Biology Goes Digital

By Karl Coryat

1 Introduction

In audio and video technology, information can exist in either analog or digital form. There is reason to believe that the universe is, in some way, part "analog" and part "digital" as well. Complementarity is a central theme in quantum mechanics, first encountered by students in the form of "wave/particle duality." We learn that in certain situations, light and matter exhibit continuous wave behavior, while in others, they manifest as discrete phenomena. Given that complementarity can be demonstrated in any high-school physics lab, it is clear that a complete theory of the world will need to accommodate both aspects.

But, how do analog and digital fit together to create reality? Why can we see evidence of interference as well as quantization, continuity as well as discreteness? Does this dichotomy have a deep, foundational significance?

In this essay, I will look at features of quantum mechanics and decoherence that require the partitioning of a closed system in order for its "analog" characteristics to give way to discrete phenomena, including distinct measurement outcomes, and for decoherence to occur, leading to the classicality we observe. While the exact nature of this symmetry-breaking is unclear, such an event seems to be a prerequisite for the objective "reality" that we experience. I will argue that this reality is an emergent digital phenomenon within an otherwise smooth, analog universe, consisting of information registered exclusively through biological and technological processes.

2 Closed systems are analog

According to quantum mechanics, a closed system evolves in a linear, deterministic fashion as described by the Schrödinger equation:

$$i\hbar \frac{\partial}{\partial t}\Psi = \hat{H}\Psi$$

After eighty-odd years of research, no evidence has been found that an isolated, pure quantum system deviates from unitary evolution. A wave function, being the mathematical description of such a system, is a solution of the Schrödinger equation, and so any wave function describing a real system in the world must be differentiable and therefore continuous.

A core principle of Hugh Everett III's many-worlds interpretation [1] is that the entire universe is a quantum system described by a "state function," and therefore, if quantum mechanics is an accurate description of the universe, then the universe (as a closed system) evolves deterministically according to the Schrödinger equation. Given the success of the statistical predictions of QM, and barring any future experimental finding of deviations from unitary evolution in a real closed system, we conclude that all closed quantum systems, including the universe *as a whole*, are continuous and therefore fall definitively under the "analog" banner.

3 Decoherence & the early universe

Historically, some QM interpretations have supposed that wave functions somehow "collapse" into discrete particles upon observation; however, the mechanism that consistently produced macroscopic classicality was unclear. In recent decades, however, decoherence theory [2] has helped to explain the appearance of classical objects rather than quantum superpositions. An ordinary object in superposition tends to interact with environmental photons, air molecules, etc., and so its coherence is rapidly lost to the environment and the degrees of freedom therein. As the theory accurately predicts, these effects can be avoided in carefully prepared experiments; for example a superconducting quantum interference device (SQUID) can be put into a truly macroscopic superposition of magnetic-flux states [3]. Experiments such as this need to be performed at temperatures near 40mK in order to decouple the system from the environment. When a pure quantum state couples to a warm environment, the off-diagonal interference components of the combined systems' density matrix vanish with astonishing speed; for a 1 g mass at room temperature (~300K), quantum coherence is destroyed faster than thermal relaxation by a factor of 10^{-40} [2].

In contrast with the historical notion of a physical wave function collapse, decoherence offers an explanation for the *appearance* of classical behavior and discrete measurement outcomes, even of microscopic systems. For example, the gas in a particle detector tube is coupled to the tube and an electronic circuit with many degrees of freedom. Decoherence explains the spread-out quantum's apparent collapse into sharp "particle" behavior by way of information leaking irreversibly into the gas's and tube's environmental degrees of freedom, its coupling to an amplifier, etc.

In demonstrating how classical macroscopic behavior emerges from the unitary-evolving world of the Schrödinger equation, Zurek [2] points out that the everyday objects we encounter are open systems, meaning they are subsystems of a larger system:

> Macroscopic quantum systems are never isolated from their environments … they should not be expected to follow Schrödinger's equation, which is applicable only to a closed system.

Later [4] Zurek adds,

> In the absence of systems, the problem of interpretation seems to disappear. There is simply no need for "collapse" in a universe with no systems. Our experience of the classical reality does not apply to the universe as a whole, seen from the outside, but to the systems within it.

