Non-commutative Structures from Quantum Physics to Consciousness Studies

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Abstract It has been an old idea by Niels Bohr, one of the architects of quantum physics, that central features of quantum theory, such as complementarity, are also of pivotal significance beyond the domain of physics. But Bohr—and others, such as Wolfgang Pauli—never elaborated this idea in concrete detail, and for a long time no one else did so either. This situation has changed: there are now a number of research programs applying key notions of quantum theory in areas of knowledge outside physics. In his typical way, both insurgent and conservative, Hans Primas has critically supported and crucially contributed to these developments. There are two major extraphysical directions in which non-commuting operations, the basis of complementarity, have been applied in the past 20 years. One of them refers to fertile new insights in psychology and cognitive science, due to which non-commutativity is a core feature of various kinds of decision-making processes. Meanwhile, there is a number of research groups worldwide who study these and other cognitive processes using quantum concepts. The other direction is closely related to a topic that interested Primas since his student days: the philosophical conjecture, developed by Pauli and C.G. Jung, that the mental and the physical are complementary aspects of one underlying reality that itself is psychophysically neutral. In his most recent work, Primas exploited this framework to explore the relation between mental and physical time.

1 Introduction

Hans Primas was already in his early 60s when I came into closer contact with him, at the Cortona Week in 1991 that was later turned into an integral part of the curriculum of the Swiss Federal Institute of Technology (ETH) at Zurich. The topic of the week was “Metamorphoses”, Primas was one of the keynote speakers, and I attended the conference as a postdoc at the Max-Planck Institute for Extraterrestrial Physics at Garching.

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H. Atmanspacher and U. Müller-Herold (eds.), *From Chemistry to Consciousness*, DOI 10.1007/978-3-319-43573-2_8

At the time, I was working on a publication about Wolfgang Pauli and alchemy, a theme that fascinated me after I had learned that the series of dreams Jung reports in his *Psychology and Alchemy* actually was from Pauli's dream diary. Since I knew that Primas was interested in the exchange between Pauli and Jung, I had sent him a preprint of the first part of my work some time before the Cortona meeting, but hadn't heard anything back from him. When we spotted each other in front of the lecture hall, we immediately started discussing—as if this wasn't the first time we met. For me, a young scientist, it was especially impressive how a scholar with his accomplishments and worldwide reputation had acquired the inner freedom to attend to themes that many other scientists would readily dismiss as abstruse (or worse).

Over the days, our conversation expanded from the Pauli-Jung dialog in particular to more general questions, all related to the age-old topic of the relationship between the mental and the physical.[1] I will get back to this in Sect. 4, which addresses the philosophical framework for mind-matter relations, a chapter in speculative metaphysics, that we could later reconstruct from more or less scattered remarks in articles by Pauli and Jung as well as from their correspondence.

Yet the conversations with Primas at Cortona had an additional side which I could not possibly have anticipated. In the late 1980s, he had started to work on how various interpretations of quantum physics might be intelligible within the formal framework of algebraic quantum theory. This became a topic of discussion almost the first day of the conference—actually I should say the first night, when I found myself embroiled in his explanations of C*-and W*-algebras, GNS-constructions, KMS-states and so on at the bar of the Cortona hotel. Obviously, my ignorance sparked his teaching instincts, and so we spent almost every night with a high-density crash course on algebraic quantum theory and the way it helps understanding a number of conceptual riddles of quantum physics—spiced with one or another drink from the bar.

For me this was a revelation. Many of the issues that are hardly mentioned and even less explained in the regular quantum mechanics courses became transparent and fell into place. A subject that I had learned to accept as both formally demanding and conceptually counterintuitive was transformed into a coherent framework of old puzzles appearing in new and consistent connections. Needless to say, my acquaintance with the algebraic approach, as rewarding as I experienced it at first sight, required much more work in detail to become a solid basis for thinking—not to mention truly original work in the field, for which I am not knowledgable enough until today.

