Realism escaping Wittgenstein's Silence: The Paradigm Shift that renders Quantum Mechanics Natural

Sascha Vongehr

National Laboratory of Solid-State Microstructures, Nanjing University

The most severely misleading of our basic physical assumptions is a tacitly held *direct realism* and its way of physical actualization of future. It makes quantum mechanics (**QM**) incomprehensible and lets relativity theory impose a 'block universe' in spite of QM. Under *tautological modal realism*, which is based on trivial truths, QM appears naturally. Tautological modal realism belongs to the fundamental theory of totality by definition. Indeterminism emerges inside determined totality. Adding special relativity, demands Everett relativity, which conceivably could have become obvious to Einstein almost a century ago, if he had only further doubted his brand of realism. None of this is yet QM! Wheeler's "*utterly simple idea*" demands certain correlations between alternative possibilities, namely those that force *modal realism* into physics; this is the core of QM. Actualization cannot be contained and spreads to all possible 'worlds'. Visually intuitive models can illustrate these concepts, much like Minkowski diagrams resolve the twin paradox. Apparent non-locality in the Einstein-Podolsky-Rosen (**EPR**) paradox is suddenly as simple as the fact that twins have different ages after they aged differently (on separate space-time paths). With QM becoming self-evident, later generations, as usual, hardly grasp what the hang-up was, because they utilize improved language. This generally defines paradigm shifts, which can never be consistently expressed in the previous terminology. However, this is especially relevant today: With realism being suspect, fundamental physics is mainly a *description* (of itself, not presupposed reality). Wittgenstein's core insight is crucial; universal limits of language limit the universe.

"*... the most revolutionary discovery in science is yet to come! And come, not by questioning the quantum, but by uncovering that* ***utterly simple idea that demands the quantum****.*" Wheeler, 1984[1]

INTRODUCTION: Describing the Fundamental Description

A too 'direct' realism is *the* profoundly wrong assumption obstructing progress in physics. ***Direct/naïve* realism**[2] means naively taken, seemingly directly from the senses. In physics, it presents a '*universe as a lonely box with things bumping around inside*' feeling: Systems interact with other systems but without observer dependency. Stuff is a certain way '*really out there*' (this includes "localism"!). Everything is as it happens to be in that one box. I will not discuss 'counterfactual definiteness' but **actualization** (~ "turning real"[3] of potential). Alternative possibilities are thought to not 'really exist'; the past is 'dead' (called "Presentism"). Direct realism traditionally holds that actualized alternatives, for example the now-moment, are absolutely actualized for all observers that 'count'. However, what 'counts' is precisely that which is actualized. There is no verifiable distinction that *dis*counts: Alternatives that do not count (here and now) may as well be assumed to be actualized relative to themselves. The absolute/relative distinction fails.

What is wrong and how can we deal with it? Ludwig Wittgenstein may have missed the profound relevance to modern physics, but he knew what is wrong. Wittgenstein seems arrogant and idiosyncratic beyond comprehension. He claimed to know with certainty. Why did he not merely claim a promising idea? And why, if he knew what is wrong, could he not just simply express what is wrong? Well, both precisely because he knew what's wrong!

A description cannot be inconsistent if it is tautological like $P = P$. You cannot be wrong inside of a consistent code (though it may not fit something *outside* of itself). On the fundamental level, when we describe totality, which has nothing outside of itself, we deal with tautological logic, and so theories fail due to *meaningless* ingredients. I desire to express *correctly* what is 'wrong', but it is impossible if the 'wrong' is "not even wrong" but meaningless. An improved description may assign the truth-value "false" to a similar, but updated and therefore meaningful concept, but it is silent about inconsistent previous ones:

"*Whereof one cannot speak, thereof one must be silent*" Wittgenstein, 1922[4]

This is at odds with our evolved ways of thinking and culture of discourse. If you avoid the meaningless, your "eliminativism" is rejected as vacuous, which implicitly acknowledges the description's tautological nature. I argue below (3) that QM is that fundamental.