Zeh [5] notes that as a consequence of the "bird's view" universe being a closed system,

> The universe as a whole never decoheres … Quantum decoherence is meaningful or "relevant" only with respect to local *parts* of the nonlocal quantum world [emphasis his].

If all of this is true, one wonders about decoherence *within* the universe in its early history. Consider the ontological condition of anisotropies shortly after the Big Bang (i.e., irrespective of anisotropies that are observable to us 13.7 billion years later): Presumably the universe begins in a pure quantum state, being a closed system by definition. We therefore seek a kind of partitioning within the universe, or perhaps contact between the universe and systems external to the universe, in order to explain the (apparently) ontological heterogeneous structure of the cosmic microwave background — features that we consider "classical" when we study the microwave sky.

Viewed in this way, the ontology of the early universe becomes a cosmological expression of the measurement problem: We observe classical features among the deepest reaches of the Cosmos, but we do not know what would constitute an initial "measurement" within the unpartitioned universe — an event that would precipitate the emergence of such classical features. What might delineate a subsystem that led to the classical universe we observe? What process "selected" the first macroscopic accretions of matter over other statistical possibilities?

This question has been discussed in the literature. Steven Weinberg [6] writes,

> Just as in the measurement of a spin in the laboratory, some sort of decoherence [within the early universe] must set in; the field configurations must become locked into one of an ensemble of classical configurations ... It is not apparent just how this happens.

Roger Penrose [7] observes,

> The key is that irregularities arising from "quantum fluctuations" cannot come about without some [reduction]-like action, whereby the single initial quantum state somehow resolves itself into a probability mixture of different states.

Mukhanov [8] believes that this difficulty points us toward the many-worlds interpretation:

> Decoherence is a necessary condition for the emergence of classical inhomogeneities and can easily be justified for amplified cosmological perturbations. However, decoherence is not sufficient … It can be shown that as a result of unitary evolution we obtain a state which is a superposition of many macroscopically different states, each corresponding to a particular realization of galaxy distribution. Many of these realizations have the same statistical properties … Therefore, to pick an observed macroscopic state from the superposition we have to appeal either to Bohr's reduction postulate or to Everett's many-worlds interpretation of quantum mechanics. The first possibility does not look convincing in the cosmological context.

We have seen that the universe as a whole is a closed system; closed systems do not experience decoherence; yet decoherence is a real empirical effect in the world. The appearance of classical behavior means that the universe must be partitioned in some manner. But for this partitioning to occur, one concludes that there had to be some *initial symmetry-breaking event*, or "first first intervention," that disrupts the universe's symmetry. This would serve as a necessary causal antecedent of all observable classicality, the origin of life, and the observations we humans make and the measurement results we obtain.

4 The emergence of digital

While unitary evolution is continuous and "analog," and while we witness wave-born interference of photons and matter alike in experiments such as the double-slit, reality — *the world we empirically experience* — is fundamentally built out of discrete facts. Stapp [9] illustrates the discreteness of reality in a straightforward manner: If we consider an unstable atom S in a particular location, an emitted particle is described quantum mechanically as a wave function evolving unitarily, and permeating all of space. However, if we choose to surround S with a sphere of a finite number of particle detectors, we will find that one and only one detector fires, at a specific time t. This result is evocative of familiar digital technology: The single firing detector returns a “yes” or “1” at time *t*, and all other detectors return a “no” or “0” at all other times. In its apparent transformation from unitary wave function to a discrete measurement outcome, the decay product of *S* seems to undergo an analog-to-digital transition. Notice that the number of particle detectors in an experiment like this, whether real or imagined, will always be *countable* — returning a *finite* number of no’s and (perhaps) one yes within a finite interval. This is why the outcome is quantized and “digital.”

Consider also a human subject in an experiment detecting photons, with the aid of an apparatus that masks all but one rod cell on the subject’s retina. The subject can turn his head at will toward one of two sources, A or B, thereby choosing the preferred basis of the measurement. At every time t_P,[1] the subject’s rod cell is effectively asking the question: “Given the measurement parameters (for example, photon + source B), is the result affirmative?” And the answer is either a definite “yes” or “no” — a digital outcome. The situation is similar for the particle detector measuring *S*: Given a location in 3-D space and a time t_P, it definitively either does or does not detect a particle. However, choosing *not* to place any detectors around *S* would under no circumstances lead to a measurement outcome. Unintervened upon, and interacting with no other systems, the emission is assumed to evolve according to the Schrödinger equation, remaining distinctly “analog.”