At a moderate level, though, the algebraic approach became familiar to me to an extent that made it possible for Primas and myself to discuss and, later, publish our ideas together with their implications for the philosophy of physics. A basic result of this work was the insight that many of the alleged mysteries of quantum theory originated in two basic classes of category mistakes: one of them arising from classically misguided discussions of quantum phenomena, the other from the

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[1] Needless to say, this became the focus of Primas' interests way after his early work on physical and theoretical chemistry, which is addressed in the chapters by Ernst, Bodenhausen, and Müller-Herold in this volume.

confusion of ontic and epistemic descriptions of quantum systems. This second point will be addressed in Sect. 2.

Eventually, there was one more significant step that I became infected with through our interactions: the mathematical tools that algebraic quantum theory uses are not necessarily restricted to physics. The non-commutativity of operations is at the heart of these tools, and Primas has been a source of inspiration and encouragement to try and apply them to areas beyond the limits of physics. This novel field of research, much of which concerns topics of psychology and cognitive science, has spread out to numerous places across the globe by now, with considerable initial success and with a lot of momentum to expand, as will be discussed in Sect. 3.

Hans Primas in his office at floor G in the ETH chemistry building at Universitätsstrasse Zurich in the mid 1990s: “I am not Boolean.”

As Primas showed in his *opus magnum* of 1981, non-commutative operations in physics are isomorphic to non-Boolean lattices of propositions (about such operations) in logic. In a nutshell, this logic entails that binary yes-no alternatives are too limited to understand our minds and the world around us. Non-Boolean logic rejects the law of the excluded middle, the *tertium non datur*. It expresses the fact that we need more for truth judgments than the categories of right and wrong, and that the context of a statement is often decisive for its significance. In discussion with Primas one could occasionally experience that what he said one day seemed to contradict what he said another day. Upon requests for clarification, it happened more than once that he mastered this challenge with the sibylline remark: “I am not Boolean”.

2 Ontic and Epistemic Descriptions

2.1 Kinds of Realism

Most working scientists believe that there is an external world, which has the status of a reality to be explored by science. The goal of science is to achieve knowledge about how this external world is constituted and develops. Although scientific methodology requires observations and measurements for this purpose, the reality to be described is believed to "exist" independent of its possible empirical accessibility. This view is succinctly formulated by Einstein (1949a, p. 81):

> Physics is an attempt conceptually to grasp reality as it is thought independently of its being observed.

On the other hand, there is a different stance to the effect that quantum theory does not admit such an observation-independent realism. This view, which has been perpetuated in many modern monographs and textbooks, goes back to Bohr's claim that in quantum theory a realism with respect to measuring instruments is the only possible realism (sometimes even referred to as "anti-realism"). According to Bohr (quoted in Petersen 1963),

> it is wrong to think that the task of physics is to find out how nature is. Physics concerns what we can say about nature.

The two quotations by Einstein and Bohr indicate a basic point of disagreement between the two in their ongoing conversations concerning the interpretation of quantum mechanics in the 1920s and 1930s (compare Bohr 1949 and Einstein 1949b). Bohr focused on what we could know about and infer from observed quantum phenomena. By contrast, Einstein's position led him to consider Bohr's characterization of quantum theory as incomplete.

Now it would be premature to infer from Einstein's realist position that observations of features of the assumed observer-independent reality exhibit that reality as an exact image, by a one-to-one mapping as it were. And it would be equally premature to think that Bohr denied that there is a world out there. His stance only insists that all we can know about it is restricted to be relative to observations and the way we talk about them. So the contrast between the two positions may ultimately be less sharp than the two quotes might indicate.

Many discussions about realism in science nevertheless took the positions by Bohr and Einstein as a blueprint for the belief that arguing in favor of one of them implies logically to argue against he other. Primas realized early on that this strictly Boolean move might be mistaken. In order to introduce a more advanced position, the first thing he did was to look for a way in which the differences between them can be formalized explicitly and in detail. In the late 1980s, he discovered that algebraic quantum theory offers exactly such an option, which can be combined with the philosophical distinction of ontic and epistemic descriptions as introduced by Scheibe (1964, 1973).

