Quantum Phenomena within a New Theory of Time

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A few discontents in present-day physics' account of time are pointed out, and a few novel quantum-mechanical results are described. Based on these, an outline for a new interpretation of QM is proposed, based on the assumption that spacetime itself is subject to incessant evolution.

In a few crucial passages in the history of physics, seemingly-unrelated riddles turned out to merely reflect different facets of the same phenomenon. Such, we submit, may be the lot of the quantum oddities on the one hand, and the elusive nature of time on the other.

Our path to this hypothesis went through puzzling over several physical issues, which we shall first recount in the following chapters before describing our findings and proposing our theory. Chapter 1 briefly introduces the two old enigmata of time's apparent transience and asymmetry. Chapters 2-4 point out a simple argument for an intrinsic time arrow. Chapter 5 briefly introduces the Advanced Action interpretations of QM and their implications. Chapters 6-7 describe some novel experiments that seem to indicate that the wave function evolves in a way that defies ordinary notions of space and time. Chapter 8 proposes an interpretation of these findings, which in chapters 9 we broaden to a sketchy outline of a new theory of spacetime.

1 Two Peculiarities of Time: Transience and Directionality

Ordinary experience notoriously clashes with physical theory with respect to time. We keep feeling that time "goes by," that there is a special "Now" moving from past to future, and that future events are born anew out of the present. These characteristics of reality are referred to as "Becoming." Yet theoretical physics dismisses this so-natural impression as mere illusion, and for good reasons. Time is the *parameter* of all motion and change; ascribing motion or change to time itself is bound to run into absurdities. For example, if time flows, or if the "Now" moves, how fast is this motion? To apply such terms to time would entail a higher time parameter, which would in turn necessitate a yet higher time and so on *ad infinitum.* The vast literature on this issues (see e.g. [1, 2] and references therein) makes it clear why the overwhelming majority of physicists have avoided this line of thinking altogether, opting instead for the simple and self-consistent "tenseless" account, which has culminated in relativity theory. Time, by this account, constitutes the fourth dimension, alongside with the three spatial ones, of spacetime. All events – past, present and future – coexist along time, just as different sites coexist along space.

It should be stressed that this "Block Universe" picture is not just an interpretation of relativity theory but an integral part of it,[3] for even familiar relativistic effects such as length contraction entail it. Consider the following exercise, which may be regarded as the spatial analogue of the "twin paradox." A spaceship of length L_0 passes at near-c velocity through a space tunnel of the same length. From the tunnel's reference frame, the spaceship's length is contracted to

$$L = L_0\sqrt{1 - \frac{v^2}{c^2}} \tag{1}$$

due to its motion, hence there is a certain time interval during which the tunnel's two gates can be briefly shut while the entire spaceship travels within the tunnel. From the spaceship's reference frame, however, it is the tunnel that contracts, hence at no time can the entire spaceship reside within it, let alone with the two gates shut!

The two conflicting accounts are compatible only because the two events – *i*) the entering of the spacecraft's rear through the tunnel's entrance, followed by the entrance gate's shutting, and *ii*) the emergence of the spacecraft's front from tunnel's exit, following the exit gate's opening – occur in opposite time sequences for the two reference frames (Figs. 1, 2). In the relativistic framework, then, the only objective elements are the two *world-lines* of the spacecraft and the tunnel, extending from past to future, while the "now" plane is observer dependent.[4] This "tenseless" picture is even more pronounced in general relativity, where the reciprocal effects of mass and spacetime on one another presuppose the objective existence of a 4-D spacetime. Time's geometric aspect is pronounced even more strongly in several exotic solutions of relativity that allow spacetime tunnels and closed timelike loops. Relativity, then, allies with basic logic in dismissing time's passage.

[3] Even Einstein himself [3, p. 151] has regarded the absence of the moving Now in his theory as "a matter of painful but inevitable resignation."

[4] Notice that even the familiar temporal "twin paradox," when resolved within special relativity without appeal to acceleration, is achieved by employing different "now" planes for the two observers [4].

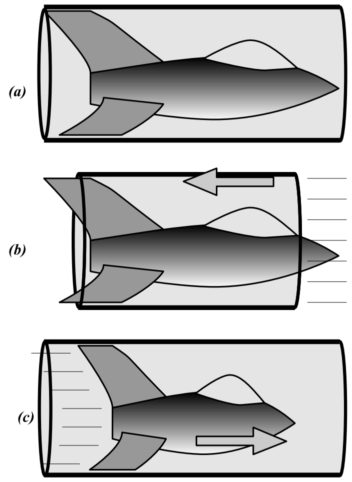

Fig. 1. Different relativistic reference frames give different accounts: (a) the spaceship and the tunnel are of equal length when in relative rest; (b,c) conflicting accounts arise due to the spaceship's and the tunnel's relative motion.

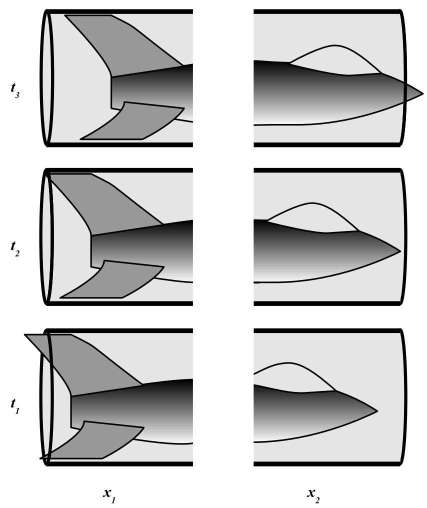

Fig. 2. From what seems to be an objective four-dimensional set of events, the spaceship's reference frame picks (x_1, t_1) and (x_2, t_3) as simultaneous, while for the tunnel (x_1, t_3), (x_2, t_1) are simultaneous.

