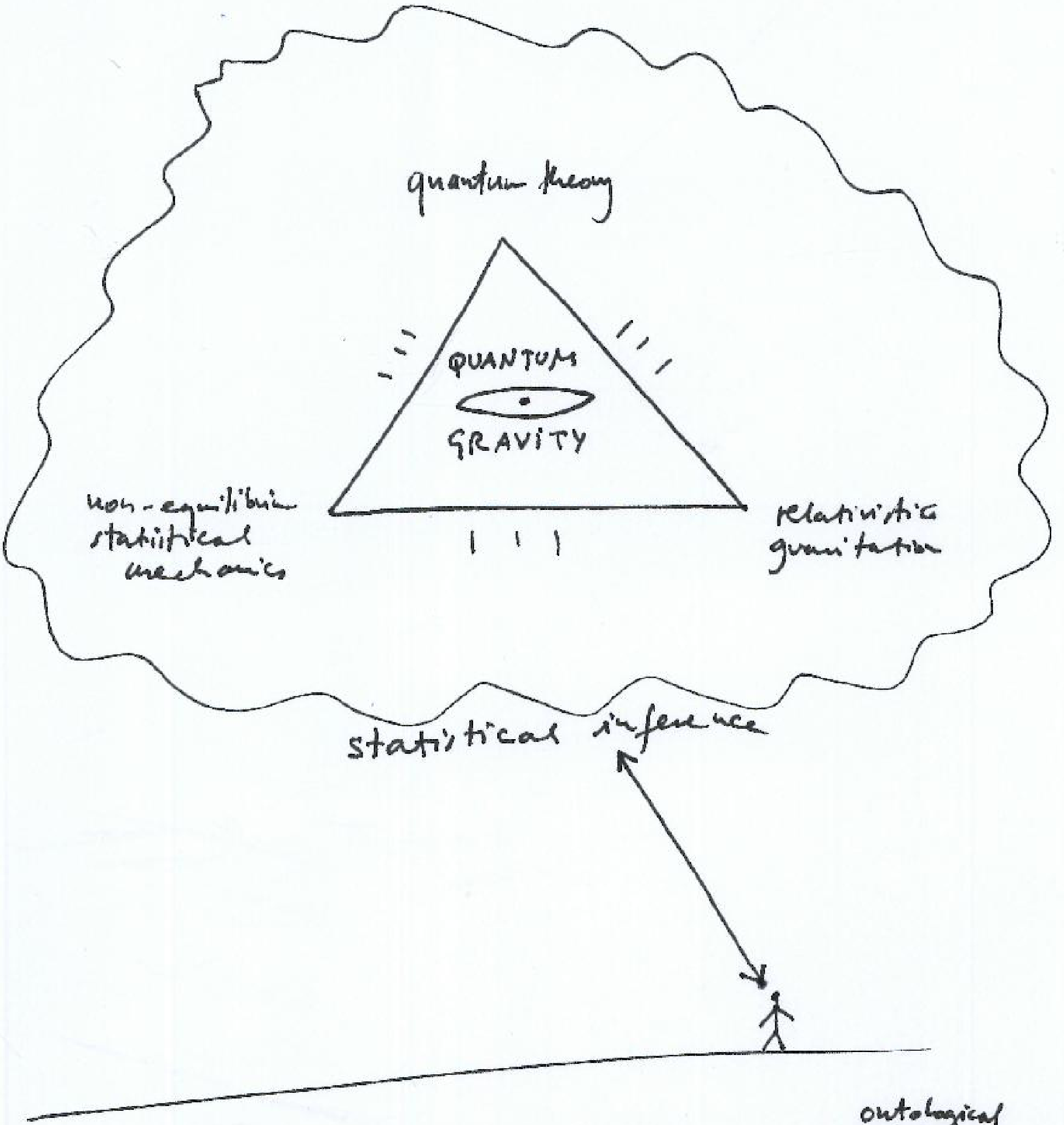
<u>17xx – 1933</u>
probability theory
↓
problems!
↓
<u>18xx⁺ // 1930's +</u>
<u>statistical inference</u>
lacking fixed abstract framework
lacking fixed intersubjectively shared assumptions

