Plato's Cave Revisited: Science at the Interface

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Scientific exploration and thus our knowledge about the outside world is subject to the conditions of our experience. These conditions are condensed here into an interface model, which, besides being physical, has an additional interface structure not reducible to physics. We suggest that this structure can dynamically be characterized by separate modes, M_i. Their selection and operation presupposes free will and a rudimentary concept of time and space. Based on some analogies with quantum networks it is argued that the "observed" gets "dressed" as a consequence of the observing. Interface-dynamics and system dynamics supplement each other, without over-determination.

I. INTRODUCTION

Science is arguably the most powerful tool for understanding the outside world. Nevertheless, despite all the impressive advances in technology and experimentation leading to ever refined scientific theories, we should still be aware of Plato's cave parable [1], according to which we are to consider ourselves as being prisoners in a cave restricted to seeing only shadows of the world outside.

There can be different reactions to this reminder. One is to query if the apparent world out there, time [2, 3], free will [4, 5] are all illusions. This was a radical conclusion indeed. But if accepted, how could this illusion come about, based on which assumptions considered to be fulfilled? A challenging task indeed, a happy playground for some philosophers [6]. However, for most physicists, Plato's allegory essentially points in a different direction: (i) there is something "real" outside, independent of us, but (ii) we have only limited access to this outside world. The cave may thus serve as a metaphorical description of the interface between observing and observed. What then can we know [7, 8]?

As our point of departure we consider that a basic incompleteness [9] of *any* theoretical scheme about the world is unavoidable: We cannot proceed without a frame of reference [10–13], a context (like axioms in mathematics), which, though not necessarily unique, must then be applied without further analysis. We consider empirical science to exist and to be confirmed (at least for many practical purposes) and exemplified by technology. As a consequence there must be conditions under which (empirical) science is possible. While these conditions cannot, by themselves, follow from that very science, they should, if given, allow to analyze and specify the appearance of such reference frames. But what is a consistent set of such conditions (or at least part of it)? And how might consistency be tested?

In a nutshell we propose the following scheme: Scientific exploration and thus our knowledge about the outside world $\mathcal{W}$ is subject to the conditions of our experience [7, 12], which can be condensed into an interface model. The interface $\mathcal{I}$ between observing $\mathcal{O}$ and observed $\mathcal{W}$, besides being physical, has an additional interface structure not reducible to physics. If one wishes, the interface may be taken as an abstract, functional model of the mind; it actively organizes the $\mathcal{O}-\mathcal{W}$-partition. The interface structure can dynamically be characterized by separate modes, M_i. Their selection and operation presupposes free will and a rudimentary concept of time and space.

How to justify all this? One may argue that the interface model could be derived – based on other (possibly hidden) assumptions, though. The present model is explicit in that respect and will have consequences in the observed world $\mathcal{W}$, by which its consistency can (empirically) be tested. In the following we leave out, e.g., sensory qualia and emotions, which should also be seen as interface properties. We rather concentrate on core properties of $\mathcal{I}$ pertinent to scientific investigations.

There are other variants of interface-oriented theories, a prominent group being information based. Here one should note that "information" enters physics only in connection with the observer (cf. [14] and Sect. V.D). For Clifton et al. [15] quantum mechanics is about representation and manipulation of information. In fact many researchers appear to believe that the quantum wave function itself represents our knowledge about the quantum state rather than "a direct description of reality" [16]. A. Caticha et al. showed [17] that Newtonian dynamics could be derived from information geometry. R. Frieden [18] intended to develop a theory of measurement that incorporates the observer into the phenomenon under measurement. The interplay between theories of knowledge and scientific theories is studied, e.g., by M. Bitbol [19]; he takes a non-representionalist stand. Also K. Popper's theory of the "three worlds" [20] offers

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some analogies. Remarkably, his main argument for the existence of world 2 (mental objects and events) is taken to be its direct or indirect causation on world 1 (physical objects and events). Similar to what we will call interface dynamics below, Penrose [21] has introduced "active manifestations of consciousness" (i.e. actions under free will) as opposed to "passive manifestations", which include sensory qualia. We prefer here to replace "consciousness/mind"by the technical term "interface" thus focusing on some purely operational aspects.
Despite its interface-orientedness, information is sometimes given a somewhat more fundamental touch: as being constitutive for our perception of the world. This notion appears to underly Wheeler's "it from bit" or Konrad Zuse's "calculating space". In a similar vein the world is described by Rucker as being resolvable into digital bits [22], by Lloyd [23] as being a quantum computer.

The present paper is organized to combine three lines of arguments: In Section II.A we define the interface structure applicable to the $\mathcal{O}/\mathcal{W}$ - partition. This structure will then provisionally be assumed to be true, from which we can address pertinent applications (II.C) and infer statements concerning an open set of empirically well documented experiments (II.B and V). This constitutes a test in the sense of A.9 as defined in Section II.A. The second line of argument (Section III) deals with quantum theory as an important part of our theoretical understanding of the external world. Here the partitioning of a closed "quantum universe" allows the quantum theorist to present some detailed properties on global and local perspectives, respectively ("system dynamics"). While the theorist has complete control in this case, he can easily select perspectives, characterized by (different) effective behavior, from which a complete picture is impossible to obtain, in principle. In the third line of argument (Section IV) this type of limitation is taken to underlie, qualitatively, also the observing/observed partition ("interface dynamics"). In Section V we give examples for the "peaceful coexistence" between interface- and system-dynamics. Section VI summarizes our main message.

II. THE OBSERVING/OBSERVED PARTITION

A. Interface Model $\mathcal{I}$

Our interface model $\mathcal{I}$ tries to formalize the interaction between observing and observed with emphasis on the process of scientific exploration (see Fig.1). Insofar as $\mathcal{O}$ and $\mathcal{W}$ are physical subsystems, also the interaction will be physical. But in addition $\mathcal{I}$ supports non-physical interrelations, which are assumed to be characteristic for the $\mathcal{O}/\mathcal{W}$ partition. Their level of description might be called phenomenological. Statements A1 to A.4 are considered basic, A.5 to A.12 supplementary. This set is certainly not unique, but its consistency can be tested (see Sects.II.C, V).

A.1. [**Structure**] Given the division into observing $\mathcal{O}$ and observed $\mathcal{W}$ ("the world outside") the notion of an interface $\mathcal{I}$ is indispensable. Any such a partitioning and thus $\mathcal{I}$ presupposes a rudimentary concept of (abstract) space.

A.2. [**Dynamics**] We assume $\mathcal{I}$ to be characterized by an operation space, on which mental and/or material operations are being induced. In analogy with physics parlance these operations may be said to define the interface dynamics. Its existence presupposes a rudimentary concept of time (sequential order). Free will being involved [24], we need not investigate here how and why specific operations are selected.