Similarly dismissive is mainstream physics towards the other distinctive property of time, namely, its apparent *directionality*. In this respect too, time radically differs from the spatial dimensions: There is no universal "south" or "up"[5]. Not so with time, as "past" and "future" strongly differ everywhere in the universe, due to the second law of thermodynamics. Most physicists, however, belittle this directionality by pointing out that physical law itself is T-invariant. Hence, as nearly all microscopic interactions are time-symmetric,[6] the second law is often denied the status of a real law. Irreversibility, so goes the argument, occurs only in *ensembles* of particles, hence it may merely reflect the universe's initial state, which, for some reason, happened to be highly ordered. One could equally conceive of a universe whose initial state was totally disordered but which, by the same T-invariant laws, gradually becomes *ordered* in time.[7]

It is a very impressive feature of mainstream physics' position that these two negative assertions – *i*) dismissing time's passage as illusion and *ii*) dismissing time's arrow as an artifact of the initial conditions – neatly accord with one another. If the universe is a four-dimensional collection of equally-existent events, with no privileged "Now," then both readings of its history are equally valid. Entropy increases *as well as decreases* with time, depending on whether the observer chooses to read the universe's history forwards or backwards! Whether one likes this account or not, it is admittedly coherent and paradox-free.

Yet, a few dissenting voices are heard, most notably Davies [6], and for convincing reasons too. To believe that even *future* events, including all actions what we may decide to take, "already" exist in time, just as other places exist in space, is very awkward. True, intuition has often proved deficient by modern physics, but it should not be dismissed off-hand. Our immediate perception of time might be directly sensing an inherent feature of it that has not yet found its place in the formalism. Even relativity theory indicates that time differs from the spatial dimensions in some yet-unclear way: It bears the imaginary sign. Why, in Minkowski's equation

$$\Delta s^2 = \Delta x^2 + \Delta y^2 + \Delta z^2 - \Delta t^2, \tag{2}$$

[5] True, weak interactions do not conserve parity, therefore mirror images of the same physical process are not always equally probable. Nevertheless, there are still no absolute directions of space.

[6] Only "nearly all." The CP violation exhibited by weak interactions entails, by CPT invariance, a basic T violation too. "It is hard to believe," says Penrose [5, p. 583], "that Nature is not, so to speak, 'trying to tell us something' through the results of this delicate and beautiful experiment." Hear, hear!

[7] In fact, due to the ergodicity of physical laws, a universe with any initial condition, given a long enough period of time, will reach both entropy increasing and entropy decreasing phases. But the huge amount of astronomical and other scientific observations are all compatible with the proposition that the universe was created some thirteen billion years ago, a period much too short for the spontaneous occurrence of entropy-decreasing phases.

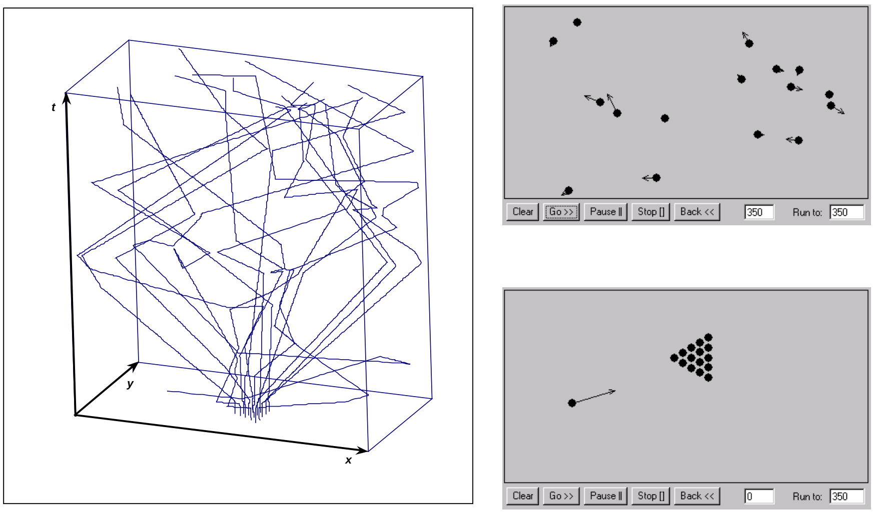

Fig. 3. A computer simulation of an entropy increasing process, with the initial and final states (right) and the entire process using a spacetime diagram (left). One billiard ball hits a group of ordered balls at rest, dispersing them all over the table. After repeated collisions between the balls, the energy and momentum of the first ball is nearly equally divided between all the balls.

is t assigned the minus sign? Relativity simply *presupposes* rather than explains this difference between t and its three counterparts.[8]

But if the conventional dismissal of time's directionality is congruent with the dismissal of its transience, wouldn't a loophole in the former challenge the latter? Such a possible loophole is discussed next.

2 Indeterminism Entails an Intrinsic Time-Asymmetry

It is embarrassing to observe how rarely the vast literature on time's arrow (See, e.g., [8, 9]) refers to the closely related issue of determinism. Are the basic interactions between particles truly random, or is information always preserved at some smaller level? This issue is crucial, as it straightforwardly bears on the origins of irreversibility. We shall point out this bearing first, and in the next chapter discuss determinism itself.

Recall again the conventional approach: The second law is not a real law but a mere fact – albeit ill-understood – about the beginning of the

[8] The question may be better put this way: Why can world-lines extend only in a timelike, never a spacelike fashion? The answer would be that the speed of light must never be exceeded, but as Sudarshan [7] has shown, relativity does not forbid the existence of tachyons, whose world-lines would be spacelike. Why, then, are such entities never observed?

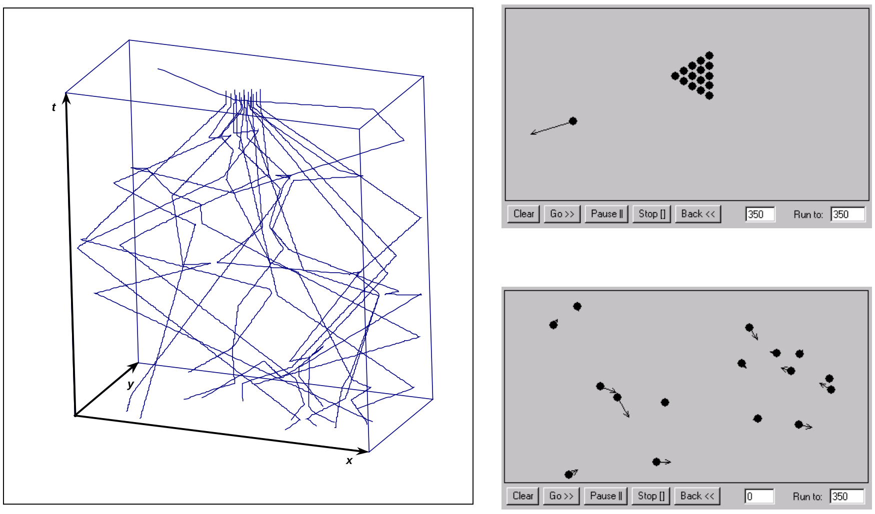

Fig. 4. The time-reversed process. All the momenta of the balls are reversed at t_{350}. Eventually, the initial ordered formation is re-formed, as at t_0, ejecting back the ball that has initiated the original process.

universe. “What needs to be explained is the low-entropy past, not the high-entropy future – why entropy goes down towards the past, not why it goes up towards the future” [8, p. 262]. One could, so goes the argument, conceive of a closed system, such as the entire universe, where the initial conditions lead to increasing *order*. All that such an evolution takes is that the system’s particles would be pre-arranged with the appropriate precise correlations that would ensure their later convergence into increasingly ordered states.