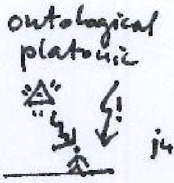
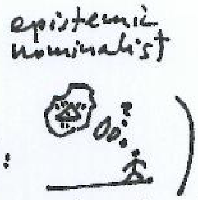
<u>1905 – 1908</u>
special relativity
↓
problems!
↓
<u>1920's +</u>
<u>general relativity</u>
fixed abstract framework
(but there exist not falsified reliable alternatives)
fixed intersubjectively shared assumptions
(but lacking operational foundations)

- All "problems" are always:
  - * conceptual : paradoxes = lack of consistency in interpretation
  - * operational : experimentally considered situations do not fit into scheme
  - * mathematical : old structures are insufficient for the new purposes

So...

- <u>Where do we are</u> <u>now</u>?:
  - <u>Thinking in terms of "forces"</u>: outdated 350+ years! (pre-Lagrange/pre-Hamilton) used only due to purposes of school education.
  - <u>Thinking in terms of "matter"</u>: outdated in stat. mech. since Smoluchowski '05 (no phase space) and outdated in quant. theory since Haag '55 (no Fock space), never really present in GR (<u>ad hoc</u> introduced $\mathcal{L}_{\mathrm{mat}}$, no internal method of its definition due to the failure of Einstein's "unified field theory" programme), never present in stat. inference
  - <u>Thinking in terms of "energy"</u>: invalid in stat. mech. & quant. theory, because energy does not specify probabilities, invalid in GR (the local energy is ill defined, the $\mathcal{L}_{\mathrm{mat}}$ is introduced externally), invalid in stat. inference.



- Thinking in terms of statistical inference:
  1. against mainstream ideology (which claims:  instead of: )
  2. since Laplace '1810 in statistical inference, since Jaynes '57 in statistical mechanics, growing underground stream in quantum theory (e.g. Fuchs), still to do in general relativity.
  3. is a main candidate for a new Denkstil.

Problems of foundations of quantum theory

III. OPEN PROBLEMS IN FOUNDATIONS: BRIEF LIST.

- Extensions of formalism of quantum mechanics:
  - * convex sets / semispectral measures (= POVM's)
  - * rigged Hilbert spaces = Gel'fand triplets
  - * C*/W*/vN-algebraic approach
  - * "geometry of Hilbert spaces" approach & Kähler QM
- Problems of "interacting" quantum theory (⇒QFT)
  - * Haag's thm & the problem of unitarily inequivalent representations & the failure of particle interpretation
  - * Borchers's theorem and the failure of ontological interpretation of "quantum field"
  - * the lack of mathematical meaning of path integrals
  - * the issue of lorentzian / euclidean "Wick" rotation, and the link between quantum theory and statistical mechanics
  - * the problem of meaning and of different frameworks for renormalisation
  - * Schwinger's source theory as a non-perturbative quantitative alternative to renormalisation
  - * the failure of multitude of different inequivalent "quantisation" rules
- Problems of interpretation
  - * paradoxes: Einstein-Schrödinger, Einstein-Podolsky-Rosen, Bell, Kochen-Specker, Reeh-Schlieder, quantum Zeno, quantum vacuum
  - * interpretations: internal problems of epistemic and ontological interpretations.
  - * "classical" limits: in what sense 'classical mechanics' is a limit of quantum theory and in what sense 'classical probability theory' is a limit of quantum theory?
  - * observables / measurement: what is an observable in "quantum theoretic compatible" measurement (= ~~experimental~~ quantitative procedure)? → Böhm, Muynck, Peres, Busch-Grabowski-Lahti, Holevo.