A.3. [**Modes**] The following dynamical modes of interaction across the interface $\mathcal{I}$ are distinguished:
M_1: logical inferences (about $\mathcal{W}$),
M_2: concrete actions (on $\mathcal{W}$), and
M_3: observations and descriptions (of $\mathcal{W}$).
Note that M_1 takes place within $\mathcal{O}$ (while referring to $\mathcal{W}$), M_2 is a transaction from $\mathcal{O}$ to $\mathcal{W}$, and M_3 is a transaction from $\mathcal{W}$ to $\mathcal{O}$.

A.4. [**Judgments**] Based on these modes statements (judgments) of the form: "If A then B" are generated within the operation space. Here A will be called the context for B. Judgements are considered building blocks for the process of scientific exploration.
Supplementary details are now specified by A.5 to A.12:

A.5. [**Inference**] Inferences M_1 are answers to the question: Given A, what can be inferred about $\mathcal{W}$?
A is the "prior-knowledge" recorded in $\mathcal{O}$ consisting of an input and a method of inference (mental operation); it implies an output B, which may then count as a hypothetical "fact" (under condition A). If the input is the description of an initial state of some part of $\mathcal{W}$, B could then be the predicted state at some later time. We also include counterfactual reasoning: B would result, if the action plan A was carried out. Or: Fact A would allow us to decide between alternative theories B and B'. This is the basis for planning of experiments, tests.

A.6. [**Action**] Concrete actions M_2 are answers to the question: Given A, what can be done on $\mathcal{W}$?
Here A consists of some starting conditions and, typically, a tool such that its material operation under the control of $\mathcal{I}$ (via a corresponding man-machine interface) gives rise to an effect B within a specific part of the outside world

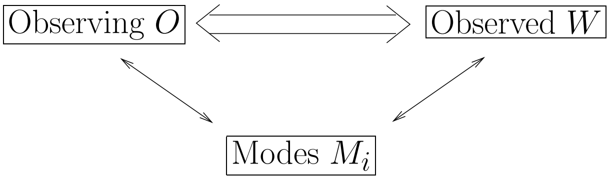

FIG. 1: Partition scheme for $\mathcal{O}/\mathcal{W}$. Here the interface consists of: Physical interaction $\Longleftrightarrow$; additional interactions via modes M_i (see text) $\longleftrightarrow$

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$\mathcal{W}$. This procedure underlies the interventionalist notion of cause [25]. The tool will have been designed for this purpose (mental operation involved); the M_2 are goal-directed [26]. There is no general theory telling us what kind of tools are possible or impossible; they must be compatible with the properties of $\mathcal{O}$ and $\mathcal{W}$. We do empirically know, however, that tools exist. They typically involve top-down causation [27].

A.7. [**Observation**] Observations M_3 are answers to the question: Given A, what can be learned about $\mathcal{W}$?
This is similar to A.5, but here condition A typically consists of a tool in $\mathcal{O}$ (an apparatus), the material operation of which allows to correlate a specific property of a specific part of $\mathcal{W}$ with the reading B of that apparatus, the “measurement result“ (which will have to be recorded as information on some memory pad in $\mathcal{O}$). The encoding of that information is part of the “description“. The apparatus will have been designed for this purpose (mental operation involved): A careful arrangement allowing to distinguish between the alternative outcomes of interest is needed. Again, there is no general theory telling us, what can or cannot (directly or indirectly) be measured.

A.8. [**General Context**] Note that in all the above relations the context A also includes our communally shared overall frame of understanding F (which we generally take for granted). This could explicitly be expressed as “If A and F, then B“. However, we usually suppress F.
Furthermore, the concrete formulation of the relations is dependent on a correspondence rule between a representation space $\tilde{W}$ and $\mathcal{W}$, this correspondence depending on a measurement reference frame R involving choices of coordinates, units, etc. So the real relation is “If A and R and F, then B“. Unlike F, the reference frame R must always be made explicit.

A.9. [**Testing**] Consistency between the various statements generated via those modes M_i requires tests. Such a test often depends on examination of the inverse relation: If B, then A? The uniqueness or not of this relation is crucial. Also useful in this context is to set B equal to “not C“, i.e. the form: If A then not C.

A.10. [**Cumulative Model**] Sets of statements are typically organized in the form of a “theory“, which is contextual, as its constituents are. Theories, if critically tested, build up a corpus of reliable (structural) knowledge (e.g. in terms of laws). Taken together, they form a model of $\mathcal{W}$ and how it functions (a large part of the framework F).

A.11. [**Irreducibility**] Being defined on the interface $\mathcal{I}$, not on $\mathcal{W}$, this interface model (including the modes M_i) cannot be reduced to physics. (Rather, physics and our knowledge about $\mathcal{W}$ is conditioned by this interface structure.) The model may be termed “classical“ in the sense that “decisions“ are being made and “facts“ registered. Subsystems $\mathcal{O}$ are also subject to physics, but distinguished from the other subsystems $\mathcal{W}$ by being the general referent of $\mathcal{I}$.

A.12. [**Borderlines**] The modes M_i are constrained by properties of $\mathcal{W}$ as well as properties of $\mathcal{O}$. While additional modes cannot be excluded, they could be considered only in so far, as they do not violate those constraints.

B. Comments and Examples

We add some further comments on the interface model of Sect. II.A.
(1) [Structure, cf. A.1] We accept Kant's proposition [7] to consider space as an a priori form of sensibility, real space being one variant only. There is no need to refer here to mathematical models like Euclidian space (as Kant mistakenly did).
What we here call the “observing“ may, in turn, consist of various subsystems (brains, tools, memory pads etc.); likewise will the “observed“ typically be defined by a substructure.

(2) [Dynamics, cf. A.2] We accept here Kant's proposition [7] to consider time as an a priori form of sensibility. We do not need a mathematical model for time at this stage.
In general, it is not entirely clear, what could be meant by free will [28]: Actual interface modes are not chosen randomly, but in additional to rationality are influenced, e.g., by emotions, societal constraints and cultural background. Furthermore, there are many situations, like the control of walking or bicycle riding, where freedom of choice in every moment would neither be practical nor welcome [26].

In the present context, however, choices are based in rational selection procedures relating theory to data as part of a research program [29]; it suffices to guarantee that the observer can freely follow his plan of investigation (cf. A.5; see also [30, 31]). Without free will in this sense the impressive success of technology (based on scientific knowledge) would have to be the result of a "script", written down at the time of the big bang, say, thus making us victims of a grand conspiracy, which is not a believable option.