There is, however, a crucial difference between the normal, entropy increasing evolution, and the time-reversed, order increasing one. *The latter, not the former, requires an infinitely precise pre-arrangement of all the system’s elementary particles.* Consequently, when setting a system to evolve into a lower entropy state, and given sufficiently many interactions between the system’s constituents, any failure of a state to precisely determine the consecutive state will ruin the increase of order. Boltzmann’s entropy measure,

$$S = k \ln W, \tag{3}$$

is based on the trivial arithmetic fact that there are countless non-special microscopic arrangements that make disordered states, while very few, special arrangements make ordered ones. So, if nearly every initial arrangement will eventually give rise to entropy increase, then any interference following such an initial state is very unlikely to alter this destiny. Not so for the few initial arrangements that lead to order increase: They can give rise to eventual order only if nothing interferes with their later evolution.

Fig. 3 shows the results of a computer simulation of an ensemble of billiards balls. In the initial state, the balls are ordered and all the momentum is concentrated in a single ball that hits them. The consequent evolution of the system takes it to a higher entropy state, where the balls are scattered and the momentum is evenly distributed amongst them. Fig. 4 shows the development of a very unique initial state, which looks disordered but its consequent evolution takes it to an ordered state. So far so good. Now we introduced a small random disturbance into the progression of the two systems. Allowing the entropy-increasing system to evolve (Fig. 5), the disturbance causes only an insignificant shift in its destiny, from one high-entropy configuration to another, practically indistinguishable one. Not so with the time-reversed process (Fig. 6): The slightest variation in the position or momentum of a single particle creates a disturbance in the system's evolution that – given sufficiently many interactions between the particles – further increases as the system evolves. Consequently, entropy increases in the time-reversed system too.[9]

The relevance of this observation to the origins of irreversibility is immediate [10]: Had physics been able to prove that determinism does not always hold – that some interactions are genuinely probabilistic – it would follow that entropy *always* increases, regardless of the system's initial conditions.[10] An intrinsic time arrow would then emerge in *any* closed system under *whatever* initial conditions, congruent with the time arrow of the entire universe, of which closed systems are supposed to be shielded.

3 "Hidden-Variable Theories" are "Forever-Hidden-Variable Theories"

In other words, if God plays dice, irreversibility is inherent to nearly any process. But *does* he? QM is the natural place to look for an answer.

[9] The ergodicity argument can be raised here too: In an indeterministic but ergodic system, given long enough time, the system will display both entropy increase and decrease. One might therefore argue that the universe's relatively ordered state at present is due to a mere fluctuation, within which all our scientific observations just happen to comply with a systematic physical theory. No need to bother to refute such a possibility as, by the laws of probability, it is susceptible to a powerful *reduction ad absurdum* into solipsism: It is much more probable that it is only the reader's brain state, rather than the entire universe or even a part of it, is the result of such a unique fluctuation.

[10] For many years, Hawking has been claiming that unitarity is lost during black hole evaporation. At the same time he has been maintaining that the thermodynamic asymmetry is only due to the universe's initial condition. We have pointed out the contradiction between these two assertions [11]. Interestingly, Hawking recently recanted his unitarity loss hypthesis [12].

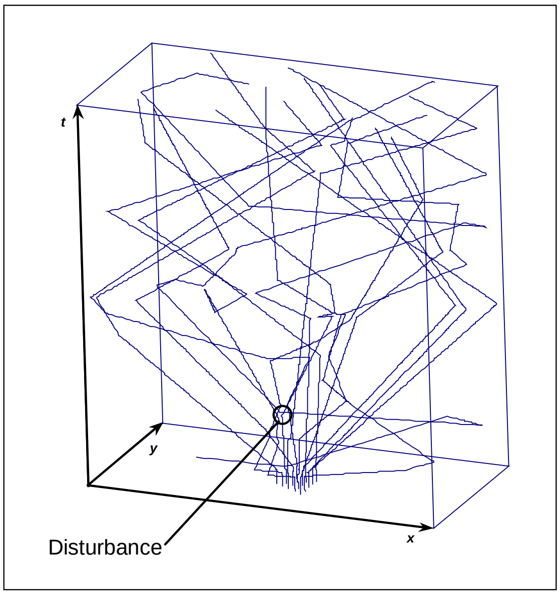

Fig. 5. The same simulation as in Fig. 3, with a slight disturbance in the trajectory of one ball (marked by the small circle). Entropy increase seems to be indistinguishable from that of Fig. 3.

QM's bearing on the issue can be summarized with three observations: *i*) The Schrödinger equation is deterministic and works perfectly well for the pre-measured state. *ii*) It fails miserably once the state is measured, observed or interacts in any other way with the environment, whereby superposition gives its place to one out of the many equally-possible states. *iii*) This new, "collapsed" state is not known to be causally determined by the pure state that preceded the instance of measurement. For example, when the spin superposition

$$\Psi = |\uparrow\rangle + |\downarrow\rangle \tag{4}$$

gives its way, upon measurement, to either $|\uparrow\rangle$ or $|\downarrow\rangle$, nothing in the original state is known to have determined the outcome. Indeterminism, therefore, seems to sneak in during this transition.

