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When bodies are borne downwards sheer through void by their own weights, at quite uncertain times and uncertain spots they push themselves a little from their course: you just and only just can call it a change of inclination. If they were not used to swerve, they would all fall down, like drops of rain, through the deep void, and no clashing would have been begotten nor blow produced among the first-beginnings: thus nature would never have produced aught. (Lucretius *De Rerum Natura*, in *The Stoic and Epicurean Writers* ed. Oates p. 95).

Tails of Schroedinger's Cat

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In his famous thought experiment Schroedinger (1935) imagined a cat that measures the value of a quantum mechanical observable with its life. Adapted to the measurement of the x-spin of an electron the experiment is this. At the start of the measurement interaction if the state of the cat is $|R\rangle$ (the ready to measure state) and the state of the electron is $||\uparrow\rangle$ (the electron's x-spin is up) then at the conclusion of the measurement the state of the cat and electron is $|Alive\rangle||\uparrow\rangle$ and if the state of the electron is $||\downarrow\rangle$ (the x-spin of the electron is down) then at the conclusion of the measurement the state of the cat and electron is $|Dead\rangle||\downarrow\rangle$. The cat records the x-spin of the electron in its state of aliveness. According to quantum theory the state of an isolated system evolves in conformity with a deterministic linear law -Schroedinger's equation. If the interaction between the electron and the cat follows Schroedinger's equation then, as is well known, it follows from the linearity of that equation that if the initial state of the electron

and measuring device is $(c|> + c^*|>)|R>$ then at the conclusion of the measurement the state of electron + cat is

CAT $c|>|Dead> + c^*|>|Alive>$.

What are the physical properties of a cat whose state is CAT? The answer to this question depends on the connection between quantum states and physical properties. On the standard textbook understanding of quantum theory that connection is¹

EER) an observable (i.e. any genuine physical property has a well defined value for a system S when *and only when S's quantum state is an eigenstate* of that observable.

Since CAT is not an eigenstate of the observable corresponding to the observable Aliveness (whose values are alive and dead) it follows from EER that the unfortunate cat that finds itself in CAT is neither alive nor dead. This struck Schroedinger and most others who have thought about it subsequently as absurd. Avoiding this absurdity has come to be known as "the measurement problem."

The measurement problem is a special instance of what Philip Pearle calls the *reality* problem. What he means by this is that if all physical processes evolve in conformity with Schroedinger's law then in all sorts of commonplace physical interactions - not only measurements - states of systems are produced that are not eigenstates of ordinary physical properties. Given EER the ordinary properties of these systems will almost invariably fail to possess determinate values.

What

We have seen that the following three propositions are incompatible:

- i) All physical processes are governed by Schroedinger's law.
- ii) The eigenstate-eigenvalue rule

iii) Ordinary properties (pointer position, aliveness, etc.) always possess determinate values.

Solving the reality (and measurement) problems will mean giving up or modifying one or more of these three.

Here we will be discussing a very ingenious proposal thought up about 10 years ago by Ghirardi, Rimini, and Weber (1986) - the GRW theory - and subsequently developed by these authors, Bell (1987), and Pearle (1993) that involves modifying Schroedinger's law. Prior to explaining it we will briefly review the so called "orthodox" approach that also involves modifying the Schroedinger dynamics. Our comparison will make the attractions of GRW evident.

The orthodox account attempts to solve the measurement problem by claiming that in measurement interactions the quantum state of the measured system plus the measuring system does not evolve in accord with the Schroedinger equation but instead *collapses into one of the* states that is an eigenstate of the measurement observable (i.e. the observable that records the result of the measurement) with a probability proportional to the square of the coefficient of that state. For example, if Schroedinger's cat measures the x-spin then the post measurement state CAT collapses either into $||>|Alive>$ or $||>|Dead>$ each with a probability proportional to the square of the coefficient associated with each state. So on the orthodox account there are *two* fundamental laws that govern the evolution of quantum states. In non-measurement situations Schroedinger's deterministic law holds sway. But in measurement situations the collapse dynamics takes over.