(3) [Modes, cf. A.3] The modes M_1 to M_3 are considered a minimal set and separable, at least for the present purposes. Their initialization cannot be the (exclusive) effect of some other causes (see item (2) above). Their properties are constrained (cf. A.6).

(4) [Judgment, cf. A.4] Judgments (like theories) are by themselves non-physical concepts, as are qualia. Statements that have to be accepted unconditionally (like our tentative statements A1 – A12) are expressions of the "basic incompleteness" and may be seen as variants of Kant's "synthetic judgments a priori" [7]. By definition they should be true without reference to experience. Otherwise there are no absolute statements; the absence of these underlies problems we have with AI (artificial intelligence) or in signaling potential alien societies "self-evident" indications of our existence as intelligent beings (SETI , search for extraterrestrial intelligence [32]).

(5) [Inference, cf. A.5] Inferences may take up different forms:

a. Prediction: Given the initial state of a pendulum at time t_0, we can infer its position at some later time t_1 (using Newton's law and gravitational force as prior knowledge).

b. Reconstruction: Given fossil records and their similarity with living creatures on the one-hand side, the diversity of living turtles from island to island on the other side, Darwin [33, 34] inferred adaptive continuity in the development of species. This is a theory-driven re-interpretation of data present today with respect to the distant past.

c. Cause and effect [27, 35]: Why does the needle of my compass alwas point in a specific direction? I can proof that it is because of some weak magnetic field by showing that the effect is absent under sufficient magnetic shielding (an intervention based on prior theoretical reasoning).

(6) [Action, cf. A.6] Most actions [26] involve tools. While their operation is in accord with physics, the question of why they work as they do cannot be answered without reference to design and purpose (cf. Section IV.A). This already applies to a simple key-lock system (whether mechanical or electronic).

a. Macro-control: Thermodynamics [36] can be considered as a classical control theory on the level of macroscopic variables like volume, temperature, pressure (cf. V.B, though). For this theory to be operative it is essential to note that the observer must have tools by which he can indeed control, e.g., the volume of a gas container and thus affect the pressure in a predictable way.

b. Micro-control: The recent development in nanoscience is largely a consequence of the availability of new tools [37]. A decade ago hardly anybody would have dreamed of what is routinely possible today in terms of manipulation of individual atoms or photons.

While the scanning tunneling microscope [38] allows one to get structural images at atomic resolution, its cousin, the atomic force microscope is able to manipulate the position of individual atoms/molecules on a material surface. Both these tools are macroscopic thus exhibiting top-down action from the experimenter down to the nano-level. (Note, however, that the structure and position appear here as classical concepts.)

c. Quantum control: In the classical domain we can either prepare a desired state, or measure what already existed before. In quantum theory [39] preparation and observation are, in general, not separable and are not describable by deterministic equations of the theory.

To prepare a special (pure) state within a high-dimensional state space is an extremely ambitious task experimentally, requiring state-of-the-art tools. One method of choice (motivated by quantum computation [40]) is a two-step process: i. Cool down to the (unique!) ground state. ii. Decouple the bath and apply a unitary transformation (via a sequence of quantum gates) to reach the desired state. Such procedures are prone of errors, though. Error correction (feed back) is possible, in principle, but severely increases the overhead.

(7) [Observation, cf. A.7] Observations are obviously needed to get information about the outside world. Nevertheless, observations are not possible without prior theoretical concepts leading, e.g., to expectations: To observe the tides we have to abstract from the individual waves focussing on average water levels.

Observations are also required to confirm the effect of some previously applied action; this is the basis for scientific testing (e.g. for finding causal relationships in $\mathcal{W}$) as well as technology.

(8) [General Context, cf. A.8] As stressed by our interface model, concepts are necessarily contextual, not absolute. As indicated in the introduction and taken up in chapter IV, we have, in general, no access to the world $\mathcal{W}$ as such. A convincing explanation has eventually to appeal to intuition based on well-established metaphors and concepts like forces, fields, particles [41]. The electric field or the Schroedinger wavefunction are useful descriptions, to what extent they are "real" is undecidable from the point of view of the underlying partition $\mathcal{O}/\mathcal{W}$.

(9) [Testing, cf. A.9] Testing is not as straight forward as one might expect. There can be no valid derivation of a law of nature from any finite number of facts [42]. This holds, likewise, for any refutation of a theory. A belt of auxiliary hypotheses separate the core theory from the relevant data and cushion it from easy disproof [29].

(10) [Cumulative Model, cf. A.10] Maxwell's theory [43] represents a fine example for unifying a broad set of diverse phenomena, in this case magnetic, dielectric, and optical effects. A closer look reveals that this very successful theory is actually a patchwork of fundamental concepts (relativistic field theory) and phenomenological modeling (coarse grained, often classical schemes related to material properties), thus covering a huge range of experimental scenarios.

(11) [Irreducibility, cf. A.11] The operation of the interface $\mathcal{I}$ is not reducible to physics (or neurophysiology etc.). Our everyday experience is full of pertinent examples: While the subway we enter in the morning is certainly a system subject to physical explanation, the fact that it leaves the station at 8:06 is not. The traffic lights are physical devices, their phase, though, is not determined by physical law, neither is the mere fact that they are where they are. (There are no boundary conditions and physical theory such that a traffic light would result at the corner of the street.) It is definitely more plausible to consider those many details as a consequence of voluntary design rather than being predetermined by the big bang – at least until there is compelling evidence for the latter.

(12) [Borderlines, cf.A.12] Additional modes M_i would have to be introduced, if, e.g., one were to accept para-phenomena like teleportation or precognition [44]. While there seems to be no a-priori reason to exclude such extensions, they are not consistent with present day physics understandings (cf. A.9) and it is hard to see how these could lead to extended models of $\mathcal{O}/\mathcal{W}$, that would, in turn, allow to predict new testable and stable observations, i.e. more than what has been put in by allowing for such actions [42].

C. Applications

The workings of the interface (as based, in particular, on free will, space and time) are taken as preconditions of empirical sciences and their development.

(1) [Experimental science] Experiments are a compound of successive interactions across the interface: Inference M_1 (planning), concrete actions M_2 (setting up and initiating the experiment), observations M_3, and again inference M_1 (analyzing the results). They usually involve the idea of an isolated system, that is in a strictly regulated part of $\mathcal{W}$, where all other influences are either constant or very small (by design), so that the action M_2 is the only important causal event during the relevant observational time interval.

(2) [Observational science] In the case of sciences such as astronomy, only observations can be carried out; experiments are not possible. Observations are a compound of successively, inference M_1 (planning), carrying out the observations M_3, and again inference M_1 (analyzing the results). This is the learning cycle: for this analysis now provides the basis for the next observational plans, based on a better understanding of the system observed.

