Fragment of dialogue

> *You: What is the world like?*
>
> *me: Like that!*

Unassailable. Also uninteresting.

> *You: What is 'like that' like? (or maybe: What physical theory is true of the world?)*

If I'm cooperative, I might start to tell you about key physical properties.

Claim: to tell you much about how the world *is*, according to physics, I have to tell you quite a bit about how the world *might be*, according to physics.

Properties and possibilities

Trying to say what position is.

- How it's measured.
  Not going to take you very far into the physics. Suppose the physics is Newtonian.
- *position*'s rate of change is *velocity*. And velocity's rate of change is *acceleration*.
- And how a system's *position* changes over time is governed by equations of motion determined by Newton's second law which relates that system's *acceleration* to the *forces* acting on it.
- ...

An account of how Newtonian theory relates position to other magnitudes. Also an account of the role position plays in characterizing and structuring situations that, according to Newtonian theory, are possible (aka Newtonian possibilities).

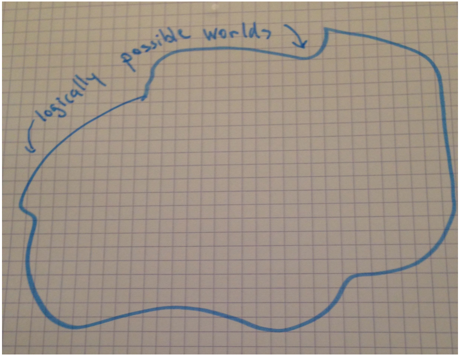
Lapsing into philosophy-speak

To fully illuminate what Newtonian position is, I need to tell you what worlds are possible according to Newtonian theory, and what role position plays in circumscribing that collection of possible worlds.

- if, rather than Newtonian, the world were aristotelian, or galilean, or relativistic, or quantum mechanical or ..., the list of properties and/or the ways they were organized would be different.
- So would the collection of worlds possible.
- This is as it should be: my account of what the world is like should vary with the theory of physics true of the world.
- Also, these accounts aren't all-or-nothing. And it is probably a question of taste at what point the characterization of possible worlds ceases to be useful ("what would the world be like if it contained no matter...?").

Interpretation, possibility, and realism

An illuminating account of what the world *is* like, according to a theory of physics T, is also an account of the ways the world *might be*, according to T.



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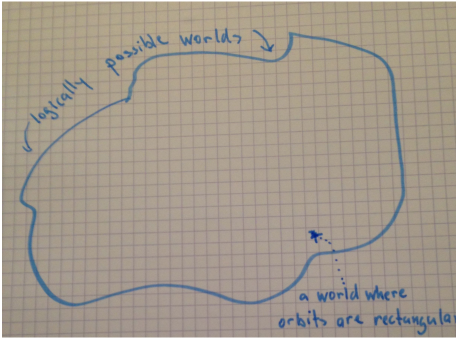

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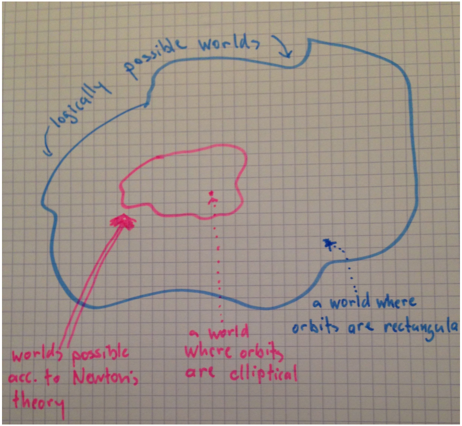
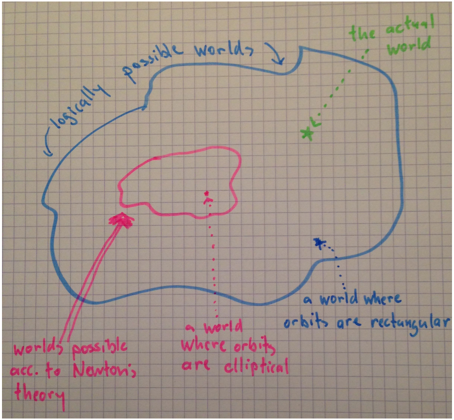


Following van Fraassen, call such an account an interpretation of T.

Interpretation, possibility, and realism

A scientific realist about T believes that the actual world is the way T says it is



She believes the worlds possible according to T include our actual world.

