A "Free Will" Interpretation of Quantum Field Theory

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Introduction

Decius:

Most mighty Caesar, let me know some cause, ...

Caesar:

The cause is my will. I will not come.

Shakespeare, Julius Caesar

"Will" is an inner experience and I comment on its relation to matter later. The adverb "free" implies that will allows for non-causal actions.

No wonder, that free will is despised by many physicists, whose goal it is to explain everything by physical causes (from initial conditions).

But, it appears natural to the layman, who thinks that she or he can freely choose from alternatives.

Is the "will" really free or causally determined?

Is the future set? Many scientists, philosopher and playwrights have considered this question without concluding on definite answers. Shakespeare's play answers it ambivalently ...

The Phenomenon in Physics Terms

What are the apparent choices?

In physics terms the answer is astonishingly simple. Free Will appears to be an Ability To Make Decisions, which are all about converting or not converting some form of energy into another.

Whether a decision is made in one or another way leads to macroscopic differences in the energy-momentum (including angular momentum) distribution of the world, while the sums of these quantities stay conserved.

An Example

John finds

No Beer in the Fridge!

The decision to be made:

Drive ten miles to the supermarket or go to bed without enjoying beer first.

What's the difference?

(Besides having beer or not.)

Chemical energy stored in the gas tank of John's car is or is not converted into heat resulting in distinct energy-momentum distributions of the world.

What is the cause of this difference? Tracking it back we arrive at John's thoughts and emotions, which are associated with electromagnetic (EM) currents and fields created by John's brain. Assuming that the brain is a state of ordinary matter to which the laws of physics apply we realize that these laws appear to be incomplete: There is nothing in the physical equations, which tells us that a bunch of atoms and/or their fields could enjoy themselves, feel pain, and so on. We only know this through our inner (subjective) experience and communication with other humans. Still, whenever we apply our physics equations they seem to work.

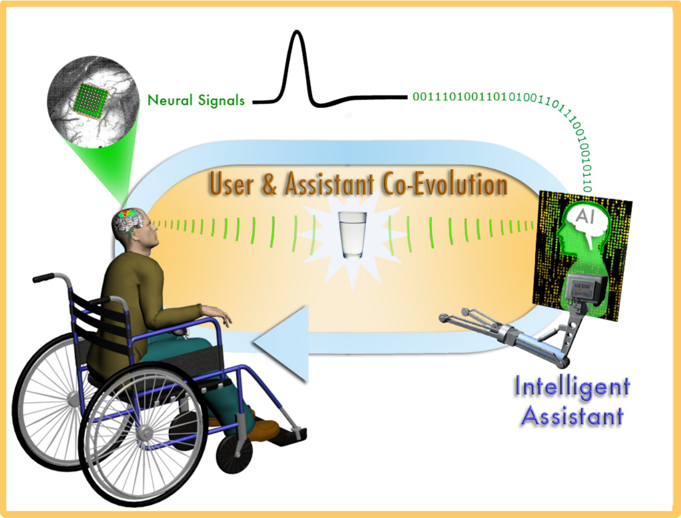
By analogy we expect sensations also in the brains of higher mammals, while we are even less sure about lower biological organisms. We do not expect them in a digital computer and certainly not in in a rock. But, do we really know? It is all ordinary matter and we have no fundamental theory about its subjective side.

However, there has been considerable phenomenological progress in neuroscience:

Thoughts $\rightarrow$ Specific EM output.

Specific EM input $\rightarrow$ Sensations in the brain.

Neuroprosthetic Controls



From: www.bme.miami.edu/nrg/ (University of Miami, Neuroprosthetic Research Group (NRG)).

Robot controlled by thoughts.

Feed back? Presently through the eyes. No sense of touch (makes control difficult). Work on feedback through artificial input to the brain.

Examples of such input:
Cochlear devices, rewiring to other body parts.
Problem: Fine tuning to single neurons.