The orthodox account looks like it succeeds in solving the measurement problem since it entails that measurements possess outcomes and assigns to those outcomes the usual quantum mechanical probabilities. But it has increasingly come to be seen as unsatisfactory. One cannot

help but feel queasy about the way it introduces the notion *measurement* into the statement of the fundamental physical laws; especially since the account doesn't provide an explicit definition of measurement. In any case, the orthodox account utterly fails to handle the reality problem. All sorts of interactions involving macroscopic systems that on any reasonable contrual of the notion are not measurements will evolve by Schroedinger's law into states that aren't eigenstates of ordinary physical properties. And even though the post measurement state of the cat and the electron collapses into an eigenstate of Aliveness (either $|\text{Alive}\rangle$ or $|\text{Dead}\rangle$) this state very quickly spreads out so that the cat is no longer determinately alive or determinately dead. The orthodox account appears adequate only as long as we think of quantum theory instrumentally; that is, as providing an algorithm for predicting the outcomes of measurements and not as a true description of physical reality.

GRW also modifies the fundamental dynamical law but in a very different way than the orthodox account. According to GRW Schroedinger's law is not exactly correct. In its place is proposed a dynamical law according to which the wave function of an N-particle system $\Psi(r_1, r_2, \dots, t)$ *usually* evolves in accordance with Schroedinger's equation; but every so often (once in $1/N \times 10^{15}$ seconds), at random, but with a fixed probability per it time, the wave function is multiplied by a Gaussian (and normalized). The form of the multiplying Gaussian is

$$G) \quad K \exp(-[x-rk]^{2/2D}2$$

where r is chosen at random from the arguments of the wave function and the width of the Gaussian D is 10^{-5} cm. The probability of G 's being centered at any particular point x is proportional to the absolute square of the inner product of Ψ and G . The effect of the multiplication is to collapse Ψ into a more localized wave function.

What immediately strikes one about the GRW theory and what is so nice about it is that, unlike the orthodox account, it proposes a uniform dynamical law for all processes and that law

makes no mention of measurement. On GRW the quantum state of a system is its complete physical state and that state evolves linearly except when random collapses cause it to be localized around the center of the collapsing Gaussian. Although GRW is not empirically equivalent to the orthodox theory (or to non-collapse theories) the theory is so designed so that empirical differences will be very difficult to detect. For isolated microscopic systems (i.e. systems containing a small number of particles) the Gaussian jumps will be so infrequent as to be unobservable in practice; and D (the width of the multiplying Gaussian) has been chosen sufficiently large so that violations of the conservation of energy (which are inevitable on any collapse theory since a collapse localizes the position of a wave function) will be sufficiently small as to be unobservable even in macroscopic systems.

Of course the crucial questions concerning GRW is whether its collapses produce states in which observables like pointer position and aliveness of cats possess determinate values. Here is the GRW account of measurement. Consider, for example, a spin measurement which leads to the state CAT. On GRW CAT is very unstable. In a very short time (about $1/N10^{15}$ seconds where N is the number of particles in the cat, about 10^{20}) CAT will be multiplied a GRW Gaussian. The center of the Gaussian will either be in the region $|\text{Dead}\rangle$ or the region $|\text{Alive}\rangle$ and so the collapse will lead to a wave function in which one of the two terms in CAT all but disappears. We can picture the collapse as follows:

After the jump, the state of $M+e$ will be either $GRWCAT(U)$ (in which almost the entirety of the amplitude of the composite wave-function locates the pointer in the U-position) or $GRWCAT(D)$ (in which almost the entirety of the amplitude of the composite wave-function locates the pointer in the D-position). And that would seem (but of this more later) to justify the claim that this jump leaves the pointer in one or another determinate location.

Moreover, if we suppose that the value of a cat's aliveness is determined by the positions of the particles that make it up, or at any rate by the histories of those positions over a certain interval (and this seems a perfectly reasonable, perfectly innocent thing to suppose), then such jumps will apparently leave cats determinately either alive or dead too.