One can think of the measurement process as partitioning the universe. Selectively measuring the environment, as happens in any measurement where a preferred basis is chosen, means making some kind of *fundamental distinction* in the world. With each measurement, a particle detector distinguishes a specific and defined spacetime location from the rest of the universe, and inquires with regard to the presence/absence of a charged particle. And every measurement, at every time t_P, produces a yes-or-no bit of information that answers the inquiry. In real experiments a detector is on for much longer than a Planck time, so it is making a series of measurements. If you like, you can think of each “yes” answer as one bit of information.

Of course, a “bit” is a discrete, indivisible unit of information — a discontinuity by definition. But outside the realm of human measurement results, are such discontinuities seen in nature? Are “quantum jumps” and particles as discrete as they appear? Zeh [5] appeals to decoherence to suggest that even these are part of a smooth analog world:

> Decoherence preferentially destroys interference between those parts of the wave function which differ markedly in position. This leads to density matrices which are effectively equivalent to ensembles of narrow wave packets. Such wave packets may then be interpreted as representing individual “particle” positions … All particle aspects observed in measurements of quantum fields (like spots on a plate, tracks in a bubble chamber, or clicks of a counter) can be understood by taking into account this decoherence of the relevant local (i.e., subsystem) density matrix.

In Zeh’s analysis, the objective world that we measure does not include discontinuities. However, when we measure, the results *are* discontinuous; there is nothing smooth about the manner in which knowledge of a measured system changes. We should therefore not confuse “particle

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1 Planck time is invoked because for any larger interval, multiple emissions could be detected (purely in principle), a result that cannot be expressed in a one-bit yes-or-no answer. Here t_P can be considered the minimum interval in practice.

behavior" with truly discrete *measurement outcomes*; the track of a particle in a bubble chamber is continuous, but yes-or-no facts about the particle's presence at specific spacetime locations are not. An electron's energy level ultimately changes in a continuous manner, but our knowledge about an emitted photon changes suddenly and discontinuously. Perhaps taking a closer look at information will help clarify how information transitions from the continuous realm to the discrete.

5 Intrinsic vs. extrinsic information

Muller [10], in his unification of symmetry and information theory, describes two modes of information: *intrinsic* information, which is dependent strictly upon an object's (internal) physical structure, and *extrinsic* information, which is defined by the object's number of internal configurational relations that can be distinguished by an observer. A perfect diamond crystal bears intrinsic information, based on its number of carbon atoms or mass, but it offers no extrinsic information — the quantitative measure of a system's asymmetry — even to an expert jeweler.[2] This is because while intrinsic information is a function of size, extrinsic information is a function of observable symmetry breaking. It is only through the presence of asymmetry that extrinsic information becomes available for measurement; a perfectly symmetrical system in a condition of zero entropy, as far as the observer's faculties are concerned, cannot be measured, because no internal group can be distinguished from any other. (See figure, next page.) Extrinsic information need not be part of our epistemology; it need only be there for the observing.

To describe an observer capable of measuring extrinsic information, Muller uses the term *information gathering and using system*, or IGUS (after Zurek [11]). He makes the point that an IGUS, in order to be able to distinguish asymmetries in an object or in the environment, must have some degree of *memory* capability; it must be capable of storing or holding information. Consider Maxwell's demon, the hypothetical entity that can measure gas molecules and open a door if they are moving fast enough, thus lowering the system entropy and violating the 2nd law of thermodynamics. In order to do its job, the demon needs to be capable of having at least two possible internal states: "do nothing" and "let molecule through."[3] The necessary resetting of the demon between cycles (the closing of the door *if* it is open) amounts to a thermodynamically irreversible mapping of the two-state system to a one-state system [12]. Such a process increases the entropy of the system overall, thus ensuring that the 2nd law holds.

Muller's unification provides a quantitative, relational definition of the information "out there" in the world. It must be emphasized, however, that extrinsic information can be defined *only in relation* to a particular observer and its acuity for asymmetry. Furthermore, extrinsic information is not necessarily quantized, or even quantifiable; a sound wave is an example of analog extrinsic information (in relation to our ears), but it has no quantifiable informational content in relation to a photocell, for instance.