2.2 Ontic and Epistemic States and Observables

In a series of papers starting in 1990, Primas picked up this philosophically grounded distinction and connected ontic and epistemic perspectives to particular elements of the algebraic approach to quantum theory. Some relevant articles are Primas (1990, 1991, 1993), Amann and Primas (1997), Amann and Atmanspacher (1999), Atmanspacher and Primas (2003).[2] It should be noted that these papers are essentially restricted to a Galilei-invariant version of quantum theory, leaving aside its extension toward relativistic frameworks.

Ontic states encode all properties of a system exhaustively: An ontic state is "just the way it is", without reference to epistemic knowledge or ignorance (due to observation or measurement). Ontic states are the referents of descriptions of *individual systems*, represented pointwise in an appropriate state space. The properties of the system are treated as *intrinsic properties*, as context-free as possible. Insofar as ontic states are observation-independent, the associated intrinsic properties are *empirically inaccessible*. They are *idealizations*, which is expressed by the fact that they refer to closed systems with a unitary (reversible) dynamics.

Epistemic states encode our (usually non-exhaustive) knowledge of the properties of a system, based on a discrete partition of the relevant state space. The referents of *statistical descriptions* are epistemic states (ensembles with probability distributions). The properties of the system are treated as *contextual properties*, i.e. they are defined with respect to a particular context to be chosen. Contextual properties associated with epistemic states are *empirically accessible* by observation and measurement. They refer to the realistic situation of open systems, which are governed by a semigroup (irreversible) dynamics.

The proposal that Primas made was essentially a mapping of intrinsic properties to elements of a C*-algebra $\mathcal{A}$ of observables, whereas contextual properties are mapped onto elements of a W*-algebra $\mathcal{M}$ of observables. The dual $\mathcal{A}^*$ of $\mathcal{A}$ is then the space of ontic states, whereas the predual $\mathcal{M}_*$ of $\mathcal{M}$ is the space of epistemic states.[3] A particular feature of quantum systems is that they posses observables that do not commute (see also Sect. 3.1). If a system has only non-commuting observables, it is called a *factor*. If a system has both commuting and non-commuting observables, the commuting observables (also referred to as classical observables) are elements of the so-called *center* of the algebra.

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[2] For a while, Primas explored a different terminology, calling ontic descriptions "endo-descriptions" and epistemic descriptions "exo-descriptions" (Primas 1994a). In this terminology "endo" was meant to indicate a perspective "from within", without external tools of observation, and "exo" was meant to indicate that a system is addressed "from outside", as coupled to an environment, including observational tools. The endo-exo distinction did not prevail, however, and he returned to the ontic-epistemic terminology later on.

[3] Note that W*-algebras are also called von Neumann algebras. The term C*-algebra replaces the old notion of a B*-algebra, which is not used any more today. See pertinent textbooks for further details, which exceed the scope of this article.

2.3 Measurement

Given that a major conceptual difference between ontic and epistemic states is the issue of empirical access, a crucial feature of the relation between ontic and epistemic states is the transition from unobserved to observed states. In the literature on quantum theory, this transition is addressed by the notion of measurement, and the problem of how to describe it properly. In Primas' terms, this can be rephrased by the question of how contextual properties can be constructed from intrinsic properties. In more formal terms, the concept of measurement is tightly connected to the way in which a (representation-free) C*-algebra is connected to its representation by a W*-algebra (for instance a Hilbert space representation).