'*Quantum mechanics promotes the mere "observer of reality" to the "participator in the defining of reality." It demolishes the view that the universe exists out there*.' Wheeler[5]

Participating in the "*defining of reality*" is good, but Wheeler also fails, because whether "*the universe exists out there*" depends precisely on *defining* "universe" and "exist" suitably. What if these cannot be consistently defined without losing their traditionally associated feelings which we want them to convey? The expressive powers of (our) language dictate what we (can) describe:

"*The limits of my language mean the limits of my world.*" Wittgenstein[4]

When doubting the universe's "reality", my description defines what "*my world*" is. Fundamental limits on 'language' are *universal* limits. Modern physics can no longer escape this.

Since language is the main difficulty, I have asked and received much help. I am sincerely grateful to the many lay persons and experts that emailed on the internet drafts, resulting in hundreds of changes. Every word has been reworked many times, but Wittgenstein is not simply a cute hook to spice up creative writing. Most has been said before in conventional ways. However, I need an extreme 'positivist' style concerning significant language in order to communicate glimpses of a future paradigm. Wittgenstein's wording is irrelevant; his usage of "world" conflicts with "many-worlds", but I need his core insight about meaningful description.

Totality and Quantum Mechanics

1) **Totality** encompasses the total of all possibilities. Something *im*possible is, for example, the square of a real number being negative. The impossible is always unobservable, but the observable/unobservable distinction should differ somehow from the possible/impossible one, in order to be significant language. Thus, we separate "possible" from "observable": Some **unobservable is possible** (e.g. virtual particles, tachyonic off shell paths, potential histories, QM fluctuation ascribed to stable ground states).

2) The mathematical description of QM obeys Murray Gell-Mann's ***Totalitarian Principle***: Everything not forbidden is compulsory. Whether or not you do non-relativistic QM with path integrals, when it comes to field theory, *every* way a process could happen does contribute. This includes possibilities like a photon turning intermittently into an electron-positron pair. Particles seem to take every possible path simultaneously. Quantum electrodynamics (QED) predicts the interaction between an electron and a magnetic field correctly to 14 decimal places. For more accuracy, interactions that do not strictly belong to QED must be taken into account and measurement accuracy would have to improve to be able to even test more accurate predictions. In order to predict so enormously well, one must take ridiculously complex interactions into account, ideally including *all* processes that *could have* taken place *in as far as one can tell* from the outcome.

QM is about all these possibilities, including unobservable ones (1), which are, taken together with the knowledge from the already determined and actualized, QM's input. This completely constrains the background of uncertainty, so that QM can output … well what does it output? It outputs precisely *all the possibilities* with their attendant probability amplitudes, which tell us which ones are observable.

3) Relativistic QM is the most precise theory, perhaps even exact. No refuting anomaly has been found although it is still a linear theory. Strange? Not if you compare 2 with 1 and consider that QM is also the theory that is most inquisitive of the act of observation and measurement interaction, consistent with radical operationalist instrumentalism. Clearly, QM is not just a more detailed statistical physics. QM is about the totality of alternatives, both observable and unobservable.

Worlds and Modal Realism

Much of what is claimed to be entirely due to QM was evident to some probably thousands of years ago:

4) The **fundamental equivalence among alternatives** such as the fact that I wear socks today:

I) *Socks* today instead of *no socks* is not prescribed by the symmetries of the deepest level foundation.

II) If *socks* were prescribed by the initial conditions, they would be foundational only relative to the universe having those initial conditions. Even under classical determinism, totality includes all possible initial conditions. *Socks* initial conditions and *no socks* initial conditions are equivalent relative to the most fundamental description of totality.

5) The **equivalence of all alternatives relative to the most foundational description is true by**

definition. There is nothing to be believed or experimentally verified. If they are not equivalent, you simply are not yet dealing with the most fundamental description.

We *want* fundamental physics to be precisely that, namely *the* most fundamental description of totality. If QM is not yet fully that, the necessary modifications would only leave the theory fitting even better what I describe. We found the best part, and perhaps, implicitly, all of the 'theory of everything' already. QM is like that; it is the very description which treats all alternatives equally, because only in this way can it fully describe the correlations between them. These correlations tell us how much we rationally expect alternatives, revealing many of them to be unobservable. QM is part of our developing the mathematical description that does not neglect any possibilities. The theory's properties are in principle predictable *a priori*.

