The most beautiful experiment of all times [1]

Stefan Weckbach *

Abstract

In this essay we examine the role of the digital as well as the role of the analog in modern physics. We search for similarities as well as for differences between these two modes of description. By exploring the limits of these modes, we show that they hardly can be considered as the last words about the foundations of reality. Finally we expose an Gedankenexperiment that, if it could indeed be executed in reality, could shed new light onto the question about nature being either digital or analog.

1. Introduction

In 1906, a british scientist named *J. J. Thomson* was awarded the Nobel Price in Physics for discovering an elementary physical *particle*. A particle in this sense can be considered as a tiny bullet, analog to a billiard ball. This particle today is widely known also by non-scientist, and surely every reader will at least remember it, when we tell you its name. Its existence was forecast in 1874 by the irish physicist George Stoney, who at this time already gave it the name "electron". Besides, we all know what's in a name, and, ironically Thomson's own son, *George Thomson*, was awarded the Nobel Price in Physics in 1937 – for demonstrating that the electron does behave like a *wave* with which we are common for example by the behaviour of water. But behaviour of water is the total opposite to the behaviour of a bullet, isn't it? How can two scientists, besides the fact that they were father and son, have been awarded each for his own with the highest decoration in physics for their mutually exclusive results? Well, committed the Nobel Price committee a fatal logical error in awarding this Price to J. J. Thomson for asserting a particle-nature to the elementary charge? Or was the error more the awarding of the Nobel Price to George Thomson for a discovery that seems to diametrically contradict his father's findings?

The answer is, non of both assumptions are to the point. We only want to use this malicious historical anecdote to illustrate a pestering problem in modern physics, namely the strongheaded incompatibleness of two very precise tested

---

[1] FQXi essay on IS REALITY DIGITAL OR ANALOG ?, submitted January 10. 2011.

* Electronic address: 121112@gmx.org

physical theories: General Relativity and Quantum Mechanics. Both theories do work very well in their own regime of applicability, but they are of such a different conceptual structure, that until today, nobody could manage to unite them under a common deduction scheme. In this regard, it is clear to the physics community, that each of both theories we spoke of cannot be true, consistent and complete at the same time. The only solution for the discrepance between the overwhelming empirical success of these theories and their mutually exclusiveness is,- to find a more fundamental theory. Or to accept that nature is fundamentally divided into two dichotomic parts. Therefore, to not stagnate by the latter possibility, the required new theory should hopefully manage to unite General Relativity with Quantum Mechanics and let one or even both theories be understandable as special cases of limited applicability. Before we examine if either only one of the mentioned theories could be less fundamental than the other one, or, maybe both could be less fundamental than a yet-to-be-discovered extension of these theories would be, we should specify where the conceptual problems lie in concrete.

2. Infinities

In the tradition of Newtonian Mechanics, General Relativity uses a picture of reality that is continuous and steadily. Not only the movements of physical objects are considered to be continuous in space, but also the very framework of Einsteins Relativity Theories, namely time and space, are considered to be infinitely continuous out of themselves. But those kinds of infinities possibly could be no more than mathematical idealizations of reality. Because in sharp contrast to the assumed continuity of spacetime and of other parameters like energy or momentum, Quantum Mechanics has no room for a complete assignment of continuous properties to physical objects (e.g. energy, position or spin angular momentum). Quantum Mechanics, in contrast to Classical Mechanics, does only allow discrete steps of changes, regarding microscopical physical objects. Some physicists hold the opinion that between and beyond those discrete steps, there is nonetheless a hidden microscopic world of continuous changes of well-defined properties – which can't be measured because of the limitations of our macroscopic instruments. Therefore, one question we have to examine, is, if the conceptual use of infinitely changeable quantities, be them size, duration, energy or whatever, does make ontologically sense or only reveals our misunderstanding about the universe. The other question we surely have to answer is, if the conceptual use of only discrete units to built the framework of the universe also makes any sense.

Our up-today formulations of Quantum Mechanics do imply a certain nonlocal behaviour of nature. Those formulations contain this behaviour as expected *correlations* of spacetime-separated particles. Those kind of correlations, by definition, are of statistical character, because they are not computable in advance for the single case by any executable mechanism. Every single measurement outcome, due to those formulations of Quantum Mechanics, has to be considered as truly random. In practice, this nonlocal behaviour has already been discovered by a multitude of experiments. The only consistence with Einsteins Special Relativity Theory seems to be the proof that one cannot communicate faster than light with the help of that nonlocal property called "entanglement"due to its inherent randomness.