The uncertainty principle further stresses this causal void in the pre-measurement state. Intuitively, a tradeoff like

$$\Delta x \Delta p \geq \hbar/4\pi \tag{5}$$

which assigns a constant degree of uncertainty to the measurement of certain pairs of variables, suggests that there is a certain *ontological* indeterminacy, rather than mere *epistemological* ignorance, to many physical variables. Indeed, the double-slit experiment – the best visual demonstration of this

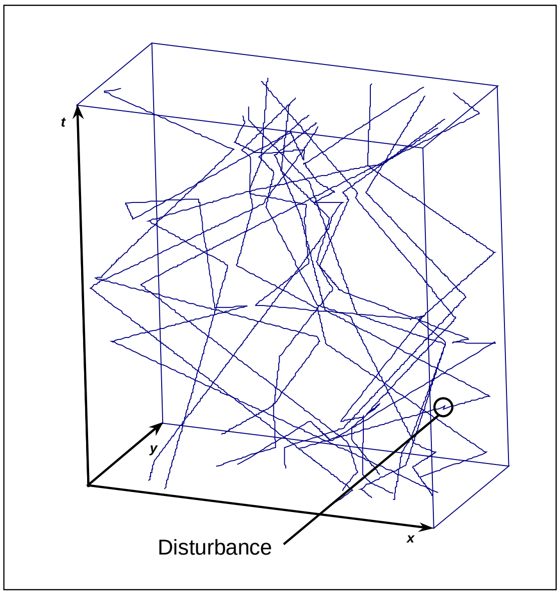

Fig. 6. The same computer simulation as in Fig. 4, with a similar disturbance. Here, the return to the ordered initial state fails.

position-momentum tradeoff – shows that, when the photon/electron wave function passes through the partition, the position is not merely unknown but, genuinely, "smeared" over space, enabling it to gauge both slits at the same time. Momentum, in turn, is similarly "smeared" when the position is accurately measured.

Ironically, it was the discoverer of the uncertainty principle that seemed not to have fully grasped its profoundness. The conceptual device known as "Heisenberg's Microscope" [13] turned out to be insufficient for explaining the true nature of the uncertainty. It only showed that the measurement's influence prevents accurately measuring the particle's position and momentum at the same time. To see that there is more to quantum uncertainty, consider the EPR-Bell experiment [14]. This setup seems to indicate that the variables are not only unknown but *do not exist* before measurement. The symmetry under rotation of the singlet state

$$\Psi = \frac{1}{\sqrt{2}}(|\uparrow\rangle_1|\downarrow\rangle_2 - |\downarrow\rangle_1|\uparrow\rangle_2) \tag{6}$$

implies that the two particles lack definite spin values, not only in the z direction but in all other directions as well. And indeed the experimental violations of Bell's inequality showed that the two particles' spins could not have have been fixed prior to the measurement. The simplest conclusion, therefore, is that, if Eq. (6) does not give any preference for either the "spin-up" or "spin-down" outcomes, then such a preference simply does not exist. Each particle's spin is probably determined *de novo* at the instant of measurement, thereby forcing the opposite direction on the other particle.

Determinism, however, proved to be too precious to be given up by all physicists. A survey of the interpretations of QM [15] shows that about half of the interpretations preserve determinism in some form of hidden variables or parallel universes, which supplement the superposition of Eqs. (4, 6) with some additional variables. These variables are believed to non-locally determine the results of measurements performed on the particles. Even radical new models, such as 'tHooft's (this volume) and Smolin's (this volume), go to great length to preserve determinacy by assuming hidden variables of one kind or another.

But can these models be scientifically proved? We have a serious concern that research on this issue might go astray for many years, claiming numerous years of futile labor, in search of something that may, *a priori*, be undetectable. Consider again the above EPR-Bell proof against local realism. While it has lead several authors to abandon the idea of hidden variables altogether, many others (including Bell himself) kept envisioning *nonlocal* hidden variables instead. What these models basically assume is that the two particles leave the source not superposed but with some pre-existing values of the hidden variables which carry on a common context for both particles' spins. Then, upon measurement of one particle, this shared context affects the result of the measurement performed far away on the other particle. Now, to the extent that these models are fully deterministic, they assume that even this change of the spin, brought about by the measurement, obeys causal laws. But here a simple question aught to be raised: Can such hidden variables ever be observed? A simple analysis can show that, *if quantum nonlocality is not buffered by indeterminacy, relativity must be empirically violated.*

This conclusion is quite straightforward, yet its bearings have seldom been explored. Elitzur [16] has pointed out that the three basic no-no's of theoretical physics – *i*) the quantum-mechanical impossibility of predicting a measurement's outcome, *ii*) the relativistic prohibition on superluminal velocities, and *iii*) the thermodynamic unlikelihood of a closed system's entropy to decrease – intriguingly preserve one another, such that violation of one principle leads to violations of the two others.

The argument, however, was qualitative, failing to give a rigorous proof. Yet an indirect support for it came from a work that has made an opposite claim. Valentini [17, 18] boldly suggested that the relativistic impossibility of superluminal velocities is merely due to entropy increase at the quantum level which has "scrambled" the quantum hidden variables, making them akin to "noise." He went on to suggest that if a technique is developed to distill a handful of particles in a low-entropy state, these particles could be used, for example, to instantaneously transmit information through the singlet state. The relativistic upper limit of c was thus rendered "fact-like" rather than "law-like," just like the second law of thermodynamics. This is a far-reaching hypothesis, with the added merit of being testable. For our purpose it should be noted that it reaffirms that, once quantum nonlocality is not buffered by indeterminacy, violations of relativity are bound to occur.

We, however, believe that the laws of relativity – so simple, coherent, and, well, so beautiful – reflect something very profound about physical reality rather than being only a consequence of noise. Similarly for quantum uncertainty: It is more likely to be conveying some fundamental aspect of causality than to be merely reflecting a technical limit of measurement. Indeed, the Bekenstein-Hawking [19, 20, 21] and the Unruh [22] effects seem to indicate that QM, relativity and thermodynamics are related in some yet-unfathomed ways. Most likely, therefore, the next revolution in physics will be a theory that will incorporate relativity and QM as important ingredients.

So, although there is no clear resolution at present to the issue of (in)determinism, our conclusion stands: *For any future theory in which relativity theory will be an integral ingredient, hidden variables must remain forever unobservable.* This places these entities in a position that is much more problematic than that of the ether. A physical theory based on entities, the detection of which is *forbidden* by the theory itself, belongs rather to the realm of religion.[11]

4 An Interim Conclusion: Time is Intrinsically Asymmetric

To summarize the issue of time asymmetry, the evidence we can point at is admittedly circumstantial, but seems fairly compelling. It is reasonable to say that:

1. QM implies an indeterminacy in any interaction in which a quantum system interacts with the environment.
2. To the extent that this indeterminacy is only apparent and deeper hidden variables underlie it, then, by relativity theory, these variables must never be detected.
3. A theory based on *absolute* unobservables is unscientific. Indeterminism, therefore, is a simpler, hence perhaps ontologically better description of Nature.