Problems of foundations of statistical mechanics

- Established framework: equilibrium statistical mechanics
- Foundational problems:
  1. paradoxes:
     - Maxwell
     - Gibbs
     - Loschmidt
     - Laplace-Krylov
  2. failure of foundational approaches:
     - kinetic
     - ergodic
- New decisive field of application of old concepts: non-equilibrium stat mech

↓

Several approaches to non-equilibrium theory:

- Prigogine
- Lebowitz
- Zubarev
- Jaynes-Grandy
- stochastic dynamics/open systems/master equations

↙

Questions:

1. how these approaches deal with the paradoxes?
2. what kind of methods of quantitative model construction they provide?
3. what is <u>the</u> general framework for the non-equilibrium statistical mechanics?

Problems of foundations of statistical inference

- Established frameworks: finite dimensional conditional probability
  infinite dimensional measure theoretic probability

- Foundational problems:
  1) conflict between mathematical frameworks of Bayes-Laplace, Borel-Kolmogorov, Huygens-Whittle
  2) conflict between interpretations of probability: frequentism, objective bayesianism, subjective bayesianism
  3) lack of unified principles of construction of the methods of statistical inference

↓

Lack of the general framework for statistical inference and a lack of commonly agreed interpretation.
Dominates conventionalism with different incompatible schools of conventions (the same story as in the case of non-equilibrium statistical mechanics, and quantum theory beyond Hilbert space based quantum mechanics).

Three main schools:

Fisher or Neyman-Pearson frequentist statistical inference

de Finetti subjective bayesian statistical inference

Jeffreys-Cox-Jaynes bayesian and maximum entropy statistical inference

There are however some results that can act as a bridge:

- Neyman-Pearson lemma and Fisher sufficiency can be characterised in terms of relative entropy
- Maximum likelihood inference and Wald's optimal decision rules are just particular applications of Bayes' rule
- Bayes rule is a particular case of $\overset{\text{constrained}}{\text{maximum}}$ relative entropy principle.

Problems of foundations of general relativity

- Idealistic vs. operational assumptions in SR and GR:
- *ideal clocks and rods ⇒ Bridgeman's and Brillouin's critique
  - *assumption that the relative velocity of two reference frames has very specific symmetry property: $V_{1/2} = -V_{2/1}$, as opposed to some form of associativity: $V_{1/2} \circ V_{2/3} = V_{1/3}$ (not necessary additive associativity) ⇒ Oziewicz's critique
- What is an observable in GR?
  - *mathematical problems:
    - — lagrangean formulation: solutions of PDE's in terms of jet spaces
    - — canonical hamiltonian formulation: nonlinear constraints and reduced phase space (Dirac's procedure)
    - — histories hamiltonian formulation (Savvidou)
    - — Rovelli's partial observables
    - — metric vs tetrad formulation and coordinate systems vs referance systems
    - — problem of definition of local energy in GR
  - * operational problems
    - — experimental tests of GR
    - — Weyl and Einstein–Cartan theories as valid alternatives to GR and the problem of comparative experimental verification between GR/W/EC + discussion of operational interpretation of non-metric connection and torsion
    - — the hole argument & space-time substantialism (Earman, Lusanna)

IV. SUB-PRINCIPAL CASE STUDY: OPEN PROBLEMS IN QUANTUM THEORY

Planck '00 – Einstein '05 – Bohr '1x – Sommerfeld '1x

$\downarrow$

Heisenberg '25 – Schrödinger '25

discrete but infinite matrices | continuous linear wave equation

$\downarrow$

Dirac '27 – '30 – von Neumann '27 – '32 (& Stone '2x – '30)

those two formalisms are essentially the same in finite dimensional case, when $\delta(x-x') = \delta_{ij}$ and $L^2(\mu)$ is isometrically isomorphic to ℓ^2.

but problems arise in ∞ dim case...

Dirac: $\downarrow$ formalism based on $\delta(x-x')$, which was undefined rigorously.