On top of that, the fact that the dynamical interaction we have been focusing on here is of the "measurement" type has nothing whatever to do with the occurrence of these collapses: *all* superpositions of states in which macroscopic objects are in macroscopically different positions (no matter how those states may happen to have been gotten into) are clearly unstable on this theory. And so if GRW can indeed solve the measurement problem, it can clearly solve the more general "reality" problem as well.

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There are difficulties, however.

Look more closely, for example, at a post GRW-collapse state like $GRW(\text{alive})$, which is pictured below:

NOTE THAT WHILE *MOST* OF GRW(ALIVE)'S AMPLITUDE IS INDEED (AS WE MENTIONED ABOVE) CONCENTRATED IN THE 'ALIVE' REGION OF THE STATE SPACE, IT ALSO HAS NON-ZERO TAILS WHICH EXTEND INTO THE 'DEAD' REGION.

AND SO IT FOLLOWS FROM THE EIGENSTATE-EIGENVALUE RULE THAT THE CAT IS AS A MATTER OF FACT NOT DETERMINATELY ALIVE (OR DEAD), WHEN GRW(ALIVE) OBTAINS, AFTER ALL.

AND SO THE GRW THEORY, AS WE HAVE STATED IT ABOVE, PATENTLY FAILS TO SOLVE SCHROEDINGER'S PARADOX.

AND NOTE THAT THE TROUBLE HERE RUNS A GOOD DEAL DEEPER THAN THE MERE NON-VANISHING OF THE TAILS OF THE MULTIPLYING GAUSSIAN, IT ISN'T ANYTHING ONE CAN ADDRESS BY (SAY) REPLACING THOSE GAUSSIANS WITH SQUARE WAVES. THE TROUBLE HERE IS WITH THE BASIC DYNAMICAL STRUCTURE OF QUANTUM MECHANICS, THE TROUBLE IS WITH THE INCOMPATIBILITY OF POSITION AND MOMENTUM, THE TROUBLE IS THAT INCOMPATIBILITY ENTAILS THAT ANY WAVE-FUNCTION WHICH AT A CERTAIN INSTANT SOMEHOW MANAGES TO LACK SUCH TAILS - TAILS EXTENDING EVERYWHERE - WILL ALWAYS INSTANTANEOUSLY GROW THEM BACK. THIS IS THE *TAILS PROBLEM*. (ALBERT AND LOEWER 1992). WITHOUT A SOLUTION TO IT THE GRW THEORY IS NO SOLUTION TO THE MEASUREMENT AND REALITY PROBLEMS.

A GOOD DEAL MORE IS APPARENTLY BEING CALLED INTO QUESTION HERE THAN JUST THE SUCCESS OF THE PARTICULAR THEORY WE HAVE BEEN DISCUSSING FOR THE LAST FEW MINUTES: WHAT'S AT STAKE HERE IS WHETHER THE REALITY PROBLEM CAN BE SOLVED BY MEANS OF ANY SORT OF A COLLAPSE OF THE WAVE-FUNCTION WHATEVER, WHAT'S AT STAKE (TO PUT IT SLIGHTLY DIFFERENTLY) IS WHETHER WORLDS LIKE OURS CAN BE FULLY AND

SATISFACTORILY REPRESENTED BY MEANS OF QUANTUM-MECHANICAL WAVE-FUNCTIONS AT ALL.

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THE THING THAT TUGS AT YOU, THOUGH, IS THAT WE SEEM TO HAVE GOTTEN SO CLOSE. THE STATES WE END UP WITH ON GRW, WHATEVER ELSE THEY ARE, ARE ALSO UNDENIABLY ALMOST THE ONES WE WANTED. AND THE INTUITION IS THAT THAT CAN'T HAVE GOTTEN US NOWHERE, THAT IT MUST BE GOOD FOR SOMETHING.

LET'S SEE IF WE CAN PUT OUR FINGER ON WHAT THAT MIGHT BE.