[11] In order to better assess the theoretical impasse involved with hidden variables within a relativistic theory, consider the status of quarks in particle physics. Quarks too cannot be directly observed, due to their confinement. Yet particle physics has pointed out several predictions that follow from the existence of quarks and are unaccountable in any theory that does *not* make this assumption. These predictions have so far been verified. No such a falsifiable prediction is proposed by the hidden variable theories.

4. But if any measurement-like interaction is truly indeterminate, then an intrinsic time asymmetry, independent of initial conditions, must be inherent to any process in which such an interaction of a quantum system with the environment is present.

This argument for time asymmetry reopens the issue of time transience. If determinism does not hold, then mainstream physics can no longer boast the consistency between denying time transience and dismissing time asymmetry, pointed out at the end of section 1. In a universe not strictly governed by determinism, one reading of the universe's history – initial order gradually giving way to increasing entropy – is perfectly reasonable, while the time-reversed account – high entropy gradually converging into order – is absurd or even solipsistic. In other words, in the absence of a proof for determinism, we have no reason to believe that the future "already" exists, causally determining the universe's present and past. The person-in-the-street picture of Becoming, in which the future is ontologically inexistent, to be genuinely created anew, regains credibility.

We shall next offer some new quantum-mechanical evidence in favor of this apparently-naïve view.

5 The Advanced Action Hypothesis

It is again to QM that we turn in search for new insights into the nature of time. Aharonov ([23] and this volume) and later Cramer [24] proposed two very appealing interpretation of QM ("the two vector formalism" and "the transactional interpretation," respectively) that, for the purpose of the present discussion, can be taken as one model, henceforth dubbed "the Advanced Action (AA) hypothesis." The adjective "Advanced" is *i*) in compliance with physicists' caprice convention that refers to retroactive action as "advanced" and to normal action as "retarded," and *ii*) to disclose our personal bias in favor of this idea. The noun "hypothesis" further conveys the hope that this interpretation may eventually yield testable predictions.

According to the AA, any quantum interaction is brought about not by one wave function but by the combined effect of two (or even more) waves, going back and forth in time. The initial wave goes from the source to the future absorber(s), such as measuring device, observer, etc. (one or more), while the reciprocal, "advanced", waves(s) return to the source backwards in time.

The famous EPR experiment provides a quick demonstration of AA's elegance: The measurement of one particle affects not only that particle's state at the moment of measurement but also all its previous states – indeed its entire world-line right down to the source – and then zigzags back to the other particle up to the present (Fig. 7). Cramer [24] has systematically applied the AA for explaining a vast range of quantum-mechanical peculiarities (see [25]

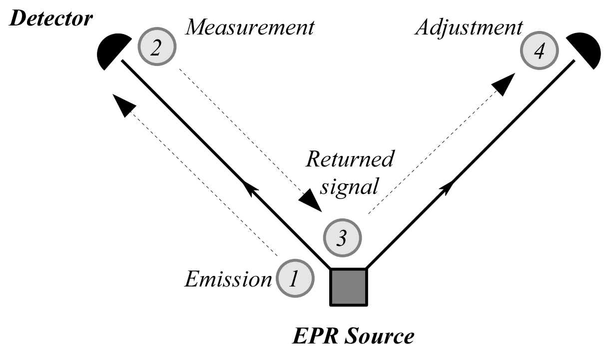

Fig. 7. AA in EPR experiment: After the emission of the particles at the EPR source (1), a measurement occurs at one of the detectors (2). The effect of the measurement then returns back to the EPR source along the past world-line of the particle (3) from there it follows the other particle's world-line to inform it of the change in the state (4).

for a recent perspective, and also [26] for some novel information-theoretic advantages of this model).

As revolutionary as AA is, however, Cramer [24] stresses that his interpretation of QM is just that, namely, an interpretation, not a theory, and hence yields just the same predictions as the quantum formalism itself. He furthermore endorses the standard Block Universe picture of time. It is within a "static" (Cramer's term) four-dimensional spacetime that the mutual "transactions" between past and future events take place.

In contrast, Aharonov, while not proposing predictions that differ from those of quantum theory, still derives from AA predictions that would probably have never been predicted within another theoretical framework. He is even more unorthodox in his approach to the nature of time, stating – although so far only in personal communication – that his interpretation entails a true dynamics of spacetime itself. Every instant in time within a quantum process, he believes, is visited twice: First by the forward propagating wave function and then by the complimentary one.

It is here that we would like to go a step further. In the next chapters we propose two experiments whose predicted results, as obliged by QM and inspired by AA, strongly clash with ordinary notions of space and time. On the basis of these experiments, we shall follow Aharonov's vision of AA within a theory that ascribes genuine dynamics to spacetime itself.

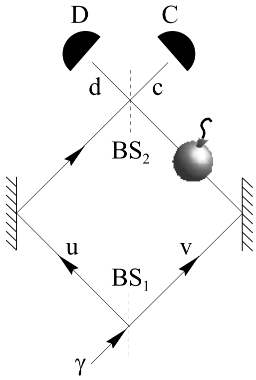

Fig. 8. Interaction Free Measurement. BS_1 and BS_2 are beam splitters. In the absence of the obstructing bomb, there will be constructive interference at path c (detector clicks) and destructive interference on path d (no click).

6 When one Quantum Object Measures another: Inconsistent Quantum Histories

The oddities of QM, whether in the form of real experiments or conceptual paradoxes, are many and famous, such as the "double-slit," the "delayed-choice," the EPR and Schrödinger's cat. They are paradoxical in that they point out inconsistencies between QM and classical physics, especially relativity. In this chapter and the next we present a new family of thought experiments[12] that are paradoxical in a deeper sense: They derive from QM an evolution that seems to be inconsistent with itself.

One origin of these experiments may be found in Elitzur and Vaidman's [27] Interaction Free Measurement (IFM) (Fig. 8). Using a Mach Zehnder Interferometer (MZI) with an object placed along its v path, EV pointed out that, in 25% of the cases, a single photon traversing the MZI may end up in detector D, indicating that it has been affected by the object on its v path, yet, by the photon's very arrival to BS2, it must have taken the opposite, u path, otherwise it would have been absorbed by the object. To make things more dramatic, EV took, as the blocking object, a supersensitive bomb that can be detonated by a single photon. Is it possible to know whether the bomb is good without detonating it? Their device allowed saving 50% of the bombs tested this way, a figure later brought close to 100% by a significant improvement proposed by Kwiat *et. al.* [28], who also carried out the experiment.