The algebraic framework offers such a representation, known as the GNS-representation, according to Gel'fand, Neimark, and Segal. Skipping the formal details, choosing a context and implementing it in $\mathcal{A}^*$, the space of ontic states, generates a contextual topology (coarser than that of $\mathcal{A}^*$) with equivalence classes of states. The properties associated with those equivalence classes are the contextual properties determined by the deliberately chosen context. This context is usually not prescribed at the C*-level of $\mathcal{A}$. In contrast to the Stone-von Neumann theorem, stating that all representations of a *finite* C*-system are unitarily equivalent, the general situation of *infinitely many* degrees of freedom leads to W*-representations that are inequivalent.

Primas often insisted that a number of popular approaches to the measurement problem are ill-defined, non-viable, or even absurd. Key requirements that he saw for a reasonable account are that a measurement process takes time (i.e., is not instantaneous) and must be considered a real process (i.e., not merely a projection onto subspaces of a Hilbert space). Moreover, acts of measurement must produce disjoint states (compare the contribution by Giulini in this volume), and the measurement outcome must be described as a classical, irreversible fact (that cannot be undone).

In this spirit he advocated, most expressively in Primas (1997), an approach based on a dynamical spin chain model originally suggested by Hepp (1972) and refined by Lockhart and Misra (1986). In this approach, classicality emerges gradually as a function of time, which is formally achieved by representing measurement as a K-flow of a W*-system within a statistical, epistemic description.[4]

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[4] Note that such a description disregards the conceptual point that the unmeasured state of a system, which is transformed into a measured state through measurement, actually should be considered ontic and individual. As a reaction to this deficit, Primas (1997) wrote a manuscript on an individual description of measurement processes, which he left unpublished. A review of dynamical models of measurement, including their own proposal, was recently published by Allahverdyan et al. (2013).

2.4 *Contextual Emergence and Relative Onticity*

Primas (1994b, 1998) realized that any selected descriptive level may contain both ontic and epistemic states. This entails that a tight distinction of one fundamentally ontic and derived epistemic domains is too simplistic. However, an idea originally proposed by Quine (1969) and later utilized by Atmanspacher and Kronz (1999) comes to help here: *ontological relativity* or, in another parlance, *relative onticity*.[5]

The main motif behind this notion is to allow ontic significance for any level, from elementary particles to icecubes, bricks, and tables. One and the same descriptive framework can be construed as either ontic or epistemic, depending on which other framework it is related to. Bricks and tables will be regarded as ontic by an architect, but they will be considered highly epistemic from the perspective of a solid-state physicist. Drinks and icecubes will be regarded as ontic by a barkeeper, but they will be considered highly epistemic from the viewpoint of thermodynamics.

Quine proposed that a "most appropriate" ontology should be preferred for the interpretation of a theory, thus demanding "ontological commitment". This leaves us with the challenge of how "most appropriate" should be defined, and how corresponding descriptive frameworks are to be identified. Here is where the notion of *relevance* acquires significance. A "most appropriate" framework provides those features that are relevant for the question to be studied (cf. Atmanspacher et al. 2014). And the referents of this descriptive framework are those which Quine wants us to be ontologically committed to.

Taken seriously, this framework of thinking entails a farewell to the centuries-old conviction of an absolute fundamental ontology (usually taken as that of basic physics), to which everything else can be reduced. The corresponding move toward a *contextual emergence* (Bishop and Atmanspacher 2006) of contextual observables[6] is in strong opposition to many traditional positions in the philosophy of science until today. But in times in which fundamentalism—in science and elsewhere—appears increasingly tenuous, Quine's philosophical idea of an ontological relativity offers a viable alternative for more adequate and more balanced world views.

Coupled with an ontological commitment to context-dependent "most relevant" features in a given situation, the relativization of onticity does not mean dropping ontology altogether in favor of a postmodern salmagundi of floating beliefs. The "tyranny of relativism" (as some have called it) can be avoided by distinguishing more appropriate descriptions from less appropriate ones. The resulting picture is more subtle and more flexible than an overly bold reductive fundamentalism, and

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[5] Similar ideas have been developed independently by van Fraassen (1980) in terms of "relevance relations", by Garfinkel (1981) in terms of "explanatory relativity", by Putnam (1981) in terms of "internal realism", and by Shimony (1993) with this "phenomenological principle". All these approaches exhibit similarities, but also differences, for instance with less, or less explicit, emphasis on issues of ontology.