SUPPOSE WE WERE TO RELAX THE EIGENSTATE-EIGENVALUE LINK, AS IT RELATES TO THE POSITIONS OF PARTICLES, IN SUCH A WAY AS TO GRANT THAT A PARTICLE CAN BE LOCATED IN A REGION EVEN IN CIRCUMSTANCES WHERE ITS QUANTUM STATE (OR, MORE GENERALLY, THE QUANTUM STATE OF THE UNIVERSE) FAILS TO BE AN EIGENSTATE OF LOCATION IN THAT REGION.

HERE'S A VERY STRAIGHTFORWARD WAY OF DOING THAT:

PosR: "PARTICLE X IS IN REGION R" IFF THE PROPORTION OF THE TOTAL SQUARE AMPLITUDE OF X'S WAVE-FUNCTION WHICH IS ASSOCIATED WITH POINTS IN R IS GREATER THAN OR EQUAL TO $1-p$.

PosR IS A NEW PROPOSAL, AN ALTERNATE PROPOSAL, ABOUT THE RELATION BETWEEN POSITION-TALK AND WAVE-FUNCTION TALK; A NEW PROPOSED *SUPERVENIENCE RULE*. OR AT ANY RATE IT IS A PART OF SUCH A RULE: IT REMAINS TO FINISH IT UP BY SPECIFYING THE VALUE OF P. LET'S LOOK INTO THAT.

TO BEGIN WITH, $1-p$ IS GOING TO HAVE TO BE SOME PROPORTION, AND SO p IS GOING TO HAVE TO BE SOME REAL NUMBER BETWEEN ZERO AND ONE.

AND IN ORDER TO GUARANTEE THAT NO PARTICLE CAN SIMULTANEOUSLY BE LOCATED IN TWO DISJOINT REGIONS OF SPACE, p IS APPARENTLY GOING TO HAVE TO BE SMALLER THAN ONE HALF.

AND IN ORDER TO AVOID THE PROBLEMS WE HAVE JUST NOW BEEN DISCUSSING IN CONNECTION WITH THE STANDARD EIGENSTATE-EIGENVALUE LINK (WHICH IS THE WHOLE POINT OF THE PRESENT EXERCISE) p IS OF COURSE GOING TO HAVE TO BE LARGER THAN ZERO.

BUT THAT'S GOING TO HAVE TO BE PAID FOR.

IT TURNS OUT (FOR EXAMPLE) THAT IF p IS LARGER THAN ZERO, IT BECOMES LOGICALLY POSSIBLE FOR A PARTICLE TO BE LOCATED IN SOME REGION A AND ALSO IN SOME OTHER (OVERLAPPING) REGION B WITHOUT BEING LOCATED IN THE INTERSECTION OF A AND B .

AND IT TURNS OUT THAT IF p IS LARGER THAN ZERO, IT BECOMES PHYSICALLY POSSIBLE (BY MEANS OF GRW-TYPE COLLAPSES) FOR PARTICLES TO JUMP, INSTANTANEOUSLY, BETWEEN DISTANT AND ENTIRELY DISJOINT REGIONS OF SPACE.

AND IT TURNS OUT THAT IF p IS LARGER THAN ZERO, THERE IS SOMETHING SYSTEMATICALLY WRONG WITH ALL OF THE FAMILIAR PHYSICAL PROCEDURES FOR COMBINING INFORMATION ABOUT THE POSITIONS OF INDIVIDUAL PARTICLES INTO STATISTICS. IT TURNS OUT (MORE PARTICULARLY) THAT WHEREAS THE PROPER PROCEDURE FOR MEASURING WHETHER OR NOT ANY PARTICULAR INDIVIDUAL PARTICLE IS LOCATED IN ANY PARTICULAR SPATIAL REGION IS ENTIRELY INDEPENDENT OF THE VALUE OF p , THE PROPER PROCEDURE FOR MEASURING THE PROPORTION OF ANY LARGE COLLECTION OF