Understanding remains phenomenological. Level of Kepler's laws instead of Einstein's gravity.

Reference for prosthetic controls:
Roberta Kwok (feature news), Nature 497 (2013) 176.

Back to John

We are interested in the transition

Undecided → Decided in John's brain,

which constitutes a reduction of a superposition of two possibilities into one reality, though ultimately only after the facts. The initial decision sets in motion an avalanche (microscopic to macroscopic) of changes in the energy-momentum distribution of the world, which all could or could not have happened.

Continuously choices are made, e.g., when approaching a traffic light that is just switching to red.

Consciousness is only rarely involved. Other (trained) parts of the brain or just the spine may act faster.

True and pseudo randomness

An outside observer can predict decisions of free will only in a statistical sense but not with certainty. Otherwise the will would not be free (chance to disprove free will experimentally!). Therefore,

Free will $\rightarrow$ True randomness in the laws of nature.

However, this is practically indistinguishable from classical chaos or causal pseudo randomness as used in computer simulations. I do not attempt to settle this, but address the more modest question:

Assuming free will, is it **consistent** with our present understanding of the laws of nature?

Quantum Field Theory (QFT)

Processes in the human body are essentially based on QED, which is part of the Standard Model. We have to neglect gravity, showing again that our understanding of the laws of nature is imperfect.

One formulation of QFT describes the time evolution of a quantum state $|\Psi\rangle$ by a Hamiltonian operator H so that

$$|\Psi(t)\rangle \;=\; |\Psi(\triangle t + t')\rangle \;=\; U(\triangle t)\,|\Psi(t')\rangle$$

with $U(\triangle t) = \exp(i\,H\,\triangle t)$ holds, called

Causal Unitary Time Evolution (UT).

Measurements

To measure a property "a" of the state $|\Psi(t)\rangle$ one has to project onto an eigenstate $|\Psi_a\rangle$ and obtains Born's probability

$$P_a(t) \;=\; |\langle\Psi_a(t)\,|\,\Psi(t)\rangle|^2 \;.$$

to observe a. When a measurement finds a at time t_0, it transforms in some small time interval before t_0

$$|\Psi(t_0)\rangle \;\to\; |\Psi_a(t_0)\rangle \;.$$

Otherwise (100% efficiency assumed) the transformation is to a state with the property $\neg\, a$ (not a)

$$|\Psi_{\neg\, a}(t_0)\rangle \;=\; |\Psi(t_0)\rangle - \langle\Psi_a(t_0)\,|\,\Psi(t_0)\rangle\,|\Psi_a(t_0)\rangle \;.$$

We call such a process Reduction (R).

A single particle illustration

We are interested in the probability $P_V(t)$ that the particle can in a time interval $t \pm \triangle t$ ($\triangle t$ small) be found in a volume V. Denoting its state by $|\psi(t)\rangle$, the wave function and probability density are

$$\psi(\vec{x},t) = \langle \vec{x} \,|\, \psi(t)\rangle \ , \quad \rho\,(\vec{x},t) = |\psi\,(\vec{x},t)|^2$$

and the probability becomes

$$P_V(t) \ = \ \frac{1}{2\triangle t} \int_{t-\triangle t}^{t+\triangle t} dt' \int_V d^3x\, \rho\,(\vec{x},t') \ .$$

It is confirmed by repeating frequently an experiment that detects the particle in V applying a measurement device to the quantum state.

Experimental Quantum Measurements

In the Lab nobody runs around with projection operators!

All real measurement devices make decisions about converting or not some form of energy into another, resulting via an avalanche mechanism in macroscopic differences of the energy-momentum distribution.

Phenomenologically, a measurement device does just what free will does.

Examples: Photographic plates, Geiger counters, bubble chambers, photo multipliers, ...

Causality and Physics

God does not play dice. (Albert Einstein)
Stop telling God what to do, Albert. (Niels Bohr)

UT is deterministic, while R is in the traditional Copenhagen interpretation truly random.