6) Many refer to different observed measurement outcomes as different "**worlds**"[6] of observers, especially since Lewis[7] popularized modal realism. You may represent such worlds with pictures and arrange them according to similarity. Thus, worlds can be arranged according to the similarity of records that the worlds are thus said to inherit from worlds before them; causal relations and time coordinates can be constructed. In this sense, worlds "**branch**" and associated space-times may be said to "**split**" into different worlds that are distinguished by the different possible outcomes of interactions. In certain, so called many-world *models*, a total number of worlds at a certain time can sometimes be defined. The "merging" of past worlds via information loss (e.g. forgetting microstate configurations) may keep the total number of worlds constant.

Many despise such world-talk and it is not perfect, but fundamental physics is (not merely!) a *description*. Wittgenstein claimed to have completely covered all the unspeakable *precisely where he refused to mention it*. Our topic is the same, namely the fundamental *description*. *In*describable is the realm of which one cannot meaningfully talk, where regress errors about all those worlds being "*really real*" dance with angels on pins. Any realism labels as "real" whatever it deems 'existing' somehow 'independent' from observers. I define "***tautological* modal realism**" as the acceptance of fundamental equivalence (4, 5) combined with labeling possibilities "real", be they worlds or not. One may call it thus "**many-world** description". (Empirical) "**modal realism**" usually labels possibilities "real" especially because QM has shown them to be necessary (8, 13) in the explaining of observed phenomena. "Necessary" is itself relative to the description! (No description gets rid of structure, thus "structural realism".)

7) As seen, for example, with the unitary evolution of wave functions, **QM is fundamentally deterministic**, and if it were not yet, the more fundamental, modified QM would be anyway, because **totality is totally determined**. Totality does not have a future; it includes all futures. Many-world tautological modal realism describes experiencing stochastic behavior: Relative to *my today*, my wearing of socks a year from now is as irrelevant as my not wearing socks then (even assuming time symmetric classical determinism). A mature physics must let this **indeterminism emerge inside of determined totality** regardless of whether it is somehow 'subjective' or 'fundamental' uncertainty.

8) ***Tautological* modal realism and emergent indeterminism do *not* need QM.** 'Many-worlds' (6) are tautologically true also if probabilities were classical (non-QM). *Modal interpretations of QM* (Van Fraassen, Kochen-Dieks-Healey, Castagnino-Lombardi, ...) need QM. Modal realism is more general than many-worlds *interpretations* of QM. None of this equals the multiverse concept.

Everett Relativity: Einstein could have Known

Though not yet the core of QM, modal realism's emancipation of alternative worlds is vital to the Everett relative state description[8] of QM. After a coin toss, heads and tails are both actualized *relative* to the observers that witness heads and tails, respectively. This alone does *not* demand QM, but with this in mind, Einstein could conceivably have anticipated the core of QM long before Everett. The infamous EPR paradox[9] would have perhaps never been an issue. But let us go step by step:

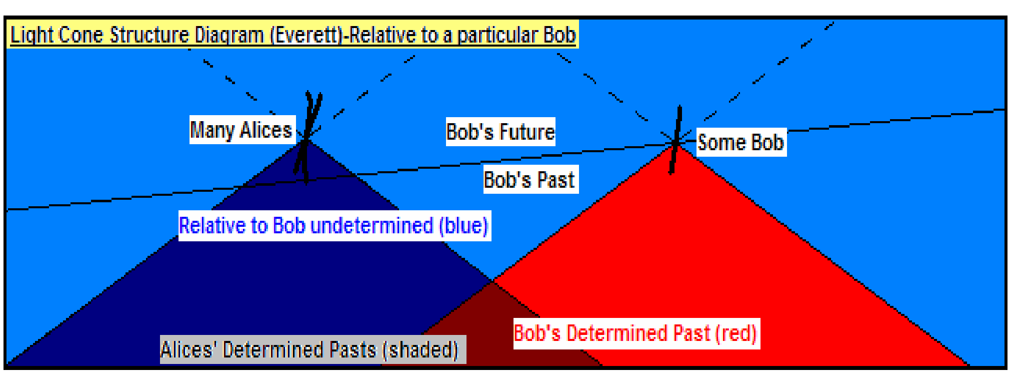
9) Special relativity is more than a 'temporal modal realism'. **Special relativity already shatters the classical past into a collection of possible past light cones, which each are an observer's *determined past*.** Assuming otherwise implies either emergent relativity in an ether[10] or a pre-determined block universe where any stochastic behavior is divine pre-arrangement drawn on Wheeler's parchment:

"*Spacetime in the prequantum dispensation was a great record parchment. This sheet, this continuum, this carrier of all that is, was and shall be, had its definite structure with its curves, waves and ripples; and on this great page every event, like a glued down grain of sand, had its determinate place. In this frozen picture a far-reaching modification is forced by the quantum.*" Wheeler[11]

Wheeler had an important insight again, but presented it somewhat upside down. Tautological modal realism emancipates all futures (7). Thus, a Galilean space-time is one parchment of many. However, physical law abiding randomness stays mysterious: Who paints the totality of parchments that way?