[6] For further elaborations of reductive and emergence-based approaches in the philosophy of science see also the contributions by Seager and by Bishop and beim Graben in this volume.

it is more restrictive and more specific than a patchwork of arbitrarily connected opinions. Both these extremes have been frankly and frequently repudiated by Hans Primas.

3 Non-commuting Operations

3.1 Non-commutativity Within and Outside Physics

As mentioned above, a key feature of observables, e.g., A, B, in quantum theory is their *non-commutativity*, less technically referred to as *incompatibility* or *complementarity*, respectively. Its meaning is that their successive operation on objects such as a state ψ of a system does not commute:

$$AB\psi \neq BA\psi.$$

An elementary example in quantum physics are spin observables with a discrete spectrum, two of which are represented by the matrices:

$$A = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}, \quad B = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}.$$

The difference of their products AB and BA,

$$AB - BA = \begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix} - \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix} = \begin{pmatrix} 0 & -2 \\ 2 & 0 \end{pmatrix},$$

does not vanish, which would be the case if the operations were commutative.

As a side remark, non-commutative algebras have an equivalent in formal logic, which leads us back to non-Boolean propositions. If an algebra contains both commuting and non-commuting elements, the corresponding logic is a partial Boolean logic. It consists of Boolean subdomains of propositions, pasted together in a globally non-Boolean fashion. As Primas (2007) argued, partial Boolean logic may still be applicable in cases where we have no clue about how to formally set up an appropriate algebra of observables.

One of the most basic operations on the state of a system is *measurement*, generally conceived as an interaction of a measuring (observing) system O with a measured (observed) system S in state ψ, where the measurement outcome typically is the numerical value of an observable. In systems with commuting observables, a measurement by O does not have a significant effect on S. However, in systems where observables do not commute, this effect is no longer negligible. In other words, while measurement in the commutative case simply means the registration of a value of an observable, the non-commutative case means registration of a value *plus* a change of the state ψ of O. This state change is the reason why the sequence of measurement operations does make a difference.

For a long time the mathematics of non-commutative algebras has mainly, if not exclusively, been successfully used in quantum physics, the physics of systems with non-commuting observables. However, there have always been voices advocating the usage of the formalism for areas outside physics as well, starting with Niels Bohr and Wolfgang Pauli. Hans Primas belongs to the group up of those who share this vision. In one of his latest publications (Primas 2009), he states his persistent conviction that non-commutative operations and non-Boolean logic apply "far beyond quantum physics and include examples from psychology, philosophy, and engineering."

In fact, psychology and cognitive science recently saw a number of particularly convincing applications of quantum reasoning in the last two decades. This confirms the plausible assumption that non-commutative operations should be the rule rather than the exception in all kinds of mental processes. Isn't it evident that *any* observation of a mental state of a subject *always* changes that state? Here is an incomplete list of areas of research in which this basic principle has been applied (with pertinent references)[7]:

- decision and judgment processes and related paradoxes (Aerts and Aerts 1995; Pothos and Busemeyer 2009; Aerts et al. 2011);
- pattern learning and recognition on networks (Atmanspacher and Filk 2006);
- sequence effects in surveys or questionnaires (Atmanspacher and Römer 2012; Wang et al. 2014);
- bistable perception and temporal nonlocality (Atmanspacher et al. 2004, 2008; Atmanspacher and Filk 2010, 2013);
- non-separable concept combinations and semantic association (Gabora and Aerts 2002; Bruza et al. 2015).