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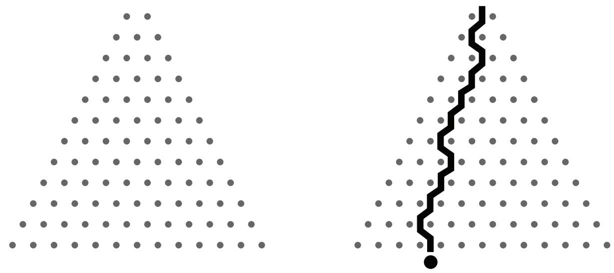
2 Extrinsic information is observer-relational; i.e., an observer with better acuity, for example a device that can distinguish among isotopes of atoms, may find extrinsic information in an otherwise perfectly symmetrical diamond crystal.

3 In addition, an IGUS needs to store a measurement standard, in this case the threshold velocity for opening the door.

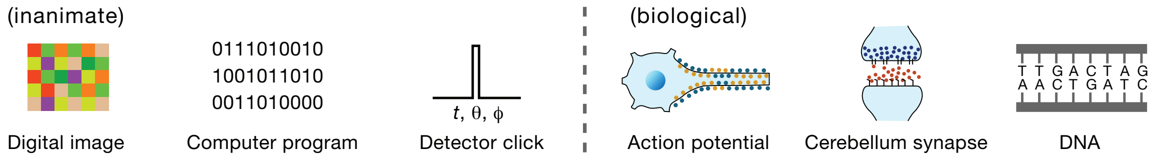


A perfectly symmetrical pattern of horizontal pegs (left) has intrinsic information, but zero entropy and zero extrinsic information, in relation to our eyes. A ball falling through the pegs (right) breaks the symmetry, thereby increasing the extrinsic information and entropy in the world. We can register one bit for each step (the ball can jog either left or right).

6 Information flow in biological & technological systems

It is not trivial for an object to meet the criteria for a working IGUS, with its uptake and storage of information. Yet, it is difficult to imagine anything that we know about the world, or anything we *could potentially* know, coming through any other mechanism. What observers are capable of distinguishing asymmetries in the world, and are also able to process and store the resulting information? Where can we find information flowing from one IGUS to another? Certainly this can be seen aplenty in biological systems, consisting of complexes of coupled-together subsystems (for example, a rod cell coupled to an optical neuron, or an enzyme that couples to inhibitors, activators, and co-enzymes). Information flow and the resulting homeostatic responses in these IGUS-complexes are largely what characterizes life.

We saw with Maxwell's demon that an IGUS needs to store a measurement standard, against which properties in the environment (such as molecule velocities) are compared. In biological systems, threshold-dependent mechanisms are ubiquitous in the sense organs and elsewhere. Wave behavior can be seen throughout the physical world, but nowhere does a biological system transduce, process, and store "information waves" that are scalar analogs of external conditions, in a continuum of amplitudes down to zero. Instead, sensory neurons produce "yes" or "no" action potentials that may be amplified tremendously (often through photomultiplier-like "cascading" processes), stored, recalled, and re-stored — proprietary information-processing mechanisms that have evolved to optimize reproductive fitness. In reacting to a photon, a grain of silver nitrate reveals extrinsic information about narrow wave-packet behavior in a world of decoherence; but even the photoreceptor molecules in a one-celled *Euglena*'s eyespot are coupled to a relatively complex causal network, which the animal employs to make "free-will" actions that causally impact the environment in turn. *All information that enters into a biological system, and is stored therein, is actively quantized for the proprietary use of the system*. It is no coincidence that living organisms have the unique ability to selectively assemble nucleic acid sequences, thereby storing truly digital (base-four) information in a durable, reproducible form. Nature is analog overall, but the "reality" of existence for any dynamic biological system, embedded in a dynamic environment, depends strictly upon digital information. I will call this third informational mode *registered information*.



Examples of registered (digital) information, both inanimate and biological.