$\downarrow$

this formalism became mathematically well founded after works of:

Mikusiński '48
Schwartz '49 – '51
Grothendieck '52 – '59
Gel'fand '5x – '6x

As a result, the Dirac's formalism for quantum mechanics is grounded in the mathematical framework of "Gel'fand triplets" = "rigged Hilbert spaces", which is a triple $(\Phi, \mathcal{H}, \Phi^{\times})$, where Φ is a space of functions ("test functions", "smearing functions"), while $\Phi^{\times}$ is the space of distributions (functionals) acting on these functions; $\mathcal{H}$ is the referential Hilbert space of the system $(\Phi, \Phi^{\times})$, with $\Phi \subset \mathcal{H}$ and $(\Phi, \Phi^{\times})$ defined using some operators on $\mathcal{H}$. In principle, this formalism is grounded in the theory of nuclear vector spaces which are Fréchet but not Banach spaces.

this formalism found its application in:

- axiomatic approach to quantum field theory (Wightman, Gel'fand), which has lead to no results of practical meaning (lack of description of "interacting" theories)
- description of resonances (Böhm et al)

$\downarrow$

gradually has faded into shadows...

von Neumann: $\downarrow$ formalism based on abstract Hilbert spaces and linear operators.

Heisenberg $\cong$ Schrödinger

by: 1. $\ell^2 \cong L^2(\mu)$ [Riesz isomorphism]

2.

$$\begin{tikzcd}
 & A = A^{*} \arrow[dl, Leftrightarrow, "\text{bijection valid for COMPLEX Hilbert spaces}"'] \arrow[dr, Leftrightarrow, "\text{spectral theorem}"] & \\
U(t) = e^{itA} \arrow[rr, Leftrightarrow, "\text{definition}"'] & & \{P_{\lambda_i}\}_{\lambda_i \in sp(A)}
\end{tikzcd}$$

(only in such case 1-parameter unitary groups of automorphisms can be represented by unitaries with self-adjoint generators).

In ∞ dim case the collection $\{P_{\lambda_i}\}_{\lambda_i \in sp(A)}$ is replaced by spectral measure $E^A(\lambda)$ on some set $\underset{(\text{or: } X \subseteq \mathbb{C})}{X \subseteq \mathbb{R}}$, which is considered to be the spectrum of the corresponding operator A. We have:

$$A := \int_{sp(A)} dE^A(\lambda)\,\lambda,$$

$$\langle \xi, U(t)\xi \rangle := \int_{\mathbb{R}} \langle \xi, E^A(\lambda)\xi \rangle\, e^{-it\lambda}.$$

this formalism was abandoned as foundational by von Neumann in ≤ 1935. Von Neumann has founded two next foundational approaches

$\swarrow$ quantum logics (von Neumann–Birkhoff)

$\searrow$ algebraic approach (von Neumann–Murray) $\downarrow$ see next page.

according to this approach, the complete information about give Hilbert space and its algebra of self-adjoint operators is contained in the lattice of projection operators. Thus, one can axiomatise the properties of this lattice in purely algebraic way (without any adherence to topology), and consider the Hilbert space based framework just as a particular representation of this lattice of "quantum logic". This lattice was meant to represent the logic of yes–no propositions regarding the experimental situation. And the most interesting question was: what are the other (non-Hilbert space) representations of "quantum logic" lattice?

Hilbert space based approach
á la von Neumann

'quantum logic' lattices

This approach was developed by:

Mackey '4x – '6x
Jauch '6x, Piron '6x

One of the crucial results in this approach was Gleason '57 theorem. However this approach was unable to give any other model of the 'quantum logic' lattice than the lattice of projections on Hilbert space. Moreover, it never was shown how this approach is able to internally handle such problems as tensor product of two Hilbert spaces, partial trace, etc...

gradually has faded into shadows...