Enter special relativity: simultaneity is relative. Therefore, if Bob's future is not determined, neither is all of his past. Only the inside of his past light cone is his *determined past*. This however excludes as *un*determined some of the past light cone of spatially separated observer Alice, which is however *her determined past*: Alice's past is *un*determined although it is already determined relative to her. Hence, we must include different possible Alices with their respective determined *pasts*. Popper[12] argued similarly for future indeterminism. However, the *past* parchment already disintegrates into all possible light cones, and this is not "*forced by the quantum*". Indeterminism (7) demands this fracturing into worlds that contain the determined empirical records of possible observers, even if it came with classical instead of QM probabilities.

Now we can ponder this light cone structure of 'worlds' and how their correlations can possibly correspond to stochastic laws, which should *force the quantum*.



10) Why could a physicist have anticipated QM in this way? Here is where a modal realist version of Einstein could have stumbled onto Wheeler's "*utterly simple idea that demands the quantum*":

What matches up the many different Bobs with the possible Alices (all observe only one Bob and one Alice) so that 'reasonable' stochastic laws emerge from this chaotic mess? A physicist naturally asks for the **'*mechanism*' that has access to the alternatives to accomplish that '*interaction*' between them**. That 'interaction' (13) is precisely what QM with its superposition and entanglement and interference between possibilities is, and **its necessity demands the quantum**.

Much like Einstein's elevator thought experiment is 'the simple idea' that leads to general relativity, this simple idea also does not immediately reveal how it is precisely expressed inside the full final theory. Nevertheless, I think this is the simple idea.

11) **Einstein-locality** (relativistic micro causality, not "separability") states roughly that there is no instantaneous interaction at a distance, because a fundamental limit (light speed) emerges from measurement theory. This section (9, 10) shows that Einstein-locality is yet more important than already widely recognized. It anticipates a lot of what is usually described as deriving from QM.

Anti- vs. Direct Realism & the Core of QM

Anti-realism denies that verification-transcendent statements are either true or false: There *is no fact of the matter as to whether or not* the meaningless is true. How to oppose the meaningless yet not fall silent about it? We may rescue actualization and direct realism in physics via verifiable distinctions:

12) If you point out a single world as thus actualized, **direct realism can hold true only as long as time-evolution actualizes single future worlds** so that the actualization stays absolute (not relative). Non-QM many-world models can conserve absolute actualization.

13) **The core of QM is correlation between alternatives** that cannot depend only on what belongs to the alternatives taken in isolation (say via 'hidden variables'). QM correlations 'entangle' mutually exclusive worlds; physical interference of alternatives emancipates them: Even if the dead Schrödinger cat[13] turns up in our world, we respect that the alive cat exists in her world, because we can physically interact with it during (and without destroying) the superposition. Her life does not just mysteriously stop; the potential impossibility of macroscopic cats[14] is here irrelevant. Not only are possibilities therefore labeled "real", but QM correlations **rapidly spread actualization to many worlds**! In this sense, Wheeler's "*forced by the quantum*" is valid:

The core of *Quantum Mechanics* is those *correlations between alternatives* that make *modal realism* inevitable in physics. Interpret this in almost the same way as "*Classical Mechanics* is those *interactions between objects* (particles/waves/strings) that actualize the future of a *directly real world*". Notice that interaction needs time, while correlation does not. Quantum computing is as effective as parallel computing on the correlated parallel alternatives' computers. 'Interaction-free' bomb testing[15,16] interacts/correlates with the alternative of the exploding bomb, however unlikely that world is. Interaction over time delimits the observable during decoherence[17], thereby further restricting (giving rise to) observed physical laws. [But beware: Worlds, defined as observed alternatives, cannot correlate self-destructively, even if their evolutions interfere destructively like electron-paths behind a double slit, quantum-erasing them. A world 'knows itself'. Once they 'exist to interact', they cannot become impossible by rendering them unseen through interaction.]