Today's Agenda

Some things QM_∞ might teach us about interpretation, physical possibility, and scientific realism.

(QM_∞: Quantum Field Theories; the thermodynamic limit of quantum statistical mechanics (that is, the limit as the number of micro constituents of a thermal system and the volume they occupy go to ∞))

Autobiographical interlude

Foundations of ordinary QM: non-locality; measurement

Compelling. Unresolved. Beautifully discussed. Also unbeautifully.

An observation: The foundational problems of ordinary QM can be motivated by appeal to a pair of two level systems.

A question: is there anything sui generis and foundationally interesting about *more complicated* quantum theories?

The existing literature: “C* algebras, “the ultra-weak topology, “the Reeh-Schleider theorem”

An epiphany: an algebra is simply a collection of elements along with a way of taking products and sums of those elements.

An idea: try to write the introductory survey article I had sought in vain.

It took me over a decade, ran to almost 400 pages, and weighed nearly 2 pounds (hardcover), but I managed it: *Interpreting quantum theories: the art of the possible* (OUP: 2011).

Something sui generis?

Ordinary QM: we know what the theory is; we just don't know how to make sense of it.

QM_∞: We don't even know what the theory is!

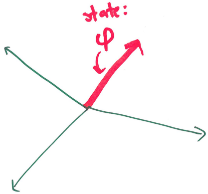
- A quantization recipe.
- Why its results for ordinary QM are consistent.
- Why its results for QM_∞ *aren't*.
- Some questions that might prompt.

Classical Mechanics: a particle of mass m moving in 1-d

- Canonical observables q (position) and p (momentum) coordinate a phase space of possible states.
- Other physical magnitudes are functions of q and p: for instance, kinetic energy $E = \frac{p^2}{2m}$.
- upshot:a system's classical state enables one to predict with certainty the values of all physical magnitudes pertaining to the system.
- These magnitudes have an *algebraic structure* supplied by the Poisson bracket $\{f, g\} := \sum_i (\frac{\partial f}{\partial q_i}\frac{\partial g}{\partial p_i} - \frac{\partial f}{\partial p_i}\frac{\partial g}{\partial q_i})$

All discourse owes its existence to the interweaving of forms. (Plato *Sophist* 259e)

Quantum theory, generically



A (pure) quantum state corresponds to a vector ϕ in a Hilbert space $\mathcal{H}$.

Physical magnitudes (aka observables) correspond to self-adjoint Hilbert space operators $\hat{A}$ on $\mathcal{H}$.

- Their possible values are quantized.
- For each observable $\hat{A}$, the state ϕ determines a probability distribution over $\hat{A}$'s possible values. Usually, these probabilities are different from 0 and 1.
- Usually, there is a tradeoff between ϕ's capacity to predict $\hat{A}$'s values and ϕ's capacity to predict $\hat{B}$'s values.

The commutator bracket $[\hat{A}, \hat{B}] = \hat{A}\hat{B} - \hat{B}\hat{A}$ sets the terms of this tradeoff, and endows the collection of quantum magnitudes with an algebraic structure.

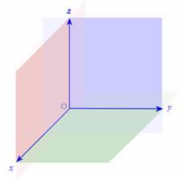
Hamiltonian Quantization Recipe

Classical theory: Poisson Bracket between p and q is

$$\{p, p\} = \{q, q\} = 0, \ \{p, q\} = 1$$

To quantize this theory is to find operators $\hat{Q}$ and $\hat{P}$ on a Hilbert space $\mathcal{H}$ that satisfy the canonical commutation relations

$$[\hat{P}, \hat{P}] = [\hat{Q}, \hat{Q}] = 0, \ [\hat{P}, \hat{Q}] = i\hbar\mathbb{I}$$



Quantizing, cont.: A recipe for quantum physics discourse

- Find operators satisfying CCRs, e.g.

$$\hat{P}, \hat{Q} \text{ acting on } \mathcal{H}$$

This is a Hilbert space representation of the CCRs; $\hat{P}$ and $\hat{Q}$ correspond to momentum and position.

- take products, linear combinations of these

$$\frac{\hat{P}^2}{2m} + g\hat{Q} := \hat{H} \text{ acting on } \mathcal{H}$$

- Add "limit points"

$$\lim_{n\to\infty}\left(\sum_{i=1}^{n} \frac{(-i\hat{H}t)^n}{n!}\right) = exp(-i\hat{H}t) := \hat{U}(t) \text{ acting on } \mathcal{H}$$

the result: the observable algebra $\mathfrak{B}(\mathcal{H})$ whose elements correspond to quantum properties.