[12] In what follows we shall not bother to distinguish between gedanken and real experiments. QM is so rigorous that no one expects a gedanken experiment not to give the predicted result when performed in reality. And indeed, most of QM's gedanken experiments have by now been successfully performed.

The essence of the EV device's novelty lies in an exchange of roles: The quantum object, rather than being the *subject* of measurement, becomes the measuring apparatus itself, whereas the macroscopic detector (or super-sensitive bomb in the original version) is the object to be measured. In their paper [27], EV mentioned the possibility of an IFM in which both objects, the measuring and the measured, are quantum objects, in which case even more intriguing effects can appear.

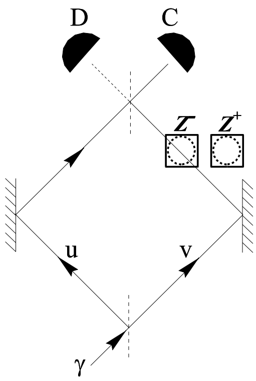

Fig. 9. Mutual IFM, where the "bomb" is also quantum-mechanical.

This proposition was taken up in a few seminal papers by Hardy [29, 30, 31]. In one paper, the bomb was replaced by another superposed atom. Fig. 9 gives a short description of this experiment. A photon traverses an MZI. On one arm of the MZI there is a spin $^1/_2$ atom prepared in a spin state $|X+\rangle$ (that is, $\sigma_x = +1$), and split by a non-uniform magnetic field M into its two Z components. A box is then carefully split into two halves, each containing either the $|Z+\rangle$ or the $|Z-\rangle$ part, while preserving their superposition state. In other words, if the atom's spin in the Z direction is "up" it resides in one box and if it is "down" it is in the other. The boxes are transparent for the photon but opaque for the atoms. The atom's $Z+$ box is positioned across the photon's v path in such a way that the photon can pass through the box and interact with the atom inside it in 100% efficiency. Then a photon is sent into the apparatus. This way, the photon and the atom, so to speak, measure each other's position.

In 25% of the cases, this mutual measurement will be completed, with the result that the photon took the v path and the atom turned out to be in the intersecting box on that v arm, hence it absorbed the photon and went into an excited state. Let us discard these cases. In another 50% cases, a photon will end up in detector C. This group gives no conclusive results, so let us ignore it too.

It is the remaining 25% cases that are the most curious. The photon ends up in detector D, indicating that its v path has been blocked and that it must have taken the u path, but this measurement has also "collapsed" the atom on the v path. In other words, the atom must always be found in the intersecting box.

Notice that this loss of the atom's superposition is a real physical effect: Prior to the photon's passage, the atom's two boxes could be reunited, and the atom's spin state $|X+\rangle$ could be measured and shown to be intact (This is quite analogous to the interference effect). Not so after the photon has traversed the MZI! The atom's position in the intersecting box is now certain and its X spin consequently becomes random. And yet, despite this physical effect exerted on the atom, the photon, which is supposed to have caused this effect, seems to have taken the opposite, u arm!

Stimulated by this result of Hardy, we began devising other setups in which several particles "measure" one another before the macroscopic detector completes the measurement. The result is a few experiments in which the history they yield seems to be inconsistent.

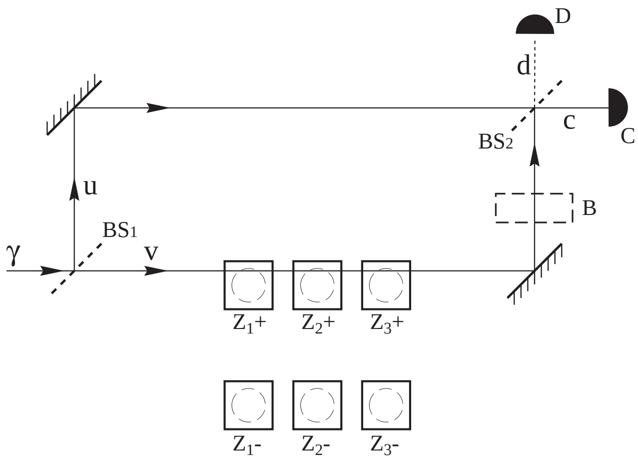

Fig. 10. One photon MZI with several interacting atoms.

In one experiment [32], we have replaced Hardy's superposed atom on path v by a row of such atoms (Fig. 10). The result predicted by QM is that only *one* out of the atoms, *not necessarily the first*, will lose its superposition, while all the others will remain intact. In other words, all atoms on path v except one will preserve their x spin when reunited.

Did one of the atoms in the row block the photon's way on path v? No, because if one places an opaque object at the end of the atoms row (object

B in Fig. 10), and no atom has absorbed the photon, *all* atoms will remain superposed! It seems that something must, after all, have passed through the row.

How can the photon's wave function affect only one out of many atoms positioned in a row along its path, leaving the others apparently intact, and yet complete its way through the row to the BS? Naturally, any answer to this question is bound to be controversial, as the Copenhagen, Guide Wave, Many Worlds and other interpretations would propose different explanations. One lesson, however, is likely to be accepted by the majority of physicists: *Measurement affects not only the system's present state but its entire history.*[13] It is the final click at d that seals the process. This, in fact, is the lesson derived from Wheeler's delayed choice experiment [33]. Wheeler himself chose to interpret it by strict adherence to the Copenhagen interpretation ("No phenomenon is a phenomenon until it is an observed phenomenon"). But perhaps it is time we do not shy away from an ontological conclusion, namely, that a measurement at the end of a quantum process genuinely affects the process's history, in both directions of time.

7 The Quantum Liar Paradox

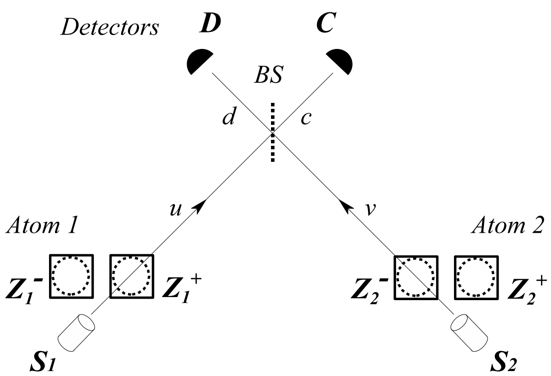

Fig. 11. Entangling two distant atoms that have never interacted.