Hidden variables in a single world cannot accomplish the emergence of QM probabilities[18]; this is easily understood through the violation of Bell's inequality[19] in the EPR setup. Simple proofs can be presented accessibly to lay-persons[20], as they should be presented right along with general (algorithmic) evolution, because the demotion of naive realism is relevant to all of science and philosophy – we no longer have any excuse for ignorance about it. Bell's and even more robust inequalities[21] have been violated by diverse experiments, most impressively by closing the so called 'communication loophole'[22]. Desperate attempts to save unmodified realism try to exploit the 'detection loophole', but they have retreated to claiming what Shimony calls[23] a *conspiracy*, one not much different from that of a deceptive creator planting fossils.

Spooky Non-Locality more Unreal than Modal Realism

EPR is usually presented as leaving two options available, namely either *non-locality* or modifying realism.

14) The local/non-local distinction is tricky. QM is fundamentally Einstein-local (11) just as it is deterministic (7). Randomness and non-locality emerge. All necessary information is right there at the space-time event, not 'hidden' in any one world, but inside the ensemble of correlated alternatives. Direct realism cannot take the QM correlations between alternative worlds into account. If this neglected information then influences a measurement, direct realism concludes that information arrived from somewhere else, which would need superluminal speeds in the EPR setup: I call this **"*apparent* non-locality"**. Unsurprisingly, EPR was misunderstood as a clash between relativity and QM, rather than as their harmony (9, 21):

15) **Without modal realism, non-locality violates Einstein-locality**. This is still often viewed as less suspicious than modifying realism, since the latter potentially corrodes our justification of the scientific method. This is aggravated by the difficulty of grasping non-locality. Even many physicists still opine that non-locality is merely a 'really complicated' correlation, but in the end, not profoundly different from the correlation that ensures Alice's getting the left sock of a pair if Bob gets the right sock.

16) Einstein, although he could not find the solution, understood the problem. He did not just say "*well, so QM is non-local and I am fine with that*". He called it "***spooky** actions at a distance*" for good reasons. He would not casually toss out micro causality (11), a most important ingredient in modern physics, to prop up a realism which, due to non-locality, is a ghost story (17) nevertheless. **Non-locality destroys direct realism anyway; modal realism is therefore more conservative.**

17) In a direct reality as a lonely world 'really out there', locality is crucial. If space is a box with objects 'really' at certain locations inside, **localism is implicit**. If spatially separated events outside of my past light cone are merely unknown yet not fundamentally undetermined/indeterminate, non-locality requires superluminal interaction. The huge success of relativistic causality argues against such, but it is not even as relevant as the following:

Non-locality observed in an internally relativistic, micro-causal billiard table, implies that there is something else, something that *interferes* in the supposedly self-sufficient dynamic, independent evolution. An interaction faster than the fastest possible in the isolated game is a sure sign of players messing with the game pieces. As Einstein said: spooky! Whether it be gods or alternative worlds, there *is* interference.

18) Modifying realism undermines that 'space is really out there'. In modal realism, although it may preserve localism, it is not implicit. Observers' empirical records depend on correlations between worlds. Conceivably, the correlations could be such as to imply locality, or non-locality, or even, if you could micromanage correlations enough to purposefully deceive at every measurement separately, that the moon consists of green cheese. If all is better described as 'in my head' instead of 'out there', it no longer matters whether that cheese is *really* at a certain location.

Behold the irony of the controversy: **Preferring non-locality holds localism implicitly critical** (17). **Those that instead keep Einstein-locality, do not.** The first is inconsistent; the latter is a mature position. If Smerlak/Rovelli, Bousso, Deutsch, Zeh, and so on state that QM is local, do not confuse them with those who desperately cling to hidden variables. I would abandon Einstein-locality if necessary, but it happens to be good physics.