The latter left many physicist uncomfortable, most prominently Albert Einstein, who favored so called hidden variables, which are now experimentally ruled out on the basis of Bell's inequalities.

Nevertheless, many physicists dislike up to the day true randomness in the laws of nature and a trend is towards accepting a process called Decoherence for the rescue.

Interaction with the Environment

There are two alternatives when one applies UT to the combined system of quantum object and measurement device:

1. UT will automatically reduce the quantum system.
2. R is an independent process, which interrupts UT.

The first option implies that the entire time evolution is deterministic, but one encounters severe difficulties as outlined in the following for a single particle. Let

$$|\psi(t)\rangle \;=\; a_1\, |\psi_1(t)\rangle + a_2\, |\psi_2(t)\rangle$$

and we are interested in the (isolated) wave function

$$\psi(x,t) \;=\; \langle \vec{x} \mid \psi(t)\rangle \;=\; a_1\, \psi_1(\vec{x},t) + a_2\, \psi_2(\vec{x},t)\,.$$

As long as $\psi_1(\vec{x},t)$ and $\psi_2(\vec{x},t)$ do not overlap

$$\rho(\vec{x},t) = |\psi(\vec{x},t)|^2 = \rho_1(\vec{x},t) + \rho_2(\vec{x},t) \quad \text{with}$$
$$\rho_i(\vec{x},t) = |a_i|^2 \, |\psi_i(\vec{x},t)|^2 \,, \quad |a_1|^2 + |a_2| = 1\,.$$

Assume $\psi_i(\vec{x},t)$ is around some time t_0' localized in V_i, then the probability to find the particle in V_i is

$$P_{V_i} = \int_{V_i} d^3x \; \rho_1(\vec{x}) = |a_i|^2 \,, \quad (i=1,2)\,.$$

If a measurement with 100% efficient detectors is performed at t_0' in these two regions, it collapses the state into either one of the alternatives:

$$|\psi(t_0')\rangle \rightarrow |\psi_1(t_0')\rangle \quad \text{with probability} \quad P_{V_1} = |a_1|^2 \,,$$
$$|\psi(t_0')\rangle \rightarrow |\psi_2(t_0')\rangle \quad \text{with probability} \quad P_{V_2} = |a_2|^2 \,.$$

We would like to describe this interaction with the measurement device now as a UT of a state $|\Psi_a(t)\rangle$, which includes $|\psi(t)\rangle$ and its environment. Some time before the interaction with the measurement device the state is approximately factorized (use pure states!)

$$|\Psi_a(t)\rangle = a_1 \, |\Psi'(t)\rangle \, |\psi_1(t)\rangle + a_2 \, |\Psi'(t)\rangle \, |\psi_2(t)\rangle \ ,$$

where $|\Psi'(t)\rangle$ is the state of the environment. Factoring out $|\psi(t)\rangle$ is permitted as long as we can neglect the interaction with its environment. Let t', $t' < t_0'$ be a time where this is still the case. If we do not care about what happens during the time interval $t' < t \leq t_0'$, the reduction can be written as

$$a_1 \, |\Psi'(t')\rangle \, |\psi_1(t')\rangle + a_2 \, |\Psi'(t')\rangle \, |\psi_2(t')\rangle \ \rightarrow \ |\Psi_1(t'_0)\rangle$$

with probability $P_{V_1} = |a_1|^2$ versus

$$a_1 \, |\Psi'(t')\rangle \, |\psi_1(t')\rangle + a_2 \, |\Psi'(t')\rangle \, |\psi_2(t')\rangle \ \rightarrow \ |\Psi_2(t'_0)\rangle$$

with probability $P_{V_2} = |a_2|^2$. These equations reveal that the measurement device may have swallowed the quantum object $|\psi(t')\rangle$.

Can we avoid to postulate R as an interruption of unitary time evolution and instead get the alternatives from UT, eventually assuming undetectable small differences in the initial conditions?