- Add states (and dynamics!)

Quantizing: summing up

So far: Poisson bracket $\rightarrow$ CCRs $\rightarrow$ representation on $\mathcal{H}$ $\rightarrow$ collection of quantum properties $\mathfrak{B}(\mathcal{H})$.

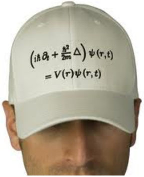
(given certain apparently innocuous assumptions about how good states behave) pure *states* of the quantum theory correspond to vectors in $\mathcal{H}$; density operators $\mathbb{T}^+(\mathcal{H})$ correspond to all states.

The point: Starting with a classical theory and following this *Hamiltonian quantization recipe* eventuates in a quantum theory whose observables reside in $\mathfrak{B}(\mathcal{H})$, and whose states are given by $\mathbb{T}^+(\mathcal{H})$.

$\mathbb{T}^+(\mathcal{H})$ gives the possibilities the theory allows; $\mathfrak{B}(\mathcal{H})$ tells us how those possibilities are structured. This is the germ of an interpretation of the theory.

Uniqueness worries

Can we, starting from the same classical theory and competently following the recipe, obtain different quantum theories?



$$\begin{pmatrix} a_{11} & \dots & \dots \\ \dots & \dots & \dots \\ \dots & \dots & a_{33} \end{pmatrix}$$

Standard answer: NO!

> *Stone-von Neumann Theorem (1931): Suppose T is a theory of classical mechanics whose degrees of freedom are finite in number. Then all Hilbert space representations of the CCRs arising from T are unitarily equivalent.*

And there are pretty good reasons [omitted] to regard theories arising from unitarily equivalent representation as *physically equivalent*.

Why the Stone-von Neumann theorem is reassuring

Suppose Werner's and Irwin's Hilbert space representations are unitarily equivalent. Then (and only then!) the quantum theories based on those representations are related as follows:

- There is an *algebraic structure-preserving* bijection from Irwin's collection of physical magnitudes to Werner's collection of physical magnitudes; and
- There is a bijection from the set of states Irwin regards as physically significant to the set of states Werner regards as physically significant; and
- These bijections "preserve empirical content": the predictions any Werner state makes about any set of Werner observables are exactly duplicated by the predictions the corresponding Irwin state makes about the set of corresponding Irwin observables, and vice versa.

Werner's quantum theory recognizes the *same set of physical possibilities* as Irwin's theory.

Why the Stone-von Neumann theorem isn't reassuring

Sometimes the classical theories we set out to quantize involve *infinitely many* degrees of freedom. E.g.: classical field theories.

We can still carry out the Hamiltonian quantization recipe to quantize such theories. But

The Stone-von Neumann theorem, presupposing that the theory to be quantized has only finitely many degrees of freedom, fails to apply to these quantizations. So

When we apply the quantization recipe to a classical field theory, we can obtain unitarily *inequivalent* representations of the CCRs encapsulating its quantization. Each purports to be the QFT that quantizes the classical field theory. Different quantizations can differ on such physically basic questions as whether there are particles at all, and if there are, whether it's possible to have only finitely many of them.

What is a quantum theory? What criteria of identity do quantum theories obey? What does it really takes to be a quantum state or a quantum property? (and how do we frame and adjudicate answers to questions such as the foregoing??)

Some Strategies

Two broad responses to the the non-uniqueness of representations of the CCRs for a QFT:

- Privileging. Identify the QFT with a unique physically significant representation of the CCRs, and consign rival representations to the dustbin of mathematical artefacts.
- Abstraction. Ascend a level of abstraction to identify the QFT with features all representations of the CCRs share, and consign features parochial to particular representations to the dustbin of physically superfluous structure.

Which interpretive strategy should we adopt?

The book sets out to examine uses to which theories of QM_∞ are put, in the hopes that a winning interpretive strategy (i.e., the strategy that makes the most sense of the most uses) will emerge.

Hopes dashed

Theories of QM_∞ are used in many contexts — particle physics, cosmology, black hole thermodynamics, solid state physics, homely statistical physics—, and with many aims — to model, explain, predict, and serve as launching pads for the development of future physics.

