Utrecht University

Theoretical Physics Department

Quantum Foundations as a Guide for Refining Particle Theories

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Milestones in physics:

Forces: Newton (17^{th} century), and Maxwell (19^{th} century),

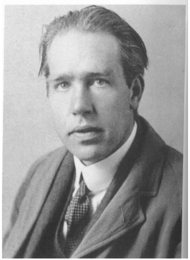
Atoms and molecules (end 19^{th} century)

Quantum mechanics and relativity (beginning 20^{th} century)

The Standard Model (second half 20^{th} century)

Should we now add 'string theory' and 'CFT/AdS duality' ?
Or are we again in a 'crisis' ?

Opinions are divided.
But we can do better: *Hidden weaknesses* in our best theories today.



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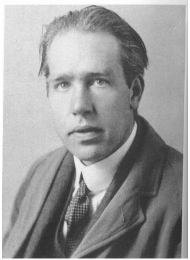
If you have the equations for the quantum limit, you can almost *derive* the quantum equations.

Even regarding the most difficult issue:



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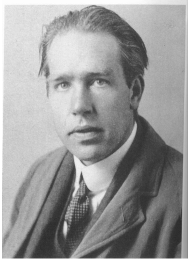

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general agreement was reached.

It is amazing how well the theory predicts all probabilities *without* the need to answer this last question. Therefore,

As for:

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Take: the Standard Model of the Elementary Particles.

Present elementary particle theories have weak points. Usual complaints:

1. The theory does not fully include gravitation;
2. No explanation of the cosmological constant;
3. No clues for further unification of all forces.

We tried all possible alleys to address these problems head on. But these attempts were all made by using the same techniques over and over again. I propose to question these techniques:

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And that is possible !

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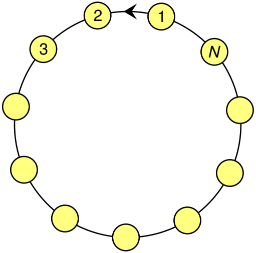
Therefore, divergent perturbation expansions should not be at the basis of our theories.

Yet today, they are!
Formulate the laws with infinite precision. Make theories that produce certain ("ontological") descriptions of what goes on. It is possible!

Basic Models: combine *realism* with *discreteness.*



1. The periodic chain. Ontological (= real) states:

$$|0\rangle,\ |1\rangle,\ \ldots\ |N-1\rangle$$

Evolution law: $|k\rangle_{t+\delta t} = U(\delta t)\,|k\rangle_t$

$$U(\delta t) = \begin{pmatrix} 0 & 0 & 0 & \ldots & 1 \\ 1 & 0 & 0 & \ldots & \\ 0 & 1 & 0 & \ldots & \\ & & 1 & & \end{pmatrix}$$

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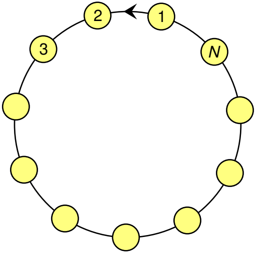

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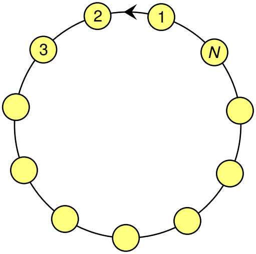

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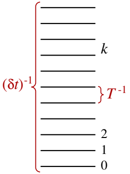
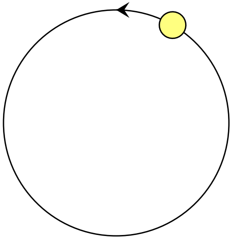


$$H = \frac{2\pi}{N\,\delta t}\,n = \omega n$$



To be used as elementary ingredients of theoretical constructions

The continuum limit.

Ontological states: $|\phi\rangle$

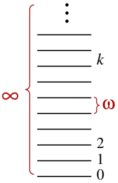
Evolution law: $\frac{\mathrm{d}}{\mathrm{d}t}|\phi\rangle_t = \omega$

$$U(\delta t)|\phi\rangle = |\phi + \omega\delta t\rangle$$

$$U(\delta t) = e^{-iH\,\delta t}\ , \quad \frac{\mathrm{d}|\psi\rangle}{\mathrm{d}t} = -i\,H|\psi\rangle$$

$$|n\rangle^E \ \stackrel{\mathrm{def}}{=}\ \frac{1}{\sqrt{2\pi}}\oint e^{i\phi n/N}|\phi\rangle^{\mathrm{ont}}\ , \qquad 0 \le \phi < 2\pi\ ; \quad n = 0, \cdots,\ \infty\ .$$

$$|\phi\rangle^{\mathrm{ont}} \ = \ \frac{1}{\sqrt{2\pi}}\sum_{n=0}^{\infty} e^{-i\phi n/N}|n\rangle^E\ .$$



We generate exactly the spectrum of the harmonic oscillator: $H = \omega\, n$

Important theorem: At integer time steps, this Schrödinger equation sends collapsed wave functions (delta peaks) into collapsed wave functions. It does not generate superpositions.