[13] One of us (AE) owes this insight to a student's question about Schrödinger's cat. She argued that, if the box is opened after sufficiently many hours, it should be possible to know whether the cat has been dead or alive during the preceding hours. If it has been alive, it would soil the box and leave scratches on its walls, whereas if it has been dead, it would show signs of decomposition. Here too, the measurement at the moment of opening the box must select not only the cat's state at the moment of opening the box but its *entire history* within the box.

If measurement can sometimes “rewrite” the history of a quantum processes, some traces of this “rewriting” may be found in the form of odd inconsistencies within the resulting history. In terms of footnote 13 above, a scenario is possible which is analogous to a Schrödinger cat found to be long dead alongside with scratches and droppings within the box that indicate that it has been alive all that time.

Consider two atoms in the $|X+\rangle$ state, each separated according to its Z spin into two boxes as in the previous chapter (Fig. 11). Two coherent laser beams are directed towards an equidistant beam-splitter (BS), behind which there are two detectors. Each beam crosses one of either atom's two boxes. The laser sources are of sufficiently low intensity such that, on average, only one photon is emitted during a given time interval t. When the atoms are not present, the two laser sources are set to constructively interfere on branch c and destructively on d. This coherency can last for a period of time $\tau \gg t$. Notice the oddity of the situation: A single photon is detected at C, yet, by QM, the very uncertainty about its origin makes it interfere constructively, as if it has originated from the two sources!

Now consider the case in which the two atoms are present and detectors D click. We know that one of the beams was blocked (thereby spoiling the destructive interference). That means that one of the atoms “collapsed” into the intersecting box, while the other, into the non-intersecting one, but we don't know which atom “collapsed” into which box. Again, this uncertainty suffices to entangle the two atoms into an EPR state [34]:

$$|\Psi\rangle = |Z+\rangle_1 |Z-\rangle_2 - |Z-\rangle_1 |Z+\rangle_2 \tag{7}$$

This experiment may be regarded as a time reversed EPR, as the two atoms do not share a common event in the past but, so to speak, in their future. It will be therefore be referred to as RPE henceforth.

But the experiment's most intriguing feature emerges once we employ the famous tool for proving a nonlocal influence between entangled particles, namely, Bell's inequality. Let us first recall the gist of Bell's nonlocality proof for the ordinary EPR experiment [14]. Let a pair of EPR particles be created with their total spin being zero. Let the two particles travel to two equidistant measuring instruments. Now consider three spin directions, x, y, and z. On each particle out of the pair, a measurement of one out of these directions should be performed, at random. Let many pairs be measured this way, such that all possible combinations of x, y, and z measurements are eventually performed. Then let the incidence of correlations and anti-correlations be counted. By quantum mechanics, all same-spin pair measurements will yield 100% correlations, while all different-spin pair measurements will yield non correlated results (half correlated, and half non-correlated). And indeed, this is the result obtained by numerous experiments to this day [35, 36, 37, 38, to name a few]. By Bell's proof, such a unique combination of correlations and anti-correlations cannot have been pre-established. Conclusion: *The spin* *direction (up or down) of each particle is determined by the choice of spin angle (x, y, or z) measured on the other spacelike separated particle, no matter how distant.*

This is the familiar EPR-Bell. Let us now apply this method to the RPE. Recall that each atom has been split according to its spin in the z direction. Therefore, to perform the z measurement, one has to simply open the two boxes and check where the atom is. To perform x and y spin measurements, one has to re-unite the two boxes under the inverse magnetic field, and then measure the atom's spin in the desired direction. Having randomly performed all nine possible pairs of measurements on the pairs, many times, and using Bell's theorem, one can prove that the two atoms affect one another instantaneously, as in the ordinary EPR, with the difference that they share an event not in the past but in the future.

However, a puzzling situation now emerges [39]. In 44% (*i.e.*, $\frac{4}{9}$) of the cases (assuming random choices of measurement directions), one of the atoms will be subjected to a z measurement – namely, checking in which box it resides. Suppose, then, that the first atom was found in the intersecting box. This seems to imply that *no photon has ever crossed that path, which is obstructed by the atom.* But then, by Bell's proof, the other atom is still affected nonlocally by the measurement of the first atom. But then again, if no photon has interacted with the first atom, the two atoms share no causal connection, in either past or future!

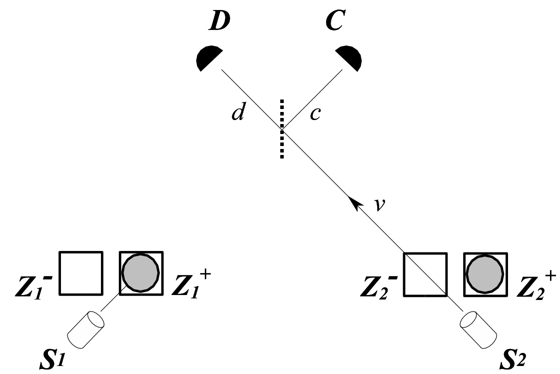

Fig. 12. Entangling two atoms.

The same puzzle appears in the cases in which the atom is found in the non-intersecting box. In this case, we have a 100% certainty that the other atom is in the intersecting box, meaning, again, that no photon could have taken the other path. But here again, whether we subject the other atom to the "which box" measurement or to an x or y measurement, Bell-inequality violations will occur, indicating that the result was affected by the measurement performed on the first atom (Fig. 12).

Put otherwise, *the very fact that one atom is positioned in a place that seems to preclude its interaction with the other atom is affected by that other atom.* This is logically equivalent to the statement "this sentence has never been written." We are unaware of any other quantum mechanical experiment that demonstrates such inconsistency.[14]

8 A Speculation: The Quantum Interaction Involves "Rewriting" of the Evolution in Spacetime

To be sure, the existing interpretations of QM will claim that they have no difficulty in explaining the above results. Yet, our search for a model that will be, at the same time, realistic, parsimonious, and, if possible, elegant, has led us to propose an interpretation of our own. We aspire to deal with the oddities of QM not by abandoning objective reality, but by working within a realistic framework that forces one to propose new hypotheses that may later be subjected to empirical test. We also seek to integrate relativity's four-dimensional spacetime with the somewhat opposite hints suggested by QM that genuine change, not static geometry, is reality's most basic property.