An interpretive strategy that supports one aim in one context may frustrate another aim in another context. Or another aim in the same context, or the same aim in another context or even the same aim in the same context ...or so I try to argue in the book.

- Privileging has worked capitally for standard particle physics, which privileges a representation by requiring obedience to the symmetries of a particularly simple spacetime (Minkowski spacetime).
- Still, there are aspects of standard particle physics—for instance, the "soft photons" involved in certain scattering experiments — that can't be modeled in the privileged representation, but can be modeled by discarded representations

Continuing to dash hopes

- And some explanatory agendas involving particles exceed the confines of a single privileged representation: accounts of cosmological particle creation appeal to different (and rival) representations, privileged at different epochs in the history of the cosmos.
- QM_∞ abounds in other explanatory agendas — symmetry breaking, phase coexistence, superconductivity, the dynamics of an expanding universe — that are hamstrung by the privileging strategy.

Abstraction lends aid and comfort to some of these agendas. But not all of them: among the surplus properties the abstraction strategy consigns to physical irrelevance are the order properties that distinguish between the distinct phases in a phase transition, as well as the properties that enable us to makes sense of the dynamics of mean field models.

There are worthwhile physical projects promoted by each strategy, worthwhile projects frustrated by each strategy, and worthwhile physical projects frustrated by both strategies. There is no winning strategy.

Hopes revived?

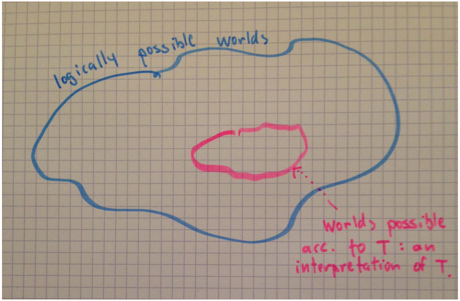
A winning strategy for interpreting QM_∞ has failed to emerge. Does it follow that we don't understand QM_∞?

On the contrary!

- Noticing the failure — noticing that equipping a theory of QM_∞ with constitutive CCRs leaves open a host of interpretive questions, questions which can be and in practice are answered in different ways in different contexts of aim and application — *is* understanding QM_∞.
- It's also understanding something about science, something that might change the terms of the scientific realism debate.

Revisiting Realism

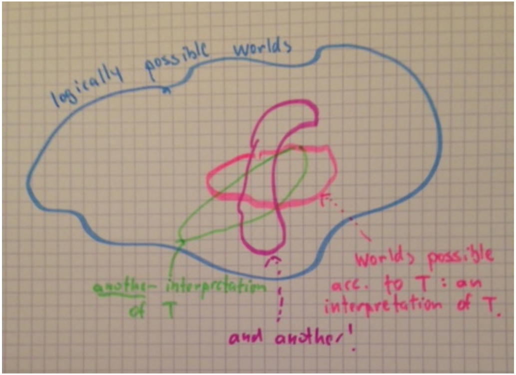
What the scientific realist believes when she believes a theory T: an interpretation of T — an account of what worlds are possible, according to T. She also believes our world is one of those.



The reason the realist typically gives for her beliefs: the best explanation of T's success is that the world really is the way T, under her favored interpretation, says it is.

Still Revisiting Realism

But if T is a theory that purchases different successes under different and rival interpretations (as I've claimed theories of QM_∞ do), the force of this reason is attenuated.



one way the world is, but a variety of collections of ways it might be, according to T.

The warrant for belief in T isn't concentrated on a single interpretation, but dispersed among the various interpretations that enable T to succeed in various circumstances.

Virtue reconceived?

Realism/Antirealism debate: a debate over the anatomy of scientific virtue. How and to what extent is the virtue of truth implicated in other scientific virtues? (Ambiguity typically doesn't appear on the list.)

> *I claim that the success of current scientific theories is no miracle. It is not even surprising to the scientific (Darwinist) mind. For any scientific theory is born into a life of fierce competition, a jungle red in tooth and claw. Only the successful theories survive—the ones which in fact latched on to actual regularities in nature. (van Fraassen 1980, 40)*

A theory that underdetermines its own interpretation is like a healthy breeding population: it has a shot at enough diversity to (under some interpretation or another) meet the variety of demands its scientific environment places on it. Like survival, 'empirical success' is a convoluted, chancy, and conditioned thing. Like genetic diversity, 'semantic indecision' situates its possessor to respond successfully to the changing circumstances on which its survival depends.