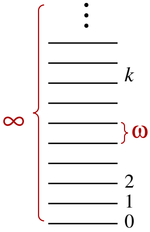
Important theorem: if system A has the same spectrum of energy eigenvalues as system B then a mapping $A \leftrightarrow B$ exists , so that the two systems are physically the same.

But to make contact with our experiences with today's physics, we may introduce perturbation expansions.
They do almost certainly diverge! And it is these, imperfect, equations that generate superpositions.

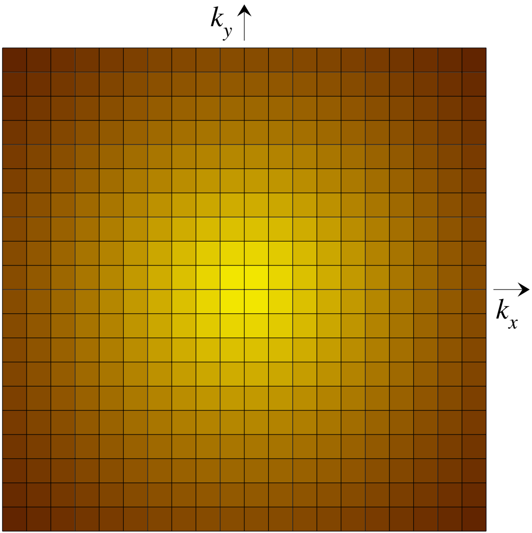
Thus, all systems that consist of *harmonic oscillators* can be formulated in a basis of Hilbert space that sends ontological states into ontological states.

With infinite precision.

Quantum field theories without interactions, consist of harmonic oscillators! It is here that we start with our improvements!



We first go to momentum space:



For a theory in a box, momentum space is discrete.

Free field theories:

$$H = \frac{1}{2}(\vec{k}^{\,2} + M^2)\Phi^2 + \frac{1}{2}\Pi^2 .$$

Single harmonic oscillator in every $\vec{k}$ box.

Apply what we did 3 slides ago, to find the ontic variables

$$b(\vec{k}, t) = e^{-i\phi(\vec{k}, t)} .$$

Fourier transform back: to get $b(\vec{x},\, t)$.

These $b(\vec{x},\ t)$ obey *classical equations!*

$$\ddot{b}(\vec{k},t)=-(\vec{k}^{\,2}+M^2)\,b(\vec{k},t)\ ,\qquad \text{or}\qquad \ddot{b}(\vec{x},t)=\big((\vec{\partial}_x)^2-M^2\big)\,b(\vec{x},t)\ .$$

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However, we must be aware of a problem: $b(\vec{x},t)$ obeys a second order field equation, while there is only one variable ϕ. The amplitude $|b|$ seems not to be ontological (while it stays 1 in $\vec{k}$ space). Related problem: in the quantum field theory we must first select the positive energy solutions, and constrain the negative energy ones.

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In our free boson model, the solutions to choose are the ones that keep the energies of the free-particle states non negative. It is well-known how to use dispersion relations and $i\epsilon$ terms in the propagators to find the correct solutions in quantised field theories.

So we have a problem where we know what goes in and what should come out, but a completely robust formalism has not been derived as yet.

I think this problem can be solved – stay tuned.

Note that, as we start off with an unperturbed theory with short periodicities, we have in our perturbative formulation, intermediate states with high energies. Of these, perturbation expansions only use the lowest energy states. This may make perfect sense in the perturbative corrections, but it is not right if we try to “go beyond” perturbation theory.

See arxiv:2103.04335[quant-ph]

About SM constants:

Earlier investigations suggested that in deterministic theories, interaction constants can only take rational values such as $1/N$. Gravity theories suggest that entropies near black holes are bounded, which would suggest that N values cannot be arbitrarily large.

About Bell inequalities:

Bell's inequalities are violated. This is because statistical independence dus not hold.

Our 'hidden variables' carry energy. The only mode without any statistical correlations is the zero energy mode. But any interaction with these hidden variables affects the energies. This means that, if the outcome of a measurement is assumed to be caused – invisibly – by the hidden variables, then after the interactions these hidden variables will be in a superposition of zero energy and finite energy modes. Their probability functions are now correlated.

To make our point in terms of models, we are constructing models that generate quantum interactions in terms of classical equations. This seems to be possible without any violation of locality; there will be violation of statistical independence in a very natural manner.

Therefore, before repeating any experiments, one must reset the hidden variables. This is why 'counter factual' measurements are not possible.

Unfortunately, this work is not finished.

the end

THANK YOU