(3) [Technology] In the case of technology, inference M_1 (planning), is followed by action M_2. High level technology always involves a feedback loop whereby the outcome is checked against the goal, that is the action M_2 is followed by observation M_3 and analysis of that observation M_1; this is the start of the next action cycle. Technology aims at devices (characterized by a purpose). These include tools as discussed before. It is hard to predict, what devices are possible or impossible. Experimental and observational science very much depend on technology.

(4) [Perception] The empirical sciences are based on perception [45], which, in the broadest sense, is governed by the "interface"- modes M_i, extended beyond our natural senses by amazing technology, which includes a form of filtering of data received by us from the environment (each kind responding only to particular kinds of sensoric activation, so we need to take detection and selection effects into account, cf. IV.A), and shaped by our conceptual understanding F (also a form of filtering: we need to recognize what we see [19, 46]). Its build-up may be an evolutionary process subject to the requirements of stability (optimization as a form of Darwinism).

D. Physical Aspects of $\mathcal{I}$

The partitioning into observing/observed does also have a direct physical basis: In closed unpartitioned systems measurements cannot even be defined: Again, an external reference frame is needed. It is anything but clear, though, under which conditions one part of the universe (the "observing") may be set aside to measure and register some other part (the "observed"), whether classical or quantum [47]. But while classical theories, at least, appear to allow for such procedures without modifications, this does definitly not hold for quantum theories: Here one faces three interrelated problems: Given a state space and an observable to be measured, how will the actual measurement outcome be singled out from the distribution of possible values (as specified by quantum theory [39])? Then, how has the observable been selected to begin with? (Note that randomly chosen observables are likely to be non-commuting, i.e. mutually exclusive!) And third, how is the measurement outcome (irreversibly) stored as information? (Without recording nothing has been measured [48].) These points indicate that the problem of the observing/observed-distinction is further enhanced on the quantum level.

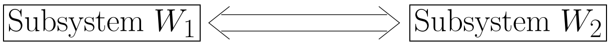


FIG. 2: Possible partition scheme for quantum system $\mathcal{W}$.

The selection of observables (the second part of the measurement problem) is a special variant of the much more general design requirement of selecting (physical) reference frames for $\mathcal{W}$, i.e. some pertinent set of distinguishable alternative states. Broad classes of frames can conveniently be studied in yet *unobserved* quantum networks (view from outside [49]), which allow one to discuss global features and the effect of internal partitioning in full detail [50] (our second line of thought). Local perspectives, i.e. “restricting attention“ to parts embedded in larger quantum environments, lead to effective dynamics and, in particular, to decoherence. The latter is a key for understanding the emergence of classicality within a quantum world [51].

But what is now the relation between this physical $\mathcal{O}/\mathcal{W}$ interaction and the interface structure introduced in Section II.A? Motivated by the observation that “global physics“ and “meta-physics“ both refer to a world as it is, without partition, we suggest that there is a structural similarity: namely of the relation between global physics ($\mathcal{W}$) and partitioned physics ($\mathcal{W}_1$, $\mathcal{W}_2$) (see Fig.2), on the one hand side, and of the relation between “metaphysics“ (dealing with the unpartitioned universe) and the partition observing/observed ($\mathcal{O}$, $\mathcal{W}$) (see Fig.1), on the other hand side.

In the former case the interaction between the parts is entirely physical, in the latter case it is defined also by the interface modes M_i as introduced in II.A. For global physics there is a complete theory, which is missing for meta-physics.

III. SYSTEM DYNAMICS

Global physics presupposes a “passive view“ from outside: Contrary to the situation addressed in the Sects. IV and V the observer does not participate. Nevertheless, he introduces/selects descriptions (for the state or specific observables). The pertinent parameters have a meaning only with respect to the respective reference frame.

A. Equivalent Reference Frames

For the states of quantum networks there are many equivalent representations based on different (“virtual“) partitions of the whole: If there are 9 “natural“ subsystems, say, we can describe them as a whole (no partition), as bipartite, e.g. (123) (456789), as tri-partite (1234)(56)(789) etc. Any combination can be considered; they constitute different reference frames (which do not affect the physics in any way).

Given a specific partition there is local state information (on each part) and a hierarchy of correlations [50] (2-part, 3-part, etc). All the various parameters add on to eventually give the complete description. These parameters are expectation values and as such not subject to any principle uncertainty. The entanglement contained in these various correlations is difficult to characterize, in general.

The local state (with respect to a selected part within a given partition) is equivalent to the reduced density matrix of that part.

Typically, the correlations comprise most of the pertinent state parameters: The finer grained the description, the more important the correlations become. The ultimate fine-graining amounts to identifying the “natural constituents“ (particles) with the subsystems of description.

The parameters of different frames are linked by transformation laws.

Any local picture (i.e. without access to corelations) is, in general, insufficient to infer the global picture.

The only complete ”local” description would be that connected with no partition at all.

B. Example: Spin-Network [50]

In classical physics a state of a system can conveniently be specified by a complete list of pertinent observables: A mass point is thus described by its momentary position in real space and its momentary momentum (3 coordinates each), i.e. a total of $p_1^c = 6$ real parameters. For an N-particle system there are consequently $p_N^c = Np_1^c$ parameters. As confirmed by observation, the initial state of a two-level system (spin) can be represented as a vector of length 1

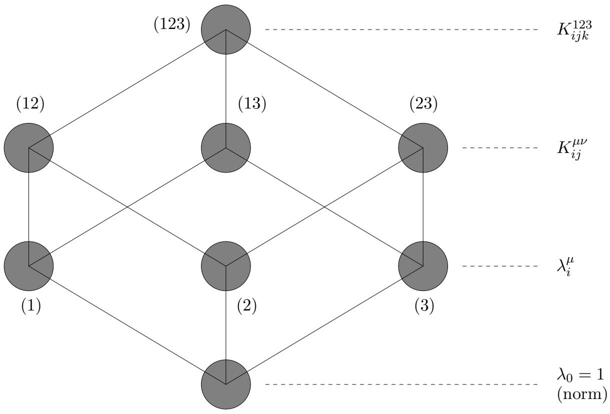


FIG. 3: Hierarchy of parameters characterizing the general state of a $N = 3$ spin-network. Subsystem number: μ,ν = 1,2,3; components: i,j = x,y,z (see Sect.III.B). Note that the local information λ_i^{μ} does not suffice in general; it would for product states (a kind of classical limit).

on a sphere. States within the sphere are also possible and represent incomplete polarization ("mixed states", vector length less than 1). This vector turns out to be a special representation of the so-called density operator, the most general way to define quantum states.