19) Today we know why QM's apparent non-localities seem so spooky: They are correlations that involve (relative to an observer) not actualized alternatives (13). This core of QM is precisely why "*quantum phenomena are more disciplined*"[24] than even perfect classical correlation via hidden variables can offer. **QM correlations are *moreover* fixed between the alternative worlds that classical physics ignores.**

20) What fixes the correlations so that we find apparent non-locality instead of cheese moons? I am unsure. In the EPR setup, photons may conceivably go 50-50 into the different polarizing beam splitter channels without violating Bell's inequality. However, you know from playing with sunglasses that polarization filters act on field vectors, diminishing intensity via a sine-dependence; nothing else is consistent with rotational symmetry and energy conservation. This sine of the angle between Alice's and Bob's measurement axes $\underline{\boldsymbol{a}} \times \underline{\boldsymbol{b}} = \sin(\delta)$, is precisely[20] the term that violates the inequality. Add the conservation of the entangled momentums, and I do not see how QM could avoid apparent non-locality yet be consistent with photons at all.

Concentrating on consistency between descriptions does not refute reductionism. It may illuminate the "*idea that demands the quantum*", which is, loosely put, the '*necessity of interaction between alternative worlds*'(10, 13). I believe thinking along these lines will get us further. A directly real universe containing objects which all consist of ever smaller thingies bumping around, slows to a cold heat death before observers evolve. But something 'keeps kicking it'; the same 'spook' that keeps inflating universes; QM! Explaining the core of QM (13) needs answering why alternatives must correlate the way they do.

Appendix: Many-World Models

To finish here would be dishonest. I personally grasped the core of QM and apparent non-locality with confidence only by constructing many-world (**MW**) toy models on paper. I came to them almost by accident, but they taught me with a clarity that I had not deemed possible.

Relational QM[25] resolved[26] the EPR paradox, but it lacks intuitive pictures. MW models prove[27] that 1) modal realism resolves EPR while preserving Einstein-locality and 2) that QM probabilities become possible with *the very step* that destroys direct realism. I do not claim that 'branch counting' escapes the cosmological measure problem, or that intuitive models replace tautological truth. I claim that MW models can illustrate all of the above to children:

21) Everett relativity is suspect without special relativity (14). A non-relativistic MW EPR model would have to branch (6) everywhere at once, into infinitely many different ones, all the time. With special relativity, apparent 'world branching' only occurs at observation events (interactions). Nothing overtakes light in the EPR setup.

22) Modal realism can be classical (8). Non-QM MW models already have many, literally parallel worlds. All possible alternative outcomes are present and in their totality totally determined (7). A pointer, call it **Actualization Arrow** (**AA**) or *A*bsolute *A*ctualization, can pick out and thus actualize (12) any particular world. The mere classical 'pair-of-socks correlations' (15) are already present. However, the Bell inequality cannot be violated, because it is still not a QM model. AA represents hidden variables that determine the outcome. Classical indeterminism ('genuine stochastic') can be introduced, but needs external randomness (and model-external time) that jerks AA to one of the possible futures. One may interpret world numbers or volumes as probabilities, but the externally supplied randomness is not forced to obey that probability. That AA picks *fairly* from the offered worlds is a further demand, starting a regress without definite termination.

23) QM probabilities arise literally *at the space-time point* where Alice's and Bob's worlds must branch again in order to match and pair up (10) consistently. After this vital but single, naturally expected, and Einstein-local step, AA (12) can no longer predetermine a particular world, but it selecting randomly cannot change the empirical, non-QM probabilities. Model-external randomness completely fails and actualization spreads to parallel worlds (13). Nothing counts worlds. Recorded frequencies depend on the number of worlds in previous trials. Over time, the empirical records (Bayesian updating) reflect QM probabilities.

24) Apparent non-locality comes for free (18): You, the god of the model, can manipulate the branching. You may change the model's parameters to let the inhabitants find locality in their perceived worlds, or apparent non-locality. But some consistency fixes the tuning (19/20). If the numbers of new worlds are proportional to the square of the dot product between Alice's and Bob's measurement axes as expected from the usual optics at polarization filters, one finds the usual apparent non-locality. (This suggests to derive Born probabilities from microstates that distinguish the different worlds if one includes the spin directions of particles that physically communicate δ.)