PARTICLES WHICH ARE LOCATED IN ANY PARTICULAR REGION IS NOT. IT TURNS OUT (MORE PARTICULARLY STILL) THAT WHEREAS ANY TECHNIQUE FOR MEASURING WHETHER ANY PARTICULAR INDIVIDUAL PARTICLE IS LOCATED IN ANY PARTICULAR SPATIAL REGION WHICH IS RELIABLE ON THE ASSUMPTION THAT $p=0$ WILL NECESSARILY ALSO BE RELIABLE ON THE ASSUMPTION THAT $p>0^2$, ANY TECHNIQUE FOR MEASURING THE PROPORTION OF ANY LARGE COLLECTION OF PARTICLES WHICH ARE LOCATED IN ANY PARTICULAR REGION WHICH IS RELIABLE ON THE ASSUMPTION THAT $p=0$ WILL NECESSARILY *NOT* BE RELIABLE ON THE ASSUMPTION THAT $p>0$.³

AND IT HAPPENS THAT THESE THREE ANOMALIES (THE ONE ABOUT INTERSECTIONS, THAT IS, AND THE ONE ABOUT JUMPING AROUND, AND THE ONE WE JUST DISCUSSED ABOUT STATISTICS) ARE ALL MATTERS OF DEGREE; IT HAPPENS (THAT IS) THAT ALL THREE OF THEM CAN BE QUANTIFIED, AND THAT THEIR MAGNITUDES ALL VARY DIRECTLY WITH THAT OF P ITSELF.

SO, WHAT'S GOING TO BE REQUIRED OF THE VALUE OF P IS THIS: THAT IT BE LARGE ENOUGH TO INSURE THAT MOST OF WHAT WE TAKE TO BE DETERMINATE IS, THAT IT BE LARGE ENOUGH (THAT IS) TO INSURE THAT THE TABLES AND CHAIRS AND POINTERS OF OUR MACROSCOPIC EXPERIENCE ARE INVARIABLY IN ONE OR ANOTHER PARTICULAR ROOM, AND SOME PARTICULAR NUMBER OF INCHES FROM THE WALL, AND POINTING IN SOME PARTICULAR DIRECTION, THAT IT BE LARGE ENOUGH TO INSURE THAT CATS ARE INVARIABLY EITHER ALIVE OR DEAD, AND THAT AT THE SAME TIME IT BE SMALL ENOUGH SO THAT THE SORTS OF ANOMALIES WE HAVE JUST BEEN DISCUSSING AREN'T GOING TO BE WORTH BOTHERING ABOUT.

AND THE ACCOMPLISHMENT OF GHIRARDI, RIMINI, AND WEBER'S DYNAMICAL MODIFICATION OF QUANTUM MECHANICS, THE THING THAT WAS TUGGING AT US, THE THING

WE HAVE BEEN TRYING TO PUT OUR FINGER ON, IS PRECISELY THAT IT RENDERS THOSE TWO REQUIREMENTS COMPATIBLE WITH ONE ANOTHER. THERE ARE VALUES OF P (THAT IS) WHICH ARE JUST SLIGHTLY LARGER THAN ZERO, VALUES AT WHICH THE MAGNITUDES OF THE ANOMALIES ARE ALL (BY ANY REASONABLE STANDARD) NEGLIGIBLE, FOR WHICH GRW COLLAPSES WILL NONETHELESS ALMOST INVARIABLY RESULT IN WAVE-FUNCTIONS WHICH LOCALIZE PARTICLES - ON POSR - WITHIN REGIONS ROUGHLY THE SIZE OF ATOMS.

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ALL THIS IS VERY GOOD. BUT NOTE THAT THE JOB WE STARTED A FEW PAGES BACK - WHICH WAS TO FINISH UP THE DEFINITION OF POSR, TO FIND A WAY OF PICKING OUT SOME UNIQUE CORRECT NUMERICAL VALUE FOR P, TO SOMEHOW NARROW THE SMALL RANGE OF APPARENTLY SERVICEABLE P-VALUES WE HAVE JUST BEEN TALKING ABOUT DOWN TO A SINGLE POINT -STILL ISN'T QUITE DONE.

LET'S SEE IF WE CAN THINK OF ANYTHING ELSE (BY WAY OF INTUITIVE REQUIREMENTS, BY WAY OF EVIDENCE) THAT MIGHT BE BROUGHT TO BEAR HERE.