How many (real) parameters are needed to uniquely specify such a density operator? In fact, for a d_1-dimensional Hilbert-space the number of independent (orthogonal) observables or operators is $D_1 = (d_1)^2$; this is the so-called Liouville space dimension. It is convenient to include as one basic operator the unit-operator $\hat{\sigma}_0 = \hat{1}$. For the spin the additional three independent observables are $\hat{\sigma}_x$, $\hat{\sigma}_y$, and $\hat{\sigma}_z$ (spin in x-, y-, z-direction). Because of the normalization requirement the number of independent parameters for a general state is $p_1^q = D_1 - 1$. A single spin thus requires $p_1^q = 3$ parameters, which can be represented as a vector within a sphere of radius 1.

For a composite system (N spins; $d_N = (d_1)^N = 2^N, D_N = (d_N)^2, p_N^q = D_N - 1$), a convenient set of operators are the so-called product-operators. As the name indicates, such an operator is specified by associating with each spin number $\mu = 1, 2, ...N$ one of the 4 possible local operators $\hat{\sigma}_i, i = 0, x, y, z$. Such an operator may be visualized as some "chord" for a "quantum piano", with each key being a spin, and the local operator specifying what to do with the key. For $N = 3$ (see Fig.3) we might have, e.g., $\hat{Q} = \hat{\sigma}_x(1)\hat{1}(2)\hat{\sigma}_y(3)$. This would be a 2-cluster-operator, as it operates on spin (1) and (3), while leaving (2) unchanged. Combinatorics tells us that in the present case there are 9 1-cluster-operators (expectation values λ_i^{μ}), 27 2-cluster operators (expectation values $K_{ij}^{\mu\nu}$), and 27 3-cluster-operators (expectation values K_{ijk}^{123}), a total of $p_3^q = 63$ operators, as required (see Fig. 3).

If the 1-cluster operators are taken to describe local properties, the ratio of non-local to local parameters is $\gamma^q = p_N^q/Np_1^q$, i.e. for 3 spins $\gamma^q = 7$, for $N = 10$ one finds $\gamma^q \approx 3 \cdot 10^4$. Note that for the classical case $\gamma^c = p_N^c/Np_1^c$ would always be 1, the local parameters suffice to specify the total state. The exponential blow-up in the number of independent parameters is a typical quantum phenomenon: it derives from irreducible properties related to larger and larger clusters, i.e. entanglement.

C. Internal Effective Dynamics [50]

In the non-relativistic quantum regime the global dynamics is controlled by the system Hamiltonian and unitary Schroedinger dynamics. This is the "complete" description; there is no space for measurement, as there is no external reference system.

According to the partition given, the global dynamics can be decomposed into the dynamics of the respective local parts and the dynamics of the correlations. In general, the respective equations of motion are mutually coupled.

Under appropriate conditions the local equations of motion can be closed thus giving rise to effective dynamics.

Changing the partition (the frame) typically changes the local behavior, i.e. its effective dynamics.

While the total dynamics remains unitary, local dynamics may show irreversibility, thermodynamic features, attractor states. Seen from the global perspective these properties may be called "emergent".

The local dynamics, in particular, is incomplete: In general, the respective equations of motion are not closed. Closing may approximately become possible under appropriate conditions; the prize to be paid is to accept indeterminism,

though.
From the local dynamics it is impossible to uniquely infer the global dynamics. There are many different partitions (environments), which – for a given subsystem – produce the same local behavior.

IV. INTERFACE DYNAMICS

Finally, as our third line of argument, we take the qualitative features as found for quantum physical partitions to apply also to the observing/observed partition. The observing/observed network is taken to consist of $\mathcal{O}$, $\mathcal{W}_1$, $\mathcal{W}_2$, $\mathcal{W}_3$ etc., where $\mathcal{O}$ is the observing (brain, tools, memories etc.) and $\mathcal{W}_\mu$ are parts of the observed as filtered out by those tools. We focus here on the interface dynamics associated with scientific goals.
The experimenter has designed/selected and (approximately) isolated his systems of interest as well as his tools according to his intended interactions M_i. These interactions constitute the interface $\mathcal{I}$.
In physical terms this special scenario typically represents a non-equilibrium arrangement and will deteriorate if left alone. (No actions, no events can occur after equilibrium has been reached.)

A. Tools as State Space Filters

The interface $\mathcal{I}$ is able to select via the modes M_i the physical implementation of a specific reference frame for $\mathcal{W}$ as well as for $\mathcal{O}$. Typically this is done by means of appropriate tools.
The observer may infer the state parameters (see Sects. III.A, III.B) from measurements (cf. statement A.7). These will allow him to distinguish between a set of outcomes, which he can interprete as the eigenstates of some observables. Most likely, the operators corresponding to these observables will not have the unknown state as their joint eigenstate and thus will necessarily exhibit quantum uncertainty.
Filtering is indispensable for retrieving information from a quantum network, but also limits the kind of observation as well as of manipulation.
The set of operators accessible to a concrete measurement tool constrains what may be considered a physically adjusted ("realistic") partition or frame. (For stability aspects see, e.g., W. Zurek [52].)
Higher order correlations are usually very hard if not impossible to measure, no efficient tools are available. (If this limitation is generally not acceptable, a meaningful empirical description of the network would be impossible!)
As a consequence "physical" partitions (frames) result, for which correlations (classical and quantum) across certain borderlines between pairs, triples etc., but also local parameters of some subsystems, are inaccessible.
These different (physical) partitions conditioned by different sets of tools are incomplete and no longer equivalent. They constitute "perspectives".

B. External Effective Dynamics: Quantum jumps

The equations of motion for some subsystem $\mathcal{W}_\infty$ within $\mathcal{W}$ are not closed. While closing may approximately become possible under appropriate conditions, the predictability deteriorates, the entropy increases.
However, contrary to this effective dynamical behavior, the "information dynamics" of $\mathcal{W}$ induced by $\mathcal{O}$ allows a partial "up-date" by measurement: The resulting quantum jump associated with the information gain is considered here to represent the effective (non-unitary) dynamics of $\mathcal{W}$ as selected by the interactions M_i.
We note that the $\mathcal{O}/\mathcal{W}$ partition tends to suppress non-classical features within $\mathcal{W}$ and by that to produce non-deterministic behavior. The information-gain associated with the jump has been registered – as a fact about the object $\mathcal{W}_1$ (see Sect. II.D and V.C).
Parts within the partitioned universe necessarily lack causal closure. With respect to $\mathcal{W}$ free will (constitutive for the modes M_i) and quantum uncertainty give rise to a causal slack [27].
This qualitative change of dynamics could presumably be derived from the "meta-physics" of the unpartitioned $\mathcal{O}$ /$\mathcal{W}$ -system, just as the internal effective dynamics for some subsystem $\mathcal{W}_1$results from the physics of the closed quantum network $\mathcal{W}$; in either case such a derivation is not accessible from the local perspective (see III.C, cf. [53]).
As a consequence this observing/observed partition severely limits the predictive power of any so-called "theory of everything" (TOE) [54, 55].
This holds likewise for $\mathcal{O}$: Despite the impressive progress in brain research (like the impressive advance in physical science), neurophysiological observations cannot suffice to describe $\mathcal{I}$. (There is no evidence that systems, in particular computers, would eventually become conscious, if only made complex "enough". Consciousness might be considered

emergent [56], but neither from $\mathcal{O}$ nor from $\mathcal{W}$ but from the very partition, cf. Sect. II.D.) Eventually, also the dynamics of $\mathcal{O}$ should be dressed.