[1]J.A. Wheeler: *Bits, Quanta and Meaning* in *Theoretical Physics Meeting: Com. Vol. on the Occasion of Eduardo Caianiello's Sixtieth Birthday*, A. Giovanni et al. eds. (Ed. Scientifici Italiani, Naples) 121-134, 1984

[2]B. Laurence: *Epistemological Problems of Perception* Stanford Encyclopedia of Philosophy, (Summer 2011 Ed.), E.N. Zalta (ed.) <http://plato.stanford.edu/entries/perception-episprob/#DirRea>, last accessed 31st Aug 2012; Wikipedia: *Direct and Indirect Realism* <http://en.wikipedia.org/wiki/Direct_and_indirect_realism>, last modified 13th Jul 2012

[3]Wikipedia: *Potentiality and actuality* <http://en.wikipedia.org/wiki/Potentiality_and_actuality>, last modified 8th Aug 2012

[4]L. Wittgenstein: *Tractatus Logico-Philosophicus* Routledge and Kegan Paul, London 1922

[5]J.A. Wheeler: *The Quantum and the Universe* in *Relativity, Quanta and Cosmology II*, M. Pantaleo and F. de Finis, eds. Johnson Reprint Corp., New York, 1979

[6]B.S. DeWitt, N. Graham (eds.): *The Many-Worlds Interpretation of Quantum Mechanics*, Princeton University Press, Princeton NJ, 1973

[7]D.K. Lewis: *On the Plurality of Worlds*, Blackwell, 1986

[8]H. Everett: *"Relative State" Formulation of Quantum Mechanics* Rev. Mod. Phys. **29**, 454-462, 1957

[9]A. Einstein, B. Podolsky, N. Rosen: *Can Quantum-Mechanical Description of Physical Reality be Considered Complete?* Phys. Rev. **47**, 777-780, 1935

[10]S. Vongehr: *Supporting abstract relational space-time as fundamental without doctrinism against emergence* arxiv.org/abs/0912.3069v3, 2009

[11]J.A. Wheeler: *Delayed-Choice Experiments and the Bohr-Einstein Dialogue*, The American Philosophical Society and the Royal Society, pp. 25-37, 1980

[12]K. Popper: *The Open Universe: An Argument for Indeterminism*, Roman and Littlefield, Lanham, MD 1956

[13]D. Leibfried et al.: *Creation of a six-atom 'Schrödinger cat' state*. Nature **438**, 639-642, 2005

[14]R. Penrose: *On gravity's role in quantum state reduction*. Gen. Rel. and Grav. **28**, 581-600, 1996

[15]A.C. Elitzur, L. Vaidman: *Quantum mechanical interaction-free measurements* Found. Phys. **23**, 987-97, 1993

[16]G.S. Paraoanu: *Interaction-free Measurement* Phys. Rev. Lett. **97**, 180406, 2006

[17]W.H. Zurek: *Decoherence, Einselection and the Existential Interpretation* Phil. Trans. R. Soc. London A**356**, 1793–1820, 1998

[18]J.S. Bell: *On the problem of hidden variables in quantum mechanics* Rev. Mod. Phys. **38**, 447–452, 1966

[19]J.S. Bell: *On the Einstein Podolsky Rosen paradox* Physics **1**, 195–200, 1964

[20]S. Vongehr: *Quantum Randi Challenge (and didactic Randi Challenges)* arxiv.org/abs/1207.5294v2, 2012

[21]J.F. Clauser et al.: *Proposed Experiment to Test Local Hidden-Variables Theories* Phys. Rev. Lett. **23**, 880-884, 1969

[22]G. Weihs et al.: *Violation of Bell's inequality under strict Einstein locality condition* Phys. Rev. Lett. **81**, 5039-5043, 1998

[23] A. Shimony: *Bell's Theorem* Stanford Encyclopedia of Phil, 2004 <http://plato.stanford.edu/entries/bell-theorem>, as last accessed 31st Aug 2012

[24]A. Peres: *Unperformed Experiments have no Results* Am. J. Phys. **46**(7), 745-747, 1978; *Quantum Theory: Concepts and Methods*, Kluwer Academic Publishers, Dordrecht 1993, pp 161

[25]C. Rovelli: *Relational Quantum Mechanics* Int. J. Theo. Phys. **35**, 1637-1678, 1996

[26]M. Smerlak, C. Rovelli: *Relational EPR* Found. Phys. **37**, 427-445, 2007 arXiv:quant-ph/0604064v3, 2006

[27]S. Vongehr: *Many Worlds Model resolving the Einstein Podolsky Rosen paradox via a Direct Realism to Modal Realism Transition that preserves Einstein Locality* arXiv:1108.1674v1 [quant-ph], 2011