Besides this somewhat magical property of nonlocality, Quantum Mechanics has one more feature that is interesting for our following discussion: The principle of superposition, means, Quantum Theory does predict superpositions of certain microscopical properties, like for example the position or the spin angular momentum of a particle. This was also demonstrated in a multitude of significant experiments. Moreover, an additional feature of modern Quantum Mechanics does come into play: The more precise we measure for example the momentum of a particle, the less precise its position at this moment can be asserted. That's the well known Heisenberg's Uncertainty Principle. Some physicists believe that due to Heisenberg's Principle, the particles in question do *not* have any well-defined properties until those properties are indeed measured. Hence, they assume an *ontological* lack of those properties and hence there would be no infinitely continuous evolution of those properties within time. In contrast to that, theories that implement Heisenberg's Uncertainty Principle as *epistemological* lack of human knowledge, like for example the de Broglie-Bohm theory does, pay the price of having to operate in one or the other way with infinite quantities, be them space, time or energy. For example, already for a single particle called a "qubit" (the simplest two-state quantum-system) *the mathematics* says that due to the principle of superposition it can embrace an infinite number of intermediate states between the classical "bit"-values of 1 and 0. This gives us an impression of the infinities that would be involved in nature – if one considers a continuous evolution of a complex quantum system to be not only a man-made mathematical idealization of nature, but being a fact.

3. The denumerable versus the nondenumerable

One hint, that infinite physical properties could be physically meaningless comes from Special Relativity Theory. This theory predicts, for the case that one should try to accelerate an object with rest mass to the speed of light, for this speed, the object would then take an infinite amount of mass. Besides such an unimaginable amount of mass, it would also take an – unimaginable - infinite amount of *time* to accelerate this object to the mentioned speed. Because we could ask *when* infinite mass would be reached. The answer is sophisticated. To accelerate an object with exponentially growing mass to the speed of light, one would need an exponentially growing amount of energy that must necessarily increase towards infinity. Moreover, if one should indeed have an infinite amount of energy available right from the start, one must continously and not fully speed up the object towards the speed of light to not destroy this object by charging too much energy onto it - within a too short time. So we are in a situation where an absurdity occurs: If we charge the object with an infinite amount of energy, we destroy it and therefore also destroy the information about its actual speed. But if we only use successive finite amounts of energy to accelerate it, we would need an infinite amount of time to reach the speed of light. Obviously, the universe described by Einstein's equations can't "calculate" neither the infinitely many successive energy submissions onto an object within a finite time nor the infinitesimally accurate measurements of its actual speed. The needed amount of required energy, time and accuracy of measurements would increase in an exponential manner towards infinity.

Unfortunately all physical parameters that came into our theories via measurements (instead of mere theoretic calculations) are real numbers (and not rational numbers). The characteristics of real numbers is that they usually have infinitely many decimal places that do not occur periodically (as is still the case for the rational numbers) but random and aren't algorithmically compressible. If one takes the picture of reality as a continuum of real numbers serious, one must ask if each of those physical real numbers is realized infinitely precise or only finitely precise in nature. The latter raises the question to *which* decimal places some physical parameters are defined by nature and why. Additionally one must ask why the one-to-one relationship with our perfect infinite "platonic realm of mathematics" would then be broken at some decimal places. On the other hand, to assume that those parameters and properties are indeed infinitely precise defined and executed by nature leaves us with the paradox of Zeno, the greek philosopher who claimed that a flying arrow cannot move its positions through the continuum of spacetime because this continuum per definition would consist quite simply out of infinitely many *nondenumerable* points.

By thinking about the laws of physics as programs of a classical computation, we are forced to admit that the universe can't be infinitely accurate, because no computer can simulate the line of the real numbers. The reason for this is, because every computer only can handle *denumerably* many units. By nonetheless trying to execute such a simulation, the needed resources would just as well strive towards infinity as the needed resources for speeding up a rest mass to the speed of light: One would need infinitely much computational time and disk space for the successive calculation and storage of nondenumerably many intermediate steps. Because our universe does only contain aproximately 10^{80} atoms and aproximately 10^{90} photons and neutrinos, there's simply not enough such disk space available. So, in the spirit of Rolf Landauer, a physicist at IBM, physical laws that demand physically impossible operations should reasonably be rejected. The same should be true if we consider the whole universe not as an analog calculator but as a digital quantum computer. With the mentioned amount of matter within the universe, if one considers every particle's interaction as a bit-flip, one only could execute 10^{123} calculation-steps and store only 10^{124} bits of information [1]. Hence, with such a limited amount of calculation-steps it is impossible to map the whole line of real numbers and therefore also impossible to execute any physical mechanism that wants to achieve nondenumerable *results*. Because every quantum computer can only deliver a finite output, and so must also a whole universe that is considered to be a quantum computer. Again, it seems to be reasonable to conclude that we live in a world that not only does *not* consist out of *nondenumerable* units, but moreover only out of *finitely denumerable* units. But the latter wouldn't hold, if we additionally do assume unknown, hidden "metaphysical" resources within nature like for example a platonic realm of mathematics or an infinite Hilbert space that would "feed" our physical world with all the infinitely many "right" values at every point of a continuous time.