V. INTERPLAY OF SYSTEM- AND INTERFACE DYNAMICS

The complete description (full state parameter space) of modular quantum networks has been discusssed in Sect. III.A. This space of possibilities is the stage on which the system $\mathcal{W}$ will perform subject to its own repertoire and the influence by the interface: As a result there is a "peaceful coexistence" between physics and human intervention. "Over-determination" [57] would result only, if we believe in physical determinism even for the partitioned world $\mathcal{O}/\mathcal{W}$, just like we do for $\mathcal{W}$ as such. There is no evidence for such a generalization to be tenable, though.

We have already argued in II.B that everyday life is full of events for which a convincing all-physical causal explanation is not available; there is no contradiction with physics, though. The following examples have been studied experimentally and are consistent with our model assumptions. They demonstrate that – contrary to reductionist believe – physics does not suffice to give a satisfactory account for what happens even in elementary experimental scenarios.

A. "Worlds" without an Observer

Being able to design "quasi-isolated" (small) quantum worlds appears to allow the observer to enjoy brief glimpses at "worlds without an observer" – by comparing the actual state change within such a $\mathcal{W}$ from a discrete preparation step to a later discrete observation step with a pertinent closed system quantum theory. (This is an intriguing example for $\mathcal{O}$ specifying $\mathcal{W}$ such that further unwanted influence of the former is suppressed.)

We may thus conclude that present quantum physics is essentially complete, but describes an unpartitioned (non-relativistic) quantum-universe, its Schroedinger dynamics being unitary and without any jumps (i.e. without any "facts", "decisions" imposed by observations, cf. IV.B) – up to the point of observation. Obviously, the question of how such an unobserved quantum world "looks" is meaningless (cf. [58]). As a consequence, to argue that the quantum wave function should represent our knowledge rather than reality is not convincing here: It is the jumps, which are, as part of effective dynamics, related to observation (and information gain), definitely not the quantum states as such.

Eventually, a realization of such quasi-isolated systems on a sufficiently large scale would allow for quantum computing (see [40]). Here the object (being composed of $N >> 1$ subsystems) should – after initialization – indeed be isolated from its environment as perfectly as possible. The exponential increase in efficiency for the so-called factorization algorithm [40] in quantum computers is due to making clever use of those tremendous state space dimensions usually considered inaccessible.

Up to now only small-N toy systems have been realized to demonstrate the working principles. While there are serious doubts as to whether such systems could ever be significantly scaled up for practical use [60], such working examples demonstrate the completeness of quantum mechanics, under the appropriate conditions. These examples support the view that $\mathcal{W}$ would be deterministic, $\mathcal{W}$ interfaced with $\mathcal{O}$ non-deterministic.

B. Thermodynamic Stability

Due to the filters/tools in $\mathcal{I}$ the observer $\mathcal{O}$ has typically access to local parameters only and often to only one (or few) selected subsystems out of many others. Under weak coupling conditions and for the object system small compared to the "rest", quantum thermodynamics [59] becomes locally applicable, even far away from the thermodynamic limit. Here the second law implies that the small object system (whether itself composite or not) will relax to a state with (under given constraints) maximum entropy. This entropy is a measure that can be defined for any state, even for a state corresponding to an individual subsystem (contrary to classical statistics, in which entropy necessarily refers to an ensemble). While the state of the total system continues to travel through its tremendeously large Liouville space, the object will appear to have relaxed to a quasi-stationary state, characterized by very few macroscopic parameters like temperature (instead of the p^q_N parameters as discussed in Sect. III.A). The marginal fluctuations in time will disappear as the embedding gets larger and larger [59]. Even though quantum mechanics remains the appropriate fundamental description, most of its remarkable properties become irrelevant. This emergent behavior is stable (with respect to perturbations). It underlies thermodynamics as control theory.

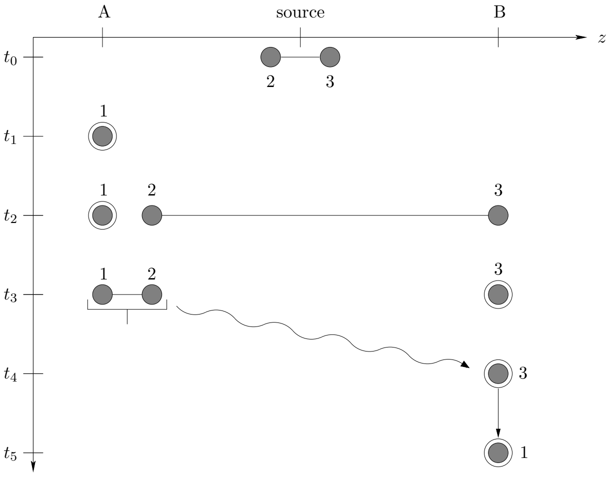
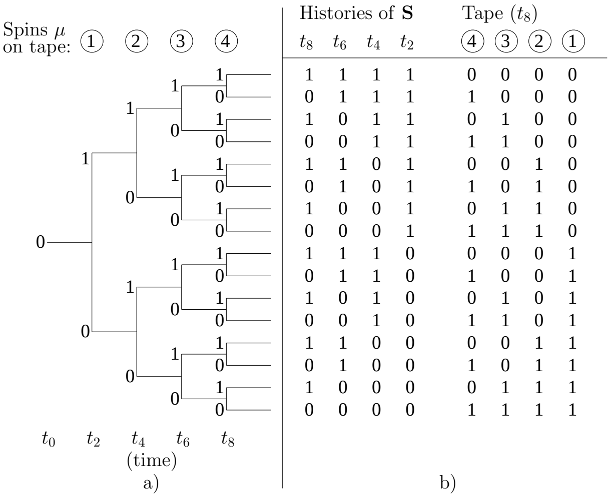


FIG. 4: Quantum Teleportation
A, B fixed positions on z-axis; time-axis running from t_0 to t_5; dots: spins with number 1,2,3; line between dots: entanglement; encircled dot: pure local state; wavy line: classical information transmission from measurement (see Sect. V.C).
At time t_1 spin 1 is locally prepared. Note that at time t_2 spin 2 and 3 are still entangled, despite spatial separation; therefore the two-spin measurement in A at time t_3 also affects spin 3 at the same time. At time t_4 measurement information from A has reached B. Based on this information a local transformation on spin 3 is applied so that after time t_5 the state of spin 3 at B is identical with the state of spin 1 at A and time t_1.