CONSIDER, FOR EXAMPLE, WHETHER ANY UNIQUELY CORRECT VALUE OF P MIGHT SOMEHOW BE DISCOVERED *EMPIRICALLY*. DIFFERENT VALUES OF P WILL CERTAINLY YIELD DIFFERENT CLAIMS ABOUT THE FREQUENCIES WITH WHICH (SAY) CERTAIN PARTICULAR SORTS OF POINTERS, WHICH START OUT IN CERTAIN PARTICULAR SORTS OF PHYSICAL SITUATIONS, WILL END UP POINTING AT CERTAIN PARTICULAR PARTS OF THEIR DIALS. AND FREQUENCIES LIKE THAT WOULD SEEM TO BE EMPIRICAL FACTS PAR EXCELLENCE. AND SO THE VALUE OF P WOULD SEEM, IN PRINCIPLE, TO BE DETERMINABLE BY EXPERIMENT.

BUT THAT TURNS OUT NOT TO BE RIGHT: ALTHOUGH DIFFERENT VALUES OF P WILL INDEED YIELD DIFFERENT CLAIMS ABOUT THE ABOVE SORTS OF FREQUENCIES, THEY WILL ALSO (AND THIS IS WHAT THE THIRD OF THE ABOVE 'ANOMALIES' WAS ALL ABOUT, AND THIS IS

WHAT THE ABOVE REASONING NEGLECTS) YIELD DIFFERENT CLAIMS ABOUT THE ACCURACY OF ANY PARTICULAR METHOD OF EXPERIMENTALLY ASCERTAINING WHAT THOSE FREQUENCIES ARE.

LET'S THINK THIS THROUGH IN ALL GENERALITY. LET'S CONSIDER WHETHER THERE CAN BE ANY SUCH THING AT ALL AS AN EXPERIMENT FOR MEASURING P. LET'S CONSIDER (THAT IS) WHETHER THERE IS ANY IMAGINABLE INITIAL PHYSICAL STATE OF THE UNIVERSE SUCH THAT, WITH THE PASSING OF SOME FINITE TIME, A CHECK-MARK RELIABLY APPEARS IN A CERTAIN BOX ON A CERTAIN PAGE OF A CERTAIN LABORATORY NOTEBOOK IN THE EVENT THAT THE VALUE OF P IS (SAY) BELOW 0.2, AND A CHECK-MARK RELIABLY APPEARS IN A CERTAIN OTHER BOX ON THAT SAME PAGE OF THAT SAME NOTEBOOK IN THE EVENT THAT THE VALUE OF P IS ABOVE 0.2.

WELL, THERE ISN'T. HERE'S WHY:

TO BEGIN WITH, P SIMPLY DOESN'T APPEAR ANYWHERE IN THE DYNAMICAL LAWS. AND SO THERE CAN BE NO INITIAL WAVE-FUNCTION OF THE UNIVERSE WHOSE SUBSEQUENT TIME-EVOLUTION WILL IN ANY WAY DEPEND ON P'S VALUE.

AND SO THE ONLY REMAINING LOGICALLY POSSIBLE HOPE OF A CHECK-MARK'S ENDING UP IN ONE BOX IN THE EVENT THAT P IS BELOW 0.2 AND IN ANOTHER BOX IN THE EVENT THAT P IS ABOVE 0.2 IS THAT THERE IS SOME SINGLE UNIVERSAL WAVE-FUNCTION WHICH, ON POSR TOGETHER WITH THE HYPOTHESIS THAT P IS BELOW 0.2, CORRESPONDS TO A CHECK-MARK'S BEING IN THE FIRST BOX, AND WHICH, ON POSR TOGETHER WITH THE HYPOTHESIS THAT P IS ABOVE 0.2, CORRESPONDS TO A CHECK-MARK'S BEING, INSTEAD, IN THE SECOND BOX.