Without modification of the theory (including its interpretation) this is impossible. The reason is that UT is linear and preserves the normalization of the states. Therefore,

$$| \Psi'(t_0') \rangle \, |\psi_i(t_0')\rangle = U(t_0' - t) \, |\Psi'(t)\rangle \, |\psi_i(t)\rangle$$

implies $|a_i| = 1$ for either $i = 1$ or 2 at times t. Is this a difficulty? For a causal interaction it is required that the outcome is determined by the initial conditions and $a_1 = 0$ as well as $a_2 = 0$ are admissible.
The problem is that interaction with a different environment allows one to demonstrate that we are able to prepare superpositions of single particle with both initial coefficients $a_1 \neq 0$ and $a_2 \neq 0$.

Double Slit Experiments Revisited

Assume that the volumes in which the two parts of our wave are localized at some time are two slits. Instead of performing position measurements at the slits, we let the wave pass. Denote the (approximate) time at which the wave passes through the two slits by t'_0 and consider times $t' > t'_0$. With an appropriate choice of initial parameters the time evolution will be so that

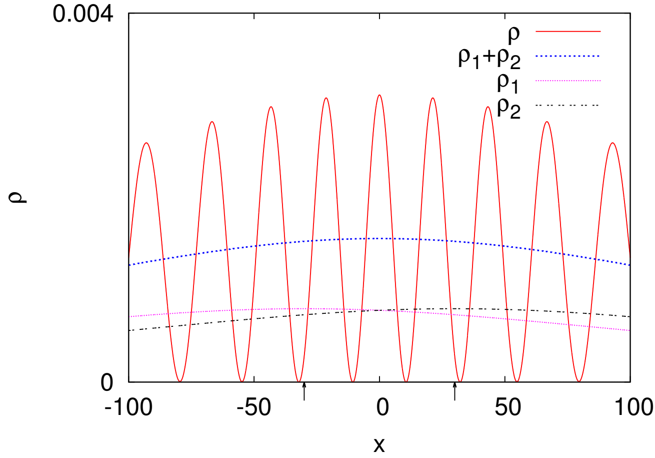
$$\rho_{\rm ifr}(\vec{x},t') \;=\; {\rm Re}\,[a_1\,a_2\,\psi_1(\vec{x},t')\,\psi_2(\vec{x},t')] \;\neq\; 0$$

holds for sufficiently large times t' at suitable positions $\vec{x}$ and the probability density becomes

$$\rho\,(\vec{x},t') \;=\; \rho_1\,(\vec{x},t') + \rho_{\rm ifr}(\vec{x},t') + \rho_2\,(\vec{x},t')\;,$$

where $\rho_{\rm ifr}(\vec{x},t')$ is due to interference.

Interference: 2D Example, $a_i = 1/\sqrt{2}$.



The positions of the two slits are indicated by arrows.

The experimental arrangement with two slits open can also be formulated as interaction with an environment. Let us denote its state vector by $|\Psi''(t)\rangle$. The initial state becomes replaced by

$$|\Psi_b(t)\rangle \;=\; a_1\,|\Psi''(t)\rangle\,|\psi_1(t)\rangle + a_2\,|\Psi''(t)\rangle\,|\psi_2(t)\rangle\;.$$

UT proceeds a bit longer than before, to t_0'', until a measurement is performed at a volume V_3 behind the slits, which collapses the state with probability

$$P_{V_3} \;=\; \int_{V_3} d^3x\;|\langle\vec{x}\,|\,\Psi_3(t_0'')\rangle|^2 \;=\; |\langle\Psi_3(t_0'')\,|\,\Psi_b(t_0'')\rangle|^2$$

into a state $|\Psi_3(t_0'')\rangle$. Again the fate of the wave is reduction, just later and with a different probability density in place.