The term “analog” has its roots in the greek syllable *ana logon*. This syllable can be translated with “appropriate relationship”, what means “of similar type”, “congruent”. The ancient meaning of the term “analog” in physics therefore alludes to the mapping of physical analogies. An example for a physical analogy would be a huge analog Computer like a differential analyser. The behaviour of its circuit diagram must be an analogue to the behaviour of the problem that one wants to map with such a circuit.

In contrast to the term “analog” as an analogue with some redundant formal information content, we all know the term “digital”. The latin syllable “digitus” has to be translated with “finger”, means, our ancestors used to count for example their animals with their fingers. Fingers by nature are a prime example of digital units, the smallest quantum to count with – because fingers don’t represent numbers with infinite decimal places, but only natural numbers. So the main differences between the digital and the analog can be subsumed by stating that “digital” can only deal with *denumerable* quantities. On the contrary the term “analog” deals, *at least in theory*, with *nondenumerable* quantities. Both modes are able to map analogue forms in a one-to-one relationship. Therefore, we now want to examine if the analogy of the universe as a quantum computer could be more than just a man-made congruence. To do this, we have to take a closer look at another interesting analogy that we already know: The behaviour of an “electron” as a “wave” with which we are common with, for example by comparing it with water waves.

4. The most beautiful physics experiment of all times

Already in 1801, the english ophthalmologist and physicist Thomas Young accomplished an experiment that could demonstrate the wave-like nature of a stream of light. Take two slits with a distance in the range of the wavelength of some monocromatic light, and you will see an interference pattern of light at the screen behind those slits, *similar* to an interference pattern of water waves. Claus Jönsson demonstrated the same wave-like nature also for electrons in a later experiment, namely in 1961. The difference to Young’s experiment was, that Jönsson did not use a stream of electrons, but performed the whole experiment by only *single electrons*, going independently from each other through the setup, one at each time. Nonetheless the same interference pattern as for Young’s experiment was observed at the screen after sufficiently many runs of single electrons. Jönsson’s experiment was later (in 2002) chosen as the most beautiful physical experiment of all times. It suggests the wave-particle duality also for more massive particles like electrons and not only for particles without rest-mass, like the particles of a lightstream – photons – are.

Those double-slit experiments seem to indicate, that every single particle that goes through the setup passes both slits at the same time and afterwards does interfere with itself to complete that interference pattern that we already know from Young’s experiment with a coherent lightwave. Every particle, Quantum Mechanics says, by passing both slits, is in a superposition of its position and therefore interferes with itself after having passed the slits. So, what happens in such experiments? Is a single particle *as wave-like as a lightwave is*? And if we say yes to the latter, can we then further speak at all of a particle as a tiny bullet? If we can’t, then Einstein would have been mistaken to claim that a stream of light is composed out of billions of tiny particles, called photons (he was awarded the Nobel Price for this in 1922) So, how can an *elementary* particle split itself and know that it has to go through both slits and complete the interference pattern that we know only from water waves and massive lightstreams? Even worser, after its passage, the particle would have to *reunite* with its "parts" to form a well-defined point at the screen. The reason for this is, observation tells us that at the screen, without exception the "thing" that went through the slit(s) does behave like a bullet, and not like two or more bullets or something like shell splinters. And for the case that one measures a particle at the slits to demonstrate if it goes through both slits, we find, that it exclusively only goes through *one* slit, the left *or* the right one and does *no more* add to the interference pattern: The particle is now able to form a point at the screen on a position that couldn't be achieved by it if it would have been an interfering wave that would have been gone through both slits! So, for the case that we measure it's passage (even *after* it went through the double-slit-apparatus!), it adds to built a pattern that would only occur if we would have had just one slit open for every passage of a particle. For the latter case, we can in all conscience say, that the particle behaves indeed like we expect it from a tiny bullet. So is it a particle after all and George Thomson was wrong? Or should we conclude that this self-similar and complementary behaviour of light at different scales is somewhat religiously meaningfull, intimately as the bible speaks of the world's light as complementary in the sense of God's own son with all the properties of his God Father ("wave"), but nonetheless also with all the properties of a human being ("particle")? No anxiety, we aren't such naïve to believe that this is more than just a limited analogy, despite the fact that father and son Thomson indeed discovered a sophisticated complementary of a particle's nature.