BUT THERE CAN'T BE A STATE LIKE THAT. IF, ON THE HYPOTHESIS THAT P IS BELOW 0.2, THERE IS A DETERMINATE MATTER OF FACT, WHEN A CERTAIN WAVE-FUNCTION OBTAINS,

ABOUT A CERTAIN CHECK-MARK'S BEING LOCATED IN THE FIRST BOX, THEN THAT CHECK-MARK MUST NECESSARILY ALSO BE LOCATED IN THAT BOX, WHEN THAT SAME WAVE-FUNCTION OBTAINS, ON THE HYPOTHESIS THAT P IS ABOVE 0.2.

AND AT THIS POINT NO HOPE WHATEVER IS LEFT.⁴

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LET'S SEE WHERE ALL THIS LEAVES US.

WHAT WE'VE DISCOVERED HERE IS THAT IS THAT THERE IS A SMALL CONTINUUM OF SLIGHTLY DIFFERENT PRECISE DEFINITIONS OF "LOCATED", ANY OF WHICH, ON THE GRW THEORY, WILL APPARENTLY DO AN EXCELLENT JOB OF UNDERWRITING THE USES WE ACTUALLY MAKE OF THAT WORD. NONE OF THEM, HOWEVER, WILL DO IT PERFECTLY, AND NONE OF THEM WILL DO A CONSPICUOUSLY BETTER OVERALL JOB AT IT THAN ANY OF THE OTHERS. AND WHAT SEEMS TO THE AUTHORS TO BE THE RIGHT THING TO SAY, UNDER THESE CIRCUMSTANCES, IS THAT THERE SIMPLY FAILS TO BE ANY PRECISE MATTER OF FACT ABOUT WHAT THE PREFERRED OR CORRECT OR CANONICAL VALUE OF P IS; THAT IF THE GRW THEORY IS CORRECT (OR IF ANY THEORY OF THE COLLAPSES OF WAVE-FUNCTIONS IS CORRECT, OR IF ANY THEORY ON WHICH THE STATES OF PHYSICAL SYSTEMS CAN EVEN BE REPRESENTED BY WAVE-FUNCTIONS IS CORRECT) THEN TALK ABOUT THE LOCATIONS OF PARTICLES TURNS OUT TO BE *VAGUE*.

THAT'S STRANGE. BUT IT SEEMS TO US NOT TO BE THE END OF THE WORLD, IT SEEMS TO US NOT TO BE OUT OF THE QUESTION.

IT WAS ONE OF THE UPSHOTS OF CLASSICAL MECHANICS, AFTER ALL, THAT OUR EVERYDAY MACROSCOPIC PHYSICAL TALK, OUR TALK OF TABLES AND CHAIRS AND BASEBALLS AND POINTERS ON MEASURING-DEVICES, SUPERVENES ONLY VAGUELY ON THE

EXACT PHYSICAL MICRO-LANGUAGE. ALL WE'RE BEING CONFRONTED WITH HERE IS THAT REPRESENTING THE WORLD ENTIRELY BY MEANS OF QUANTUM-MECHANICAL WAVE-FUNCTIONS IS GOING TO REQUIRE THAT WE SWALLOW ONE ADDITIONAL LEVEL OF VAGUENESS: THAT OUR EVERYDAY LANGUAGE WILL SUPERVENE ONLY VAGUELY (JUST AS IT ALWAYS HAS) ON THE MICRO-LANGUAGE OF PARTICLE POSITIONS, AND THAT THAT LANGUAGE WILL ITSELF SUPERVENE ONLY VAGUELY (AND THIS IS SOMETHING NEW, AND SOMETHING WHICH OTHER ATTEMPTS AT SOLVING THE QUANTUM-MECHANICAL MEASUREMENT PROBLEM - BOHM'S, FOR EXAMPLE - CAN AVOID) ON THE FUNDAMENTAL LANGUAGE OF PHYSICS.