Decoherence

Let us go back to measurement devices in place at V_1 and V_2. Continuing UT beyond the measurement time t_0' leads to a superposition of two macroscopically distinct branches: One with an avalanche in the energy-momentum distribution initiated at V_1 and nothing happening at V_2 and vice versa.
From performing such experiments we know that human observers find themselves attached to either the first or the second branch and not to both. Does this proof that the other branch has disappeared? If it is still there, how could we observe it? The way to observe two or more branches is to bring them together again for producing interference effects.

However, when one tries to follow the UT into the measurements, calculations get very involved. The evidence from the early steps of such calculations is that due to interaction with the environment decoherence sets in between the distinct branches of the state vector and makes it in practice impossible to observe interference effects between them.
In our example self-interference of a one particle wave is achieved by controlling (before measurement) carefully the interaction with its environment. The avalanche in the energy-momentum distribution accompanying a measurement prohibits this.

Many Worlds

Due to decoherence it has so far been impossible to demonstrate directly that a non-observed branch does no longer exist. Some physicists have invented a many-worlds interpretation, which rescues causal time evolution: At R the state vector, including ourselves, decoheres into branches that all survive. The $|a_i|^2$ become probabilities that one experiences when one goes through such multiplications of the world. As long as there is no interaction between the worlds, this belongs in the category of theories to which Wolfgang Pauli's remark *"not even wrong"* applies.

But gravity? $\rightarrow$ Non-linearity, chaos?

A causal scenario cannot really be ruled out.

True Randomness and Free Will

The door is wide open for true randomness in R!

This does not proof that free will exists, but if free will exists, R is the only place where it could act when we assume that QFT is applicable.

A conscious mind can explore the “other side” of random R. Unfortunately, biological systems (in particular the brain) are very complex, so that the analytical method runs into problems.

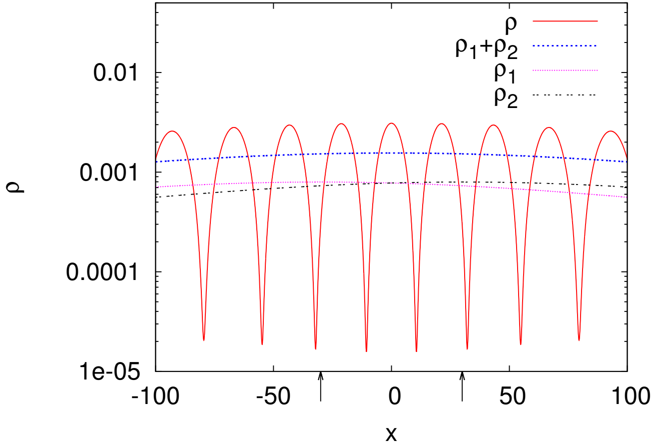
At least there is one immediate insight: The brain cannot only choose between alternatives, but also times decisions. Consequently, there should also be stochastic rules about the timing of R.

Reduction as an Independent Process

It seems to me that most laboratories are looking in the wrong direction. While many of the interference effects are amazingly counter-intuitive, this is snow from yesterday. Nowadays the real sensation would be to demonstrate R without measurement, called self-R. An example would be when for our double slit with both slits open the wave function $\psi(\vec{x},t)$ would in one out of hundred cases spontaneously collapse into either $\psi_1(\vec{x},t)$ or $\psi_2(\vec{x},t)$. The net result would be that the contrast of the interference becomes reduced:

$$\rho\,(\vec{x},t') \;\rightarrow\; \rho_1\,(\vec{x},t') + 0.99\,\rho_{\rm ifr}(\vec{x},t') + \rho_2\,(\vec{x},t')\ .$$

Interference with self-R.



Modification of the previous 2D Example.