HOWEVER

Due to research on 'quantum logic' people started to ask questions whether the "yes-no paradigm" on quantum experiment is adequate to actual* experimental practice (*or the possible). This has lead to proposal that the possible elementary answers of the experimental setup are structured not in terms of {0,1} sets, but in terms of convex sets.

Ludwig '63, '70, '83-'85
Mielnik '68 – '7x
Davies & Lewis '70, Davies '76
Holevo '73

This has lead to replacement of spectral measures in original von Neumann's setting by the semispectral measures = POVM's for which the condition $P_iP_j = 0$ does not hold, but still the remaining conditions: $\sum_i P_i = \mathbb{I}$, $0 \leq P_i \leq \mathbb{I}$ hold.

However, if one defines the "observable quantities" in terms of semispectral measures, they do not correspond to self-adjoint operators in a unique way. Hence "observable" in quantum theory is not a self-adjoint operator.

This formalism find huge practical application!

algebraic approach

The crucial perspective of this approach is to consider the algebra of noncommutative operators equipped with some suitable topology as more fundamental than the Hilbert space itself, and to reconstruct the Hilbert space from the algebra.

Developed by:

von Neumann & Murray '27 – '50
Gelfand & Naĭmark '41 – '5x
Segal '47 – '6x
Haag '58+

And many others (Araki, Tomita, Takesaki, Kadison, ~~Dix~~Dixmier, ...)

The crucial aspect/result of this approach is the Gel'fand – Naĭmark – Segal ~~theorem~~, which states that for any given C*-algebra and any given positive linear $\mathbb{C}$-valued functional on it, there exist uniquely defined Hilbert space $\mathcal{H}$ and a representation of this C*-algebra in terms of $\mathcal{B}(\mathcal{H})$, and both $\mathcal{H}$ and $\mathcal{B}(\mathcal{H})$ are constructed explicitly from C*-algebra and functional.

Thus, algebraic approach is essentially more general. It has found [illegible] practical applications in quantum field theory and quantum statistical mechanics in the case when the underlying Hilbert space is infinite dimensional and the model depends on infinite number of independent parameters. But it was found to be insufficient for describing "interacting dynamics" of "quantum fields"

See the books:

- Davies '76
- Ludwig '83 – '85
- Peres '93
- Busch, Lahti, Mittelstaedt '91
- Busch, Grabowski, Lahti '95

what is quite ironical, because since '50s it was developed mainly in order to achieve this goal, stimulated hugely by Haag's and Borcher's theorems.

Summing up the previous pages, one can say that the "inner" development of the approaches to foundations of quantum mechanics has lead to two active approaches to foundations of quantum theory:

* semispectral/convex approach
* algebraic approach

and two more or less deactivated approaches:

* quantum logic
* rigged Hilbert spaces

This leads requiring to add one more *active* approach, that arises from reconsideration of foundations quantum mechanics. It is

* geometric approach

The starting point of this approach is consideration
developed since late '70s. ~~The~~ structures on the space of rays of Hilbert space
of geometric (metrical, affine)
$\mathcal{H}$ with dim $\mathcal{H} < \infty$, that is, the consideration of the space $\mathbb{CP}^n$.
(Kibble'78, Heslot'85, Berry'84, Simon'83, Aharonov-Anandan '90, Brody-Hughston '94+,
Ashtekar-Schilling '95-'97).

All above approaches can be considered as arising from attemps to reformulate
quantum theory in a way that removes fundamental importance of Hilbert
spaces. There are two more *streams of the foundational approaches*, which have
arised from:

* the problem of interpretation of quantum theory
* the "quantum interaction problem"

The former problem ~~[illegible]~~ has not lead to development
of many new mathematical formalisms (apart from Bohm's HVT's), but
it has resulted in deepened discussion of conceptual and operational
aspects of these formalisms. The second ~~aspect~~ problem has lead to a
full bunch of new mathematical (and conceptual) approaches.