General relativity has taught us that spacetime is a real entity, namely, a four-dimensional array of world-lines with their corresponding curvatures. Within this geometric picture, the transactional interpretations reviewed in chapter 5 fit in very naturally, as they require interactions between earlier and later events. Where we break new ground is in proposing that this spacetime is not the changeless Minkowski array. Perhaps, rather, spacetime itself is subject to evolution. True, ascribing evolution to spacetime itself runs the risk mentioned at chapter 1, namely, invoking an infinity of higher- and higher-order times. We shall face this concern in the next chapter.

If this is so, if spacetime itself evolves, then experiments yielding apparently inconsistent histories, as those described above, may warrant an account like "first a retarded interaction brings about history $t_1x_1, t_2x_2, ...$, and then an advanced interaction transforms this history into $t_1x'_1, t_2x'_2, ...$" Consider the above quantum liar paradox: Perhaps there was first a forward moving

[14] It is possible to make this experiment even more striking by entangling two excited atoms, out of which only one can emit a photon within a given time interval. The atoms thus become entangled with respect to their excited/non-excited state. A bell-type inequality can be formulated for this case by using measurements that are orthogonal to the excited/non-excited state. Here too, the measurement of one atom may show it to be excited, thereby making it appear as if it has never emitted a photon, and thus could never become entangled with the other atom. And yet, by Bell's inequality, this result must also be affected by the other atom's measurement. We are currently elaborating such an experimental scheme.

evolution by which the two atoms sent virtual photons towards the BS. Then the detection of one photon retroactively entangled the two atoms backwards in the past. Finally, the measurement of one atom, which found it to be in the intersecting box, obliterated all traces of its interaction with the rest of the experimental setup. These reiterations of the process occurred by repeated spacetime zigzags *à la* Aharonov and Cramer, but in some real, higher time dimension, over spacetime itself. The remaining inconsistencies, such as an atom blocking the path of a photon which must nevertheless have traversed this path, might be the traces of this "revision." Such a model may also be better capable of explaining a few other surprising results discovered lately by similar methods [40, 41].

9 An Outline of the Spacetime Dynamics Theory

Our study was motivated by two phenomena that, on the one hand, have no trace in physical law, and, on the other hand, seem to constantly proclaim their presence.

1. Time, unlike space, seems to be flowing. However, accepting this phenomenon as a true property of time entails several logical and physical difficulties, such as an endless series of time parameters. Therefore, it has been often dismissed in favor of the simpler, self-consistent Block Universe picture.
2. The fact that we never observe the superposed states of the microscopic world in our macroscopic world, seems to imply a collapse of the wave function. However, accepting this collapse entails conflicts with relativity theory as well as with T invariance. Therefore, many interpretations avoided it.

And yet, we have pointed out several indications that these two dismissals are inadequate – that there is more to time than just a dimension, and that the wave function does undergo a unique change upon interacting with the macroscopic world. Moreover, the alleged collapse affects not only the particle's state at the moment of observation but, sometimes, its earlier history as well, suggesting that a whole segment of spacetime is subject to subtle evolution.

Perhaps, then, the two phenomena – time's passage and wave-function collapse – are not only real but the latter is the very manifestation of the former? A wave function, after all, is a sum of many equally possible outcomes, while the measurement brings about the realization of one out of them, the others vanishing. Isn't this the very difference between future and past? Isn't collapse elusive because it creates the elusive "Now"? Indeed de Broglie (Quoted in [42]) paid tribute to Bergson as a philosophical ancestor of QM. Had Bergson had a chance to study QM, de Broglie mused, he would learn that Nature hesitates at any instant between several choices, and he would reiterate what he has said in his *The Creative Mind*: "Time is nothing but this hesitation."

Here, then, is the unfavored hypothesis of Becoming again, now with a cosmological twist. Suppose that there is indeed a "Now" front, on the one side of which there are past events, adding up as the "Now" progresses, while on its other side there are *no* events, and hence - by Mach - *not even spacetime*. Spacetime thus "grows" into the future as history unfolds. Time's asymmetry would therefore be naturally anchored in this alleged progress of the "Now".

Notice that by ascribing to the "Now" the very creation of spacetime itself, we do away with all the logical difficulties which have so far beset the "moving Now" hypothesis (see chapter 1). Our hypothesis is merely an extension of the Big Bang model, taking advantage of the latter's logical rigor: If the Big Bang has created not only matter and energy but also spacetime itself, then no one needs to worry about "What happened before the Big Bang?" or "What lies outside spacetime?" Similarly for our hypothesis, the Now does not move on some pre-existing dimension but rater creates that dimension. This is not "movement" in the ordinary sense, so no endless series of time parameters is entailed by it.

Now let this Becoming be made quantum mechanical. What role does the wave function play in this creation of new events? The dynamically evolving spacetime allows a radical possibility. Rather than conceiving of some empty spacetime within which the wave function evolves, the reverse may me the case: *The wave function evolves outside the "Now," i.e., outside of spacetime, and its "collapse," due to the interaction with other wave functions, creates not only the events but also the spacetime within which they are located in relation to one another.* The quantum interaction's famous peculiarities – nonlocality, the coexistence of mutually exclusive states, backward causation and the inconsistent histories presented in the previous chapters, thus become more natural.

Can the reciprocal effects of spacetime and matter – the celebrated fruit of general relativity – thus possibly gain a quantum mechanical explanation? Perhaps it is the wave function, we submit, that is more primitive than spacetime, and the spacetime connecting two events is the product of their interacting wave functions. We shall close with a more audacious consequence of this hypothesis for quantum field theory. Perhaps the wave function of a force-carrying boson, such as a graviton or a photon, which, by our hypothesis, creates also the spacetime within which the final interaction is completed, determines the spatiotemporal distance between the events. In other words, "attraction" and "repulsion" may be the consequences of the specific spacetime metric created by the interacting wave functions.

Whether this sketchy proposal will eventually mature into a viable theory of spacetime dynamics, can be decided only by the future, be it the fixed

Minkowskian or the open Bergsonian one. We can only plead that the questions raised and odd phenomena pointed out in the preceding pages call for radically new ways of thinking about quantum and spacetime.

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