Timing of R: Physicists have not been able to find out when R happens and whether this is an independent process from decoherence. From our inside experience some people think that there are decisions which we can place arbitrarily within a certain time period. For an outside observer this should result in a probability density $\rho(t)$ and the probability for R to happen in a time interval $t_0 \pm \triangle t_0$ becomes

$$p_r(t_0) \ = \ \int_{t_0-\triangle t_0}^{t_0+\triangle t_0} dt\, \rho(t)\,.$$

When R is an independent process, all R should be timed by such a scheme. What determines $\rho(t)$?
I have no real clue, but:

A Phenomenological Model for Timing of R

Restricted to two branches in the world of possibilities with initial superposition created at time $t = 0$:

$$p_r(t) = 1 - \exp[-B\, t \triangle E/\hbar]\,.$$

Here $\triangle E$ is the difference in the energy distribution (rest frame). B is a phenomenological constant, which has to be constrained by measurements and Planck's constant is introduced to make B dimensionless.

Example: Neutron.

It decays due to weak interactions with a large half-life time τ_h^n of 10 minutes 11 seconds into a proton, an electron and a neutrino, called now decay products.

With the neutron embedded in a cloud chamber the superposition is continuously reduced to the state of either a neutron or its decay products and the latter state is further reduced to one that is consistent with the visible tracks in the cloud chamber.

The design is always the same: Apparent freedom in the future energy-momentum distribution of the world leads to initially small differences between alternatives, which are amplified until the choice becomes macroscopically visible.

What happens to the unobserved neutron in vacuum?

Say, after 1 s.

According to the dogma it is still in a superposition, i.e., $p_r(1s) = 0$, but there is no experimental evidence unless someone succeeds with a 100% contrast interference experiment. In defiance of the dogma our model yields a non-zero probability that the superposition has self-reduced and the R-half-life time is

$$\tau_h^r = \frac{\hbar\,\ln(2)}{B\,\triangle E} \quad \text{with} \quad \triangle E = 0.78\ \mathrm{MeV}\,.$$

where the $\triangle E$ comes from the neutron-proton mass difference. To give an order of magnitude:

$$B = 6 \times 10^{-23} \Rightarrow \tau_h^r = 1\ \mathrm{s}.$$

Plenty of experimentally uncovered time for self-R!

Contrast Measurements

In practice a good contrast is difficult to achieve.

1. Interference effects are often extracted from an ensemble of events and are on top of a large background.
2. Even if every incoming wave can be controlled, one has still to verify that a decrease of the contrast is not a decoherence effect.

Decoherence may be the "Friction" of our Time.

The quest for Quantum Computers (QC) may bring some insight: Once decoherence is controlled, fundamental limitations due to self-R may survive. In contrast to the brain QC do not control the R-timing.

Summary and Outlook

1. Decisions about converting or not converting one form of energy into another appear possible by "free will" and change the energy-momentum distribution of the universe.
2. While sensations in our brains do not emerge from our present understanding of QFT, neuroscience presents an increasing wealth of phenomenological observations, which relate sensations in the brain to electromagnetic phenomena. A comprehensive collection of these experimental facts would be desirable.
3. Free will implies true randomness in the laws of nature.

4. If free will exists and is embedded in QFT, it implies self-R and fundamental limitations on the contrast of interference experiments which experimatalists would have to discover.
5. Due to self-R Quantum Computers may not function as expected.
6. In our interpretation of QFT time evolution in the real world is by self-R and UT is in a space of possibilities. For higher biological systems the "cause" of self-R can be called "free will", but all we ever observe from the outside is a stochastic process of R.

7. Obviously, Schrödinger's Cat would either be alive or dead in our bimodal model for self-R.
8. Limits of Free Will? Fate of the Universe? Role of Gravity? Physicists make wild extrapolations to the beginning and the end of time, while missing to understand complex systems like ourselves. Is the universe as a whole really simpler than we are?

Supplement: Disprove free will experimentally.

Wire a subject to record brain currents and whatever you want. Predict whether the subject will move his hand left or right.

Specifics (to be convincing):

1. 30 s intervals between the movements.
2. Ask the subject to make her/his decision in the last 10 s.
3. Measurement are only allowed in the first 10 s.

Predictions with 100% accuracy required to disprove free will.