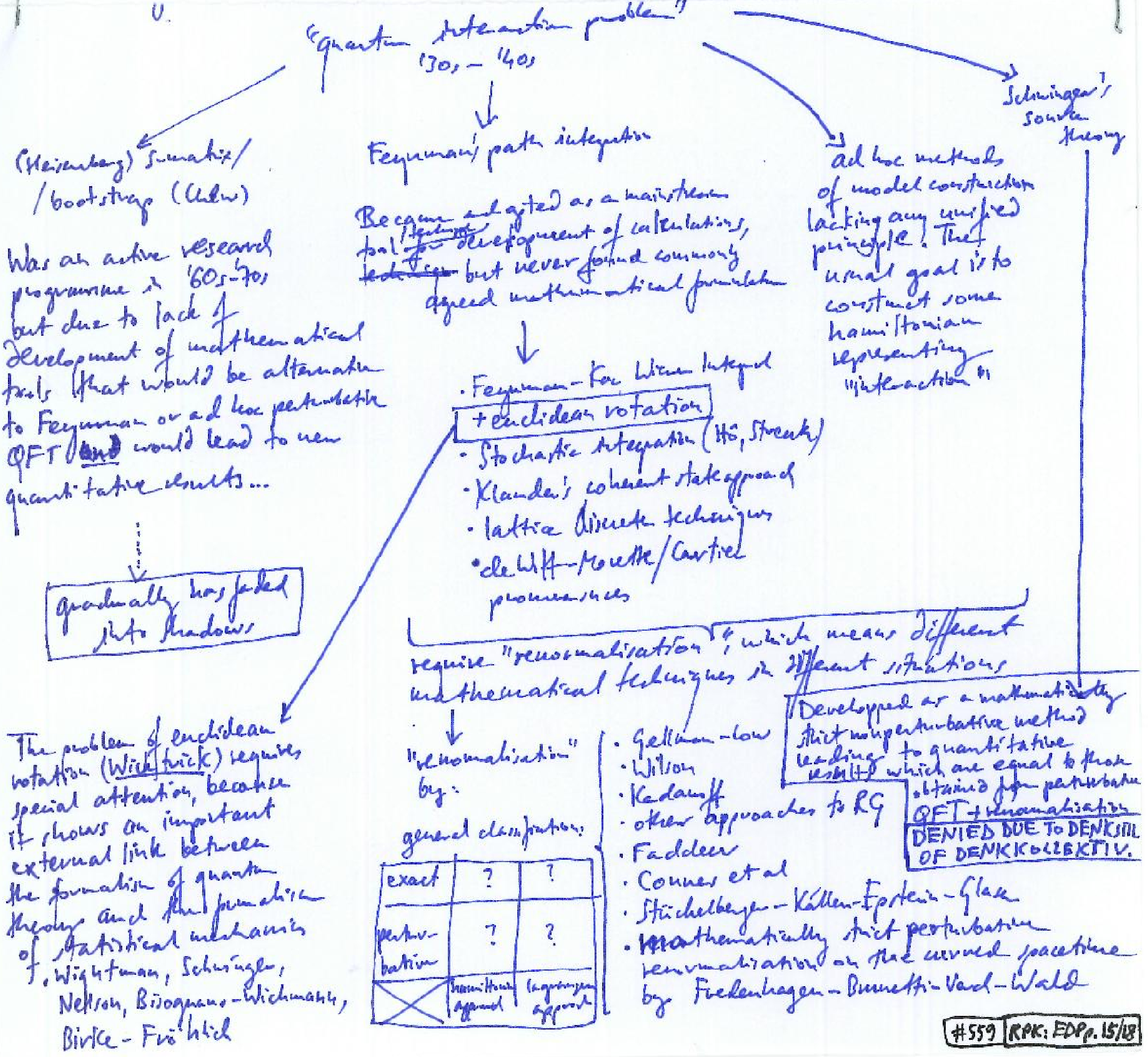
Let's start discussion from the second problem.