5. Fractal knowledge

So is the wave-particle-duality based on such a self-similarity, a *fractal*? Has a "particle" some formal aspects of its corresponding class, namely the higher class of a "wave-like" lightstream?

The picture of a particle as a fractal may be very invitingly, - but most likely it is designated to be false. Because it can be demonstrated that in all double-slit-like setups, performed with single particles, the total sum of the particle's energy does hit our measurement apparatuses locally only at one point. There haven't been observed multiple impacts of particles that would indicate a continuous energy-distribution and an accumulated absorption (together with more than one discrete emission of $h\nu$) at a screen or at a multitude of detectors. Therefore the analogy of a particle as a real three-dimensional energetic wave seems to be only a man-made analogy. If such a wave would indeed be a continuous energy-distribution of a particle's total sum of energy $h\nu$, one would arrive at the possibility of watering $h\nu$ down to infinitely grain size until a measurement of it takes place. Again, here our analogy of a particle's wave and a water wave does fail.

Indeed, the *Schrödinger's wave function*, the standard-equation of Quantum Mechanics which describes the evolution of a quantum system, is not defined in ordinary three-dimensional space (but in a higher dimensional mathematical space called "Hilbert space"). Hence it can't be used to transmit energy or any classical causes. But nonetheless, this wave function does allow nonlocal behaviour which was confirmed by our experiments. Could it then be, that this famous mathematical "wave function" is indeed the "wave" of our double-slit experiment and that we were fooled to believe at all in the existence of particles? Schrödinger's equation would then be *metaphysical* in the sense that it does not operate within Einstein's "space". What it would transmit would be purely of informational character, of logical values.

So, independently of the concrete ontological status of that wave function, our considerations suggest that due to quantum mechanical experiments, there necessarily must exist a "metaphysical" (in the sense of not defined in ordinary space) layer of nature that has something to do with "information" instead of energy. Let us therefore examine the role of information in regard to our question about reality being either digital or analog. Let us label the latter question with "question 1".

6. Information

One property of a fractal structure surely is its informational redundance. If one views a part of a modern poster with a fractal picture on it, one easily can see that the viewed part and many other parts at the poster are of the same structure. This informational redundance does not deliver new information, because we already know that there's a self-similarity of the whole picture by simply looking at the whole picture. In analogy to that, our question 1 just as well seems to offer the *complete picture of the respective reality*, because it suggests to be a question without allowing a third possibility to answer it. But without an empirical way to prove the two alternative answers contained in question 1, our answers to this question so far only depend on our *beliefs* about nature and therefore are of *self-limiting* character, they act like a hermetically closed system.

The features of self-approvement and self-limitation here are two sides of the same coin. If one *believes* in an exclusively digital picture of reality and therefore in the mutually exclusive nature of the offered two answers to question 1, one's axiom about nature being digital and the very digital structure of question 1 mutually do approve themselves – they are congruent, *analogical*. Besides this self-approving fractal structure of a digital logic, the two answers to question 1 can be coded within 1 Bit of information and therefore are caught in a hermetically closed system. The set bit then could represent the truth value ("digital") and the bit "zero" the false value ("analog"). From algorithmic information theory we know, that one cannot gain more amount of information by a calculation than it was initialy inserted into the calculation rule(s). So, the amount one puts in is the same amount that one gets handed out (surely transformed). The argentine-american mathematician Gregory Chaitin, a pionier on this topic, has proven this fact in very good detail elsewhere [2]. His results are based on the so called "halting problem", an information theoretic question discovered by the british logician Alan Turing. Just as Turing used a mathematical method called "diagonal argument" to prove that the halting problem isn't solvable for every instant of it with one and the same procedure, so did Chaitin to come to the insight that the reason for this lies in the limited quantity of our deductive systems' axioms. It is therefore a legitimate question, to ask wether the restrictions discovered by Chaitin could also hold for a widespread kind of *human logic* that is based on the *tertium non datur* and therefore can be considered also as digital. This could be only true, if one decides to use exclusively only this tertium-non-datur mode of inferencing. But we know, that human intelligence can not only distinguish between the analog and the digital, construct analogies and explore their differences, but is also aware of something that a computer can never know: The fact that there are true statements that cannot be inferenced by any computer without putting this information into it a priori. For example Gödel's famous undecidability theorems demonstrated this. By assuming human intelligence to be on the same level as a computer's ability to "inference", we never could detect certain circular arguments like for example this: If one believes that the question for human logic "being inevitably based on mutually exclusive true/false-values or not" has to be categorically answered with "yes", one also will believe that one has made the *only logical* decision between two seemingly mutual exclusive alternatives - via the power of one's either-or logic. What we have done here is to presuppose a result – for the purpose of a posteriori demonstrate it. No computer can transcendent such a circular dynamics, because no computer out of itself can question and *decide* if it's a-prioris could be true or not. But the human mind can both, so we should be aware of the fact that the human mind -, whatever it is at its foundations -, is part of the same nature we ask for being digital or analog.