In addition, there are other—more general—applications, neither limited to physics nor to psychology, which are worth mentioning:

- non-commutative time operators in ergodic theory and for innovation systems (Gustafson and Misra 1976; Prigogine 1980; Antoniou et al. 2016);
- non-commutative observables due to non-generating partitions in dynamical systems theory (beim Graben and Atmanspacher 2006);
- compatible and incompatible descriptions in science (Primas 1977; Prigogine 1980; Atmanspacher and beim Graben 2016)
- entanglement correlations beyond the quantum bound (Popescu and Rohrlich 1994; Dzhafarov and Kujala 2013).

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[7] Some more commentary on the listed items can be found in Sect. 4.7 in Atmanspacher (2015). See also the monographs by Busemeyer and Bruza (2013) or by Wendt (2015).

3.2 Bistable Perception

One remarkably successful example is the application of non-commutative structures to the bistable perception of ambiguous stimuli, exhibiting stochastically distributed, spontaneous reversals between two possible perspectives (see Fig. 1). This example is particularly compelling because it is from psychophysics, the "most quantitative" branch of psychology, which studies the relationship between physical (external) stimuli and the perceptions they induce.

There is quite some literature trying to model features of bistable perception, which limited space does not allow me to review here. One common point in all approaches so far has been that they generically use classical modeling strategies, such as Markov models or similar. By contrast, we developed a theoretical approach which essentially decomposes the perceptual process into two kinds of dynamics that—in the spirit of quantum theory—do not commute: a reversal process A and an observation process B, which can be plausibly represented by the matrices:

$$A = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}, \quad B = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}.$$

As we saw in Sect. 3.1, where A and B were introduced as spin matrices, they do not commute.

The perceptual process as a whole can then be modeled analogous to the quantum Zeno model (Misra and Sudarshan 1977), where successive observations (separated by ΔT) decelerate the reversal period from t_o in the "unobserved" case to an average period $\langle T \rangle$ in the observed case. In this way, an intrinsically unstable two-state system gets stabilized by its observation, so that the average reversal time $\langle T \rangle$ increases if the observation interval ΔT decreases. In the limit of continuous observation ($\Delta T \rightarrow 0$), the system becomes "frozen" in one of its possible states. Skipping the

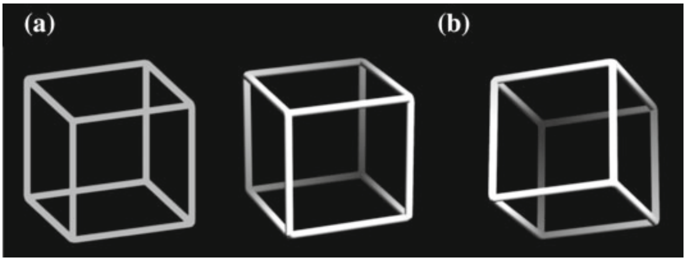

Fig. 1 **a** The Necker cube, a two-dimensional projection of a three-dimensional cube structure, as an ambiguous visual stimulus. **b** Modified cubes with depth cues removing the ambiguity of the Necker cube, so that two different, non-ambiguous stimuli are perceived

formal derivation (see Atmanspacher et al. 2004, 2008 for details), the analysis of this scenario results in the time-scale relation

$$\langle T \rangle \approx t_o^2/\Delta T$$

between three time scales at three different orders of magnitude, which were never before studied relative to one another. These time scales are $\langle T \rangle \approx 3\,\mathrm{s}$, $t_o \approx 300\,\mathrm{ms}$, and $\Delta T \approx 30\,\mathrm{ms}$, so that the time-scale relation is satisfied.

By the time this work was done, I visited Primas at his home at Goldbach and told him about the progress we had made with this model. He listened patiently, but his response was laconic:

HP: You are not finished yet.
HA: Yes I am.
HP: How do you know all this is correct?
HA: It's been derived—why should the math fool us?
HP: But you must put it to test—experimentally!