The key issue of "quantum interaction problem" was to find a
general method of quantum theoretic model construction that is able to
describe structurally complex and time-dependent quantitative experimental
control parameters and quantitative results. The notion of "interaction" was
a main idea underlying these attempts. The main source of the "quantum
interaction problem" was the lack of a general method of quantitative model

construction in quantum mechanics. The use of such methods as representation of the algebra of canonical commutation relations, group representations, or some other more awkward quantisation techniques have lead to wrong (= quantitatively falsifiable or inconsistent) results.

This aspect of "quantum interaction problem" is often blurred, so it has to be understood clearly: the "quantum interaction problem" shows that the method of model construction (and method of thinking) based on the notion of "quantisation" of some "classical theory" is inadequate for the general quantum theoretic applications. (This can be compared to trying to construct the nonequilibrium statistical mechanics using only the average values of quantities calculated from equilibrium theory!)

With these prerequisites, we can draw a picture:



v.

"quantum interaction problem"
'30s – '40s

(Heisenberg) S-matrix/
/bootstrap (Chew)

Was an active research programme in '60s–'70s but due to lack of mathematical development of mathematical tools (that would be alternative to Feynman or ad hoc perturbative QFT ~~and~~ would lead to new quantitative results...

gradually has faded into shadows

Feynman's path integration

Became adapted as a mainstream tool ~~for~~ heuristic development of calculations, ~~techniques~~ but never found commonly agreed mathematical formulation

- Feynman–Kac Wiener integral
- + euclidean rotation
- Stochastic integration (Itô, Streater)
- Klauder's coherent state approach
- lattice discrete techniques
- deWitt-Morette/Cartier promeasures

require "renormalisation", which means different mathematical techniques in different situations

"renormalisation" by:

general classification:

exact	?	?
perturbation	?	?
	hamiltonian approach	lagrangian approach

- Gellman–Low
- Wilson
- Kadanoff
- other approaches to RG
- Faddeev
- Connes et al
- Stückelberg–Källen–Epstein–Glaser
- mathematically strict perturbative renormalisation on the curved spacetime by Fredenhagen–Brunetti–Verch–Wald

The problem of euclidean rotation (Wick trick) requires special attention, because it shows an important external link between the formalism of quantum theory and the formalism of statistical mechanics, Wightman, Schwinger, Nelson, Bisognano–Wichmann, Birke–Fröhlich

ad hoc methods of model construction lacking any unified principle. The usual goal is to construct some hamiltonian representing "interaction"

Schwinger's source theory

Developped as a mathematically strict nonperturbative method leading to quantitative results which are equal to those obtained from perturbative QFT + renormalisation

DENIED DUE TO DENKSTIL OF DENKKOLLEKTIV.

Finally, we can turn to interpretations. The discussion below is incomplete, but representative. The existing interpretations of quantum theory vary wrt.:

- division into epistemic and ontological view on the contents of quantum theoretic formalism
- validity when applied to different extensions of the von Neumann's or Dirac's orthodox formalism

The rough classification of interpretations is:

1. "Epistemic"⊛:
   - Copenhagen à la some favorite interpretations of writings of Bohr and/or Heisenberg and/or somebody1 as provided by somebody2.
   - Copenhagen?, but definite! by Bohr A., Mottelson, Ulfbeck
   - statistical interpretation in frequentist sense (several versions)
   - subjective bayesian de Finetti style by Fuchs, Caves, Schack
2. "Ontological":
   - Bohm, Bohm-Hiley ("hidden variables"): this goes with its own mathematical news
   - Everett, Deutsch — multiverse
   - Ghirardi, Rimini, Weber — an example of typical thinking about "measurement problem" by ontologically-oriented physicists
   - decoherence — funded by Zurek and others, gradually lost its fame, moving from "interpretation" to "technique"

⊛ In fact, only subjective bayesian interpretation (and some of selective readings of Bohr) is really epistemic. Usually the "belief in atoms", etc. is maintained!