There is also a technological variety of IGUS: the particle detector, the radio telescope, the digital camera. Such devices demonstrate that consciousness/mind is not required to make information-bearing observations of the world. However, two unequivocal statements apply to *all* technological measuring devices: They are designed and manufactured by humans and would not exist if we had never evolved the intelligence to build them; and they are all modeled on biological sensory abilities. Any technological measuring device you can think of is an extension of animal sense; all function to help us discern extrinsic information. Many of them register and store digital information as well, by quantizing environmental asymmetries against threshold values.[4] For this reason, informationally speaking, these energetic, quantizing measuring devices — things that produce all manner of 0's and 1's through interaction with a smooth, analog world — are better classified alongside biological systems, than with passive inanimate systems such as hydrogen molecules, silver nitrate grains, asteroids, and cosmic anisotropies.

We have seen that even though the universe as a whole does not experience decoherence, we do observe the results of decoherence in the real world. Although this produces the appearance of wave-function collapse, even "discrete" phenomena such as particles and quantum jumps can be shown to be ultimately continuous [5]. The quasiclassical world of decoherence offers extrinsic information to systems capable of distinguishing asymmetries. Biological and certain technological systems quantize these asymmetries, and use and/or store the resulting digital information.

We have also established that extrinsic information has quantifiable ontology only in relation to an observer; a flawless diamond offers no internal information to a jeweler, but plenty to a device that can map its carbon-isotope atoms. In a similar manner, registered information passing through a neuron or electronic circuit has ontological status only in relation to the IGUS through which it flows. The nerve impulse from a photon registration, or the voltage spike from a detected particle, has no ontology independent of the ions or electrons carrying it, or the organism or device "experiencing" it. Even the data from an astronomical survey, written to a hard drive, has relevance only to the drive head that subsequently reads it.

The only information we have about the world, the only kind that enters into our conception of reality, comes from biological and technological measurements. In the history of life on Earth, no fact has come from any other source, and it is difficult to imagine a scenario where this generalization might be violated. Anything we know about the world or about ourselves ("reality") belongs to a set of digital information, and any facts we could ever know or discover would become part of our reality only by joining that set.

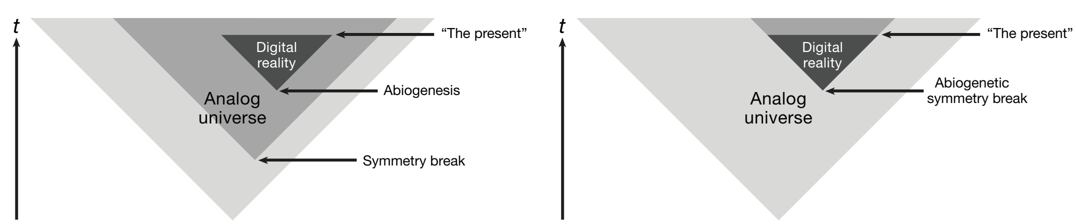
[4] Some recorded information remains in the analog realm — for example, a seismogram, EKG, and "Purple Haze" on vinyl.

7 Two pictures of the universe

In some ways our discussion leaves us no better off than where we began: We still need an origin for initial symmetry breaking. However, regardless of *how* the symmetry of the zero-entropy universe may have broken, at least two scenarios can be envisioned (see figure below) of how we techno-biological entities and our digital reality emerged from this "broken universe."

In one scenario, a symmetry break early in the universe's history initiates decoherence and the resulting classical approximation in a causally connected region. This region contains what we modern humans would call extrinsic information, although no sufficiently complex systems with memory, etc., are expected to be extant in the early period. At some point, however, conditions are right for the emergence of the first organisms of our biological lineage. Relative to these early life forms, which likely performed poorly at distinguishing asymmetries, the universe contained little extrinsic information and less registered information. However, both information sets, the extrinsic and the registered, expanded relative to the reproduction and evolution of life. Today we have registered a terrific amount of data that informs our reality, and the undiscovered information that exists in the universe is vast to say the least.

In another scenario, the symmetry of the universe remains unbroken until the point of abiogenesis, or a near-precursor event of same. In this case, "the universe" is experienced only by the partition that broke away, specifically, biological life; *all extrinsic information that we can discover* (at least in our many-worlds branch) has ontological status only in relation to us techno-biological beings. A thorough treatment of this view is beyond the scope of this essay; however, a developed theory in which a causally continuous techno-biological superorganism[5] is a "common observer" of the universe, as a special case of relational quantum mechanics [13], may shed light on "fine tuning," the Fermi paradox, the Boltzmann brain problem, and other issues.