The interaction of a quantum-system with its quantum environment typically implies entanglement: As such interaction does not mean “measurement“ – quite to the contrary, local properties get obscured rather than registered. Nevertheless, interactions are necessary for observation. Complete measurements (possible for small enough object systems) would lead to quantum jumps (see below) into locally pure states. However, in the present situation these would rapidly relax back to the equilibrium state, rendering the information gain due to measurement “useless“. Repeated measurements would merely lead to measurement-induced fluctuations around the stable state.

C. Measurement Protocols [50]

The following example shows that, in the absence of system-dynamics, an interesting sequence of events may occur induced exclusively via interface-dynamics. It may be termed information dynamics insofar as the events are generated and documented as a measurement protocol.
The most elementary quantum system is a spin. Any measurement requires the *selection* of one specific direction with the possible result ±1. This symmetry breaking thus excludes the measurement of *different* directions with the *same* (classical!) apparatus. A composite interface dynamics results, when the observer $\mathcal{O}$ chooses a sequence of interface modes M_i (usually based on a sequence of tools); this dynamics is constrained, but not determined by physics.
A remarkable example is the so-called quantum-teleportation scenario (see Fig. 4). The pertinent object system $\mathcal{W}$ consists of $N = 3$ spins. In this scenario there is no Schroedinger dynamics involved: Formally the Hamiltonian is set to zero. Note that the spatial positioning of the spins is irrelevant here; the real space structure, though, motivates the different partitions and makes the network properties more “striking“.
At time t_0 a spin pair (2,3) is prepared (“measured“) by $\mathcal{O}$ in a specific highly entangled state, one of the 4 so-called Bell states. Spin (1), which is and remains in the spatial region A, is then prepared (“measured“) by the observer in some local quantum state of his choice, time t_1; its full description with respect to a preselected frame involves real parameters (a vector), i.e. potentially “infinite information“. This whole setting is equivalent to a measurement performed on the partition (1)(2,3). There are no correlations between (1) and (2,3).
Then, the spins 2 and 3 are spatially separated so that spin (2) arrives in region A, spin (3) in some distant region B. Excluding non-local actions, the observer can henceforth operate only on pair (1,2) or on spin (3). The original state should thus conveniently be rewritten in terms of the partition (1,2)(3) (second reference frame). But with respect to this representation the original state appears as a superposition of the 4 Bell states for the (1,2)-pair, in which spin (3) contains all the information about the initial state of spin (1). Nothing, though, has “happened“ so far, time t_2; the two representations are equivalent.



Histories of **S**				Tape (t_8)			
t_8	t_6	t_4	t_2	④	③	②	①
1	1	1	1	0	0	0	0
0	1	1	1	1	0	0	0
1	0	1	1	0	1	0	0
0	0	1	1	1	1	0	0
1	1	0	1	0	0	1	0
0	1	0	1	1	0	1	0
1	0	0	1	0	1	1	0
0	0	0	1	1	1	1	0
1	1	1	0	0	0	0	1
0	1	1	0	1	0	0	1
1	0	1	0	0	1	0	1
0	0	1	0	1	1	0	1
1	1	0	0	0	0	1	1
0	1	0	0	1	0	1	1
1	0	0	0	0	1	1	1
0	0	0	0	1	1	1	1

FIG. 5: Quantum Turing Machine (QTM). Spin S is externally driven (rotated) at time $t_{2\mu-1}$ and then moved in real space to interact via a quantum controlled NOT operation with tape spin μ at time $t_{2\mu}, \mu = 1$. This is iterated setting $\mu = 2, 3, 4$.
a. Decision tree for central spin S ("Turing head") after time t_8
b. Possible 4-step-histories for S (left) as related to measurement sequences for the tape spins μ after time t_8 (see Sect. V.D). Before measurement all possible histories are "superimposed" (undecided yet). With each measurement of a tape spin more and more historical facts are "created". Remarkably, the measurement time has nothing to do with the time label for those facts.

In the third step (t_3) the pair in region A is measured in the respective Bell state basis (4 possibles outcomes). As a consequence any correlation between (1,2) and (3) are destroyed, the new "physical" partition and the old one are incompatible.

After time t_4 the (classical) information about the result of the Bell measurement is received in region B. This transfer is assumed to be physically available, even though not explicitly modelled. Then the observer applies, depending on that information, one of 4 prescribed local transformations on spin (3), time t_5. After that spin (3) is in the same state as spin (1) has been before! Apparently the state of spin (1) in region A has (instantaneously) been teleported to spin (3) in B, a remarkable feat, as A and B can be miles apart and their spins could thus not have interacted.

Quantum mechanically this effect is not that suprising at all: The spatially distributed state has been prepared strictly observing speed limitations. Due to the entanglement brought in by the pair (2,3) there is a strong correlation also between (1,2) and (3). The subsequent measurement on (1,2) selects (via quantum jump) one of the 4 possible results – also for (3). By this action information has not been transferred, it can just (locally) be retrieved from where it has been before.

We see that the interface dynamics of this example gives rise to profound non-classical features. However, this non-classicality only becomes accessible to the well-informed observer/designer: Superficially there is just a sequence of measurement "clicks".

D. "Observing the Past"

For our final example one needs to consider both system- and interface-dynamics.

Often measurements are indirect, i.e. rather than measuring the system of interest (the object) $\mathcal{O}$ measures an ancilla system within $\mathcal{W}$, but in such a way that from the respective measurement outcome one can learn something about the object. Obviously this can only work if a correlation has been established between object and ancilla. This correlation may be called the "measurement logic" (cf. Ref. [48]). For spins this logic could be implemented via a so-called quantum-controlled NOT on the ancilla with the object being the control[40]: if afterwards one finds the ancilla in state -1, the object will be in state +1, and vice versa. In the ideal case performing a projective measurement on the ancilla will thus project also the object onto the (here) anti-correlated state.