AND NOTE (AND THIS IS IMPORTANT) THAT SWALLOWING THIS ADDITIONAL VAGUENESS WILL LEAVE PHYSICS NOT ONE WHIT LESS OF AN EXACT SCIENCE THAN IT HAS EVER BEEN. THE FUNDAMENTAL LANGUAGE, THE LANGUAGE OF WAVE-FUNCTIONS, THE LANGUAGE OF THE STUFF OF WHICH (ON THESE THEORIES) THE WORLD ACTUALLY CONSISTS, IS ABSOLUTELY PRECISE. MOREOVER, ANY PARTICULAR PROPOSED DYNAMICS OF THAT STUFF (THE GRW DYNAMICS, FOR EXAMPLE) CAN IN PRINCIPLE BE TESTED - IN THE USUAL WAY: BY MEANS OF ADJUSTMENTS OF THE POSITIONS OF MACROSCOPIC KNOBS AND SWITCHES AND SUBSEQUENT OBSERVATIONS OF THE POSITIONS OF MACROSCOPIC POINTERS - TO ANY ACCURACY WE LIKE. THE TRICK THERE IS GOING TO BE PRECISELY WHAT IT WAS IN CLASSICAL PHYSICS: TO DESIGN OUR MEASURING-INSTRUMENTS IN SUCH A WAY AS TO GUARANTEE THAT THE DISTANCES BETWEEN THE POINTER-POSITIONS CORRESPONDING TO RELEVANTLY DIFFERENT OUTCOMES OF OUR EXPERIMENTS ARE VASTLY LARGER THAN THE DISTANCES AT WHICH THE POINTER-POSITION ITSELF STARTS TO GET FUZZY.

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1. The textbook understanding is sometimes called "the Copenhagen Interpretation." Its canonical formulation is in Von Neumann (1955).

2. Let's see why.

Let's start with a little notation.

Let $|A\rangle$ denote an eigenstate of the hermitian operator traditionally associated with location, let it (that is) denote a state on which the particle in question is located in A on the assumption that $p=0$.

A procedure which reliably measures whether a particle is located in region A or in region B, then, on the assumption that $p=0$, is one for which the final state of the composite system consisting of the measured particle and the measuring-device is

$|A\rangle|A\rangle$

in the event that the initial state of the measured particle was $|A\rangle$, and for which the final state of the composite system consisting of the measured particle and the measuring-device is

$|B\rangle|B\rangle$

in the event that the initial state of the measured particle was $|B\rangle$.

And of course if a procedure like that were to be applied to a particle in a state like

$|A\rangle + k|B\rangle$ with $|k| < 1$ (1)

then the state of the composite system at the conclusion of that procedure (supposing, just for simplicity, that no collapses occur) is going to be

$|A\rangle + k|B\rangle$ (2)

Good. Suppose, now, that $p > 0$.

Well, the above procedure is going to be reliable in that case as well: In the event that $|k|^2 > p$, there fails to be any matter of fact about where the particle is located when (1) obtains, and there fails to be any matter of fact about what the measuring-device is indicating about the particle when (2) obtains; and in the event that $|k|^2 < p$, the particle is located in A when (1) obtains, and the measuring-device is indicating that the particle is located in A when (2) obtains.

3. Suppose we have a large collection of particles, all of which are initially in the quantum state in formula (1) in endnote 1; and suppose that this collection is allowed to interact with a device designed (an any way whatever) to reliably measure the proportion of that collection which is, on the assumption that $p=0$, located in A. Well, it is a very straightforward consequence of the linearity of the quantum-mechanical equations of motion (see, for example, chapter 6 of Quantum Mechanics and Experience) that as the number of the particles in this collection approaches infinity, the

state of the pointer on a measuring-device like that will, with certainty, approach

[pointing at the value " $[j]^2$ " on the dial]. (3)

And here's what the trouble with that is: Suppose that $p > [k]^2$. Then, although the proportion of this collection of particles which is located in A is determinately 1, the pointer on this measuring-device is with certainty going to end up pointing, determinately, whatever the value of p, at " $[j]^2$ ".

4. There seems to be two possible causes for our inability to determine the value of p. One is that there is a determinate value of p but that the fundamental dynamical processes keep us from learning what it is. The other is that there is no matter of fact concerning the value of p since our linguistic conventions (or whatever determines the meanings of our words) are sufficient to determine the value of p only vaguely. Needless to say, the second of these options is by far the more plausible.

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