The interpretations can be understood from the perspective of paradoxes of the orthodox interpretation of quantum theory. From this perspective, one can ask to what extent the particular paradox is dis/solved by the particular interpretation, or what type of interpretations it rules out. The "paradoxes" are partially conceptual, partially mathematical, so one has to be patient: if the given author is right in his mathematics, he still might be wrong, or just too simplistic, in his interpretation/conclusions. In fact it is better to say: paradoxes and no-go results. As such, we have:

- Einstein-Schrödinger '35
- Einstein-Podolsky-Rosen '35
- Bell '64, Kochen-Specker '67
- quantum Zeno ('77+)
- quantum vacuum paradox ('89+) officially, but known since '60s)
- Reeh-Schlieder ('60s)
- Haag theorem & the problem of unitary inequivalence (including Borchers theorem)

Some form of summary

V. A SORT OF SUMMARY

The "quantum interaction problem" has shown that:

1. the mathematical formalism of quantum mechanics (von Neumann's or Dirac's) is insufficient.
2. the crucial problem is the lack of any definite (general & mathematically well-defined) method of ~~model~~ quantitative model construction which would possess non-trivial temporal behaviour corresponding precisely to the experimentally specified constraints.
3. the perturbative techniques of path-integration and renormalisation within the frames of linear theory in face of genuine presence of non-linear transformations in all approaches to non-equilibrium statistical mechanics and statistical inference, and in face of non-linear character of general relativity and in face of "1." above strongly suggests that the mathematical formalism of nonperturbative quantum theory should be non-linear in some suitable sense.

The quantum theory is something yet to construct.
But we know already some strict pieces of information about it, or — more precisely — about our own current state of knowledge:

1. the only strict general approach to mathematical formalism of quantum theory is the algebraic approach, but it provides no operational rules and no description of "interacting" models.
2. the only general description of operational foundation of quantum theory is provided by convex/semispectral approach, but it provides also no method of quantitative model construction that would be able to transcend perturbative q.f.t. techniques.
3. the only strict approach to "interacting" relativistic quantum models is Schwinger's source theory but we do not know nothing about it (learn!)
4. there exists a deep connection between the statistical mechanics and quantum theory (and statistical inference), as exposed by the methods of: 1) path integrals equipped with euclidean rotation, 2) renormalisation, these two methods are currently the main methods of quantitative model construction, but they lack a general underlying mathematical theory/foundational framework and work only perturbatively.

We also have some important interpretational hints:

1. Haag's thm: "quantum particles" are well-defined only when they do not interact and when they cannot be measured (very similar to the failure of kinetic [& ergodic] approach to foundation of statistical mechanics), Borchers's thm: "quantum fields" are irrelevant for all "quantum field theoretic" measurements ⟹ quantum theory is not about "matter".
2. interpretational problems of quantum theory disappear/dissolve when some sort of bayesian interpretation of quantum probabilities is adopted, and every ontological interpretation has some important problems ⟹ quantum theory is not about "things" but about "knowledge" (or, if you prefer, "information")

NEW!

THE DENKSTIL: (or ansatz, hypothesis, paradigm – if you want)

1. Quantum theory is a theory of statistical inference in the same sense as statistical mechanics viewed from the Jaynes–Ingarden point of view (as a branch of theory of probability/inference/information).
2. If QT and SM are regarded just as particular instances of statistical inference, then the task of solution of three unrelated problems turns into task of solving one foundational problem, and we can gain invaluable input from the knowledge accumulated in three different branches. Thus, by accepting this denkstil, we get a ⩾9x size/cost reduction of the problem!
3. If nonperturbative quantum theory is a nonlinear theory and if it contains such objects as riemannian metrics and affine connections, then it might be by itself "a quantum gravity theory" without any quantisation. This might be a "gravitating quantum theory" for free!

- "OK. And now what?"

— Well, now we have to understand better the existing structural problems and approaches, in order to turn denkstil into intersubjective reality, or in order to turn it down. In any case, we can learn sth new!