One can generalize this situation to allow for multiple ancillas $\mu, \mu = 1, 2, ...N$, sequentially arranged on a "tape" : The object system S is then briefly brought in contact with ancilla or tape spin μ at time $t_{2\mu} = 2\mu \cdot \Delta t$ to perform the quantum controlled NOT. The contact time must be long enough to generate the correlation but small compared with Δt. This scenario is reminescent of a (quantum) Turing machine [61] (see Fig.5 for $N = 4$).

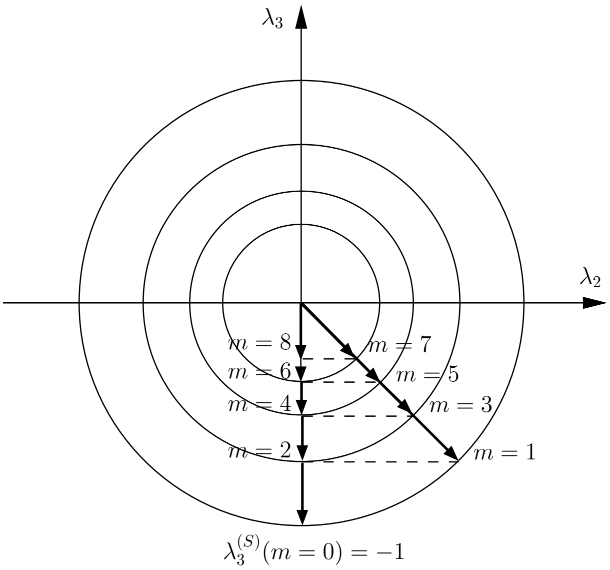


FIG. 6: Time-discrete unitary dynamics (rotation in λ_2/λ_3-plane), of the central spin S within the QTM as of Fig.5, $m = t_m$. $m = 0$: initial state, m = 1,3,5,7: state after rotation, m = 2,4,6,8: state after interaction with tape spin $m/2$.

If the measurement was just repeated, one would always have to get the same result, by definition. However, here we envisage that the object is externally driven in between (at times $t_{2\mu-1}, \mu = 1, 2, 3, 4$), so that its state continues to change: Each ancilla will thus see a different state of the object. A sequence of measurements then constitutes a history, the data being permanently stored in the ancilla states.

But what happens, if all the measurements are delayed? As long as no measurement of the ancillas (which remain isolated after preparation) has occurred yet, the object S thereafter continues to evolve, but within a subspace of mixed states (mixed because of the entanglement with the ancillas, see Fig.6). The mixing is reminescent of the emergent thermodynamic behavior (Sect. V.B). But here, with the environment (ancillas) taken to be still under control, the corrlations and thus the mixing could be undone, in principle.

Two types of measurements are possible now: A direct measurement of the object spin, which would produce a new "fact" at the time of the experiment, but destroy all the correlations with the ancillas. Alternatively, a delayed measurement of the ancillas, which could exploit the built-in logic representable as a decision tree of *possible* histories. Measuring after t_8 all the 4 ancillas (in any time order!) will project the object spin onto a concrete and consistent history, step, by step, as if the object spin had been measured immediately at the 4 respective times $t_{2\mu}$ [61]. After measurement the correlations with the object spin are completely lost [62], the object spin is in a pure state again.

This reconstruction of the history only works because a substantial part of the system has been designed as a potential memory *and this is known to the observer/controller*: Only then can he interpret the ancilla states *as information*, which encodes the past object states in local ancilla states. (The system itself "does not know", there is no physical correlation left after measurment.) Design and information are intimately connected with interface actions and cannot be reduced to physics.

How and to what extent can we talk about a history, when there has – supposedly – been no observer? The above example gives a possible answer. Observation *now* can generate facts even in the distant past. And it is undecidable now as to whether these facts had already existed then or not.

VI. SUMMARY

One of us (G. E.) has given a detailed analysis of the characteristics of science [27] in terms of cause and effect in the context of hierarchical structures (bottom-up and top-down causation). There it has been argued that physics cannot be the only form of causation, the origin of causal slack being associated with quantum fluctuations and human mind (free will). Here we further develop these ideas by focusing on the process of scientific exploration.

Incompleteness has been taken to underly any theoretical scheme about the world: There is no unconditioned "truth", neither in science nor elsewhere. Here we have based our analysis on three interrelated lines of argument,

starting and ending with Plato's cave: First we have detailed the structural model for the $\mathcal{O}-\mathcal{W}$-partition: Implicitly, the interface $\mathcal{I}$ has been taken to be both the precondition for and the carrier of mental processes – with judgements as the main building blocks for scientific exploration. We have then introduced the quantum analogy (by which a structurally similar but entirely physical case can be studied in full detail). Finally, accepting in principle limitations (as derived from the quantum analog), this analysis supports a formal picture for the development of science as a process, which is, at least, consistent with experience. To sum up:
(1) Our point of departure has been the fundamental incompleteness of *any* theoretical scheme for the description of the world $\mathcal{W}$. We need a frame of reference.
(2) This severe limitation has been counterbalanced by the conviction that empirical science, as "practically" confirmed by technology, does exist.
(3) The "workings" of empirical science has then been taken as a motivation to introduce an interface model $\mathcal{I}$ for its underpinning.
(4) While not unique, such a model – here formulated in terms of modes M_i – is not reducible to physics. $\mathcal{I}$ is meant to organize the partition between the observing $\mathcal{O}$ and the observed $\mathcal{W}$, defining, *inter alia*, frames of reference.
(5) The correlations between $\mathcal{O}$ and $\mathcal{W}$ imply a "local" dressing (reminescent of those between parts within $\mathcal{W}$). Quantum jumps are considered as an example for such a dressing of $\mathcal{W}$.
(6) Quantum physics appears to be complete for systems $\mathcal{W}$ in isolation. This could still be challenged, but doubts will diminish, we believe, as quantum technology further improves.
(7) The $\mathcal{O}/\mathcal{W}$-partition does not allow for causal closure within $\mathcal{W}$, in particular not within physics. As a consequence there is a peaceful coexistence between system- and interface-dynamics (without over-determination). There is no conflict between $\mathcal{W}$ being deterministic, $\mathcal{W}$ interfaced with $\mathcal{O}$ being non-deterministic.
(8) The world $\mathcal{W}$ is not merely fine-tuned such that we can exist (anthropic principle[63]); rather, the world *as it appears to us*, is a *result* of the interface and thus of us being observing.
(9) The implications of our model seem to be consistent with empirical findings. The interplay of system- and interface-dynamics has been discussed in some detail.

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[63] Barrow J. D. and Tipler, F. J. The Anthropic Cosmological Principle. Oxford Univ. Press, 1986