Two possible universe histories. In one picture (left), the symmetry of the zero-entropy universe breaks early on, yielding a classical approximation in a causal region (medium gray). Life arises in this region. In another picture (right), symmetry breaking and abiogenesis coincide. All observable information is unique to our biological lineage and the technology we build.

8 The analog-to-digital arrow

There is beauty in the interdependence of asymmetry, decoherence, information, entropy, and the arrow of time. When we set up a double-slit experiment in a symmetrical arrangement, we

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5 Comprising the entire history of our techno-biological lineage, whose members share a single causal branch. This particular hypothesis is informally speculated upon at the website www.biocentricity.net.

see the full wave nature of light; break the symmetry of those two slits, and the wave behavior diminishes — in exact proportion to which-way information entering the world. The double-slit is a classic experiment because it lets us toggle back and forth at will between perfect analog symmetry, complete with its superposition and interference, and an asymmetric, information-bearing setup that's more typical of ordinary experience. There are other connections: Decoherence is thermodynamically irreversible; the thermodynamic arrow of time is determined by asymmetries in entropy; entropy and information are closely related; and information is strictly unidirectional, flowing only from past events, never future ones. On a human level, it is this incessant flow — the experience of a definite digital reality endlessly crystallizing out of an uncertain (analog!) future — that creates much of our perception of the arrow of time.

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The ideas in this essay assign an intrinsic role to observers — living and nonliving alike — in the dynamics of information. But observer-participancy is not a new concept. In introducing his "it from bit" idea of a digital universe, and hinting at his participatory anthropic principle to come, John Wheeler [14] expressed the view with remarkable candor:

> We ask the yes-or-no question, "Did the counter register a click during the specified second?" If yes, we often say, "A photon did it." We know perfectly well that the photon existed neither before nor after the detection.

The registration of photons need not be a function of consciousness or any other anthropocentric notion. But perhaps, absent the partitioning and measuring of the world by techno-biological systems, no photon would register, anywhere.

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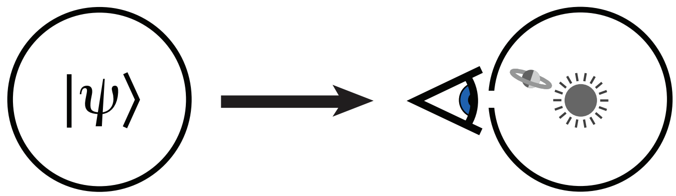
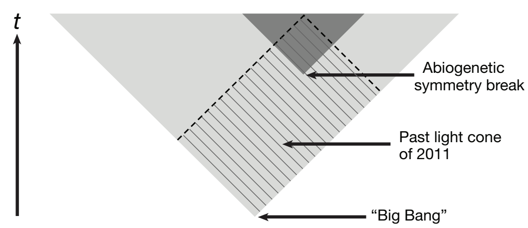
Endnote
Decoherence & locality: The ultimate superposition experiment

It may not be clear how we could observe 13 billion-year-old classical features of the Cosmos if the universe did not experience a partitioning or symmetry-breaking event in its very early history. But consider the following thought experiment: It is the year 12011. Researchers have managed to prepare an entire star, complete with a large orbiting planet, as a pure quantum state. The system is enclosed within an ideal cavity of radius one light-day.* We then go up to the cavity, open a tiny porthole, and observe the now-open system with a telescope. From our observer perspective, the system would undergo immediate decoherence, resulting in the observation of a planet with a classical position:



This is not a locality violation, because the decoherence is local at the eye, where photons are now impinging. We do not need to wait a day or two for the system to "learn" that it is open to an outside environment, partition, or subsystem. (One wonders what the scene would look like in the mean time!) For the same reason, no matter when symmetry breaking in the universe occurs, today we can observe classical features of any event that falls within our past light cone, including the early universe.



This thought experiment has macroscopic EPR-like implications as well. Consider, instead of a single observer, *two* spacelike-separated observers, each of whom opens a porthole; then they reunite to compare their measurements of the planet. Presumably, the observers' results will agree, even if one outcome seemed to "determine" the other outcome, in a nonlocal manner.

Thanks to Dieter Zeh for kindly offering to help clarify this concept.

* If you don't like the idea of a star in a cavity, then imagine that the researchers have prepared (or happened upon) a closed universe, containing only the star/planet system, into which we are then able to intrude.