The message was clear: although theoretical insights may provide first important steps toward progress in science, they need to be related to experiment to be ultimately convincing. This may not be obvious for a theoretician, but for someone like Primas, with his extraordinary formal *and* experimental skills, it was evident.

So, that's what we did—actually we were lucky that Jürgen Kornmeier's lab at Freiburg University had all the tools at hand that were needed to test the time-scale relation above. The trick we managed to work out was to control the time scale t_o as an independent variable by presenting the Necker cube with varying off-time intervals t_{off}. Then we could measure $\langle T \rangle$ as a function of t_{off} and determine ΔT from the empirical results obtained. This collaboration yielded several highly non-trivial pieces of confirmation for the time-scale relation that are shown in Fig. 2 and explained in its caption.

There is yet another important aspect of the described model that I should at least indicate, in view of Sect. 4.2 below. This aspect has to do with a temporal equivalent of entanglement correlations that may occur if system observables of temporal significance do not commute. Since this is the case for the two types of dynamics represented by A and B, we suspected that the correlations between states at different times may violate a temporal Bell inequality first proposed by Leggett and Garg (1985).

Assuming that the perceptual system is always *uniquely* either in one or the other state, we adapted the Leggett-Garg inequality to the scenario of bistable perception and showed that it is indeed violated for particular model parameters (Atmanspacher and Filk 2010, 2013). As a consequence, it must be conjectured that the uniqueness assumption does not match the situation properly. A possible way out would be that states may be extended over time rather than being assigned to time instants with vanishing duration, resembling the idea of an extended nowness.