What should we induce out of these results concerning our main question, namely if nature is digital or analog? There are now several options available: Firstly, we could induce that nature can't be exclusively digital, because this would mean that nature would operate in a certain manner fundamentally like a deterministical digital computer and the human intellect could not transcend certain circular arguments. Our above examples against the latter seem to support that the analogy between a "mechanical" digital computer and the whole universe is just another chapter within a series of enormous usefull, but nonetheless *incomplete* pictures of the universe as a clockwork, a steam-engine or a cellular automaton. It seems to us, that the founding of physics on a "digital computer"-paradigma cannot be the last word concerning the nature of reality.

Secondly, we could induce that nature is both, digital and analog. This would throw us back to the pestering dichotomy between our two most elaborated physical theories, Quantum Mechanics and Relativity. Moreover it would not really be a satisfying answer for the case that the complete discovery of a more fundamental theory should be beyond our human intellectual capabilities, say, the next one hundred years. Thirdly, we could assume nature to be fundamentally analog, but again, this would throw us back to the pestering impossibilities of a nondenumerable infinity. Fourthly, we could reason that there must be somewhat a metaphysical realm that is able to transcendent both possibilities, the digital and the analog. The latter option seems to be the most promising, it does what no computer could do in this case, namely abandon some of its own a prioris. It is at least in accordance to the theoretical and experimental facts that quantum mechanical entanglement does not operate within Einstein's classical space.

It is now time to outline an experiment that probably could shed new light on the question if nature does indeed operate within a higher dimensional Hilbert space in an anlog fashion or not. We now want to take a closer look at such an experiment and its probable results.

7. Another beautiful experiment?

We mentioned that the universe is considered to contain only a finite amount of elementary particles. These particles could only have executed about 10^{123} bit-flips since the big bang. If there are hidden resources in nature in the sense that Schrödinger's wave function is universally valid, we could examine this under the following question: Is it possible in principle to build and successfully execute a quantum computer containing between 400-500 entangled elementary particles [3]? With that amount of entangled particles we could exceed the 10^{123} bit-flips already executed by the whole *visible* universe since the big bang and therefore enourmously *outdistance* its digital calculation-speed. By doing this, let us successively boost the number of entangled particles up to 500 to be sure that the universe here and now as well as beyond the particle- and event horizont of the big bang could never have managed to compute essentially more than 10^{123} bit-flips in a digital fashion. If it is possible to construct such a quantum computer that would deliver correct answers to a specific question, we could ask the computer to factorize a large number and reverse-engineer this output by classical computers. This would demonstrate the validity of the quantum computer's results. If the universe is considered to be a quantum computer governed by a universally valid wave function, this function should deliver the right answers. But if that wave function should break down during the whole calculation, we could successively approximate by further experiments the upper bound at which this breakdown occurs.

With such an experiment we could decide the ontological status of for example an infinite dimensional Hilbert space used in the mathematics of quantum mechanics. If the unitary evolution of the Schrödinger's wave function should break down at some upper bound, this would be a strong hint for the non-existence of such an analog wave function that acts strictly deterministic. But if it would deliver always the right answers, it would deliver information that couldn't have been processed by the whole universe since the big bang without a transcendental nonlocal realm represented by the Hilbert space.

If it emerges that such an experiment isn't feasible, be it as a matter of principle or due to certain practical reasons, this also could shed new light on the possible answers to our question 1. Unfortunately the whole area of quantum computing is still in its children's shoes and therefore we should not expect some general results about the feasibility of such an experiment to soon.

References

[1] LLOYD, Seth; NG, Jack Y.: *Ist das Universum ein Computer?* In: *Spektrum der Wissenschaft* 01/2005, pp. 32-41.

[2] CHAITIN, Gregory (1993): *Randomness in Arithmetic and the Decline and Fall of Reductionism in pure Mathematics*, http://arxiv.org/abs/chao-dyn/9304002.

[3] DAVIES, P.C.W (2007): *The implications of a cosmological information bound for complexity, quantum information and the nature of physical law*, http://lanl.arxiv.org/abs/quant-ph/0703041.