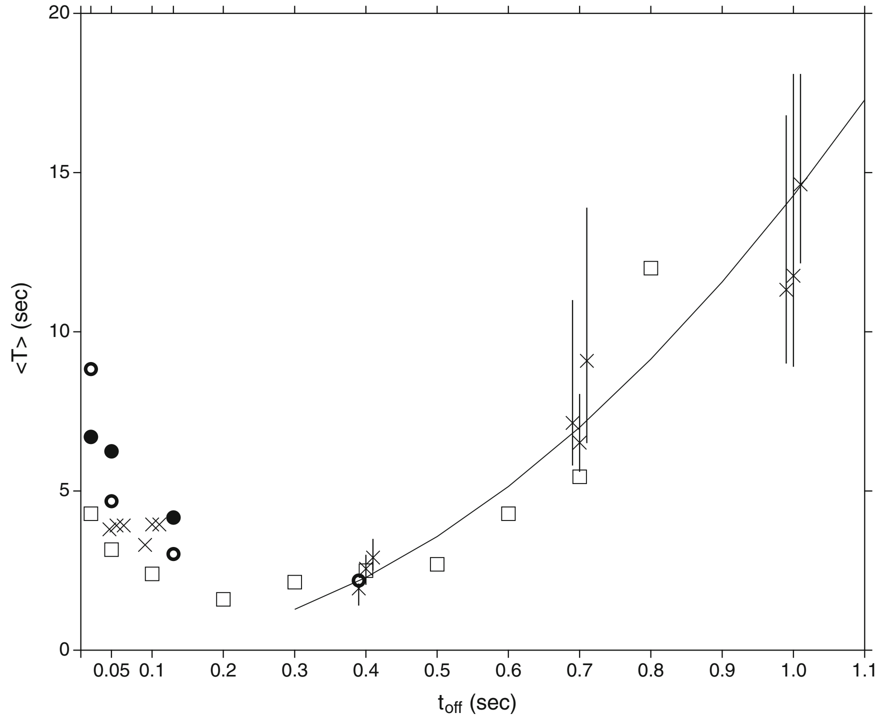

Fig. 2 Average reversal times $\langle T \rangle$ for the bistable perception of a discontinuously presented Necker cube. Two ranges of different behavior of $\langle T \rangle$ as a function of t_{off} are to be distinguished: **a** $t_{\text{off}} > t_0 = 300\,\text{ms}$, where t_{off} replaces t_o; **b** $t_{\text{off}} < t_0 = 300\,\text{ms}$, where $t_o = 300\,\text{ms}$ remains the relevant time scale. **a** Crosses mark results from Kornmeier and Bach (2004); for each off-time, $\langle T \rangle$ (including standard errors) is plotted for three on-times of 0.05 s, 0.1 s, and 0.4 s. Squares mark results without errors indicated from Orbach et al. (1966) for an on-time of 0.3 s. The *solid line* shows the best polynomial fit of $\langle T \rangle$ as a function of off-times t_{off}, which is quadratic as predicted and yields $\Delta T \approx 70\,\text{ms}$. **b** Empty circles are reversal times due to Kornmeier et al. (2007), crosses are results from Kornmeier and Bach (2004), and squares refer to Orbach et al. (1966). Full circles are due to simulations for assumed parameters $\Delta T = 30\,\text{ms}$ and $t_0 = 300\,\text{ms}$ as in Atmanspacher et al. (2008)

However, a violation of a temporal Bell inequality is difficult to realize experimentally (and, in fact, hasn't been realized so far): any measurement at one time potentially induces local correlations with any later measurement. Therefore a violation remains inconclusive if such "invasive" measurements cannot be excluded—or correlations due to invasivity cannot be distinguished from genuine entanglement correlations (cf. Dzhafarov and Kujala 2013).

4 Dual-Aspect Monism

4.1 The Pauli–Jung Conjecture

One of the long-standing interests of Hans Primas[8] was the interaction between the physicist Wolfgang Pauli and the psychologist Carl Gustav Jung between 1932 and 1958. When Pauli's correspondence with Jung and many others was published in eight successive volumes between 1979 and 2005, Primas apparently read everything that touched the *psychophysical problem*, the term that Pauli and Jung used for the problem of the relationship between the mental and the material (Fig. 3).

As this was my first point of contact with Primas back in 1991, it is not surprising that the Pauli-Jung dialog, as we called it early on, seriously occupied both of us and gave rise to conferences and workshops that we jointly organized. Over the years, we were able to reconstruct a consistent picture of their ideas, which they never published in a coherent framework, and discovered that it matches the broad class of dual-aspect monist approaches to the psychophysical problem (Atmanspacher et al. 1995; Atmanspacher and Primas 1996, 2006, 2009).

The gist of dual-aspect monism is the idea to combine an epistemic dualism of the mental and the material with an ontic monism of an underlying, psychophysically

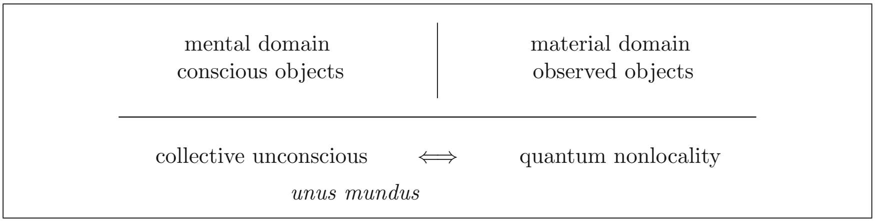

Fig. 3 In dual-aspect monism according to Pauli and Jung, the mental and the material are manifestations of an underlying, psychophysically neutral, holistic reality, called *unus mundus*, whose symmetry must be broken to yield dual, complementary aspects. From the mental the neutral reality is approached via Jung's collective unconscious, from the material it is approached via quantum nonlocality

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[8] In his meticulous biographical notes Primas indicates, almost indiscernably hidden among references to oodles of books on science and engineering, an awakening interest for consciousness and the unconscious in November 1944, as a 16-year-old. A year later he became fascinated with Jung's *Psychology and Alchemie* in 1945 (translation by HA): "The impact of this book—which I read only partially and diagonally at the time—was peculiar and lasting… It was striking that Jung's thoughts, somewhat odd relative to my materialistically shaped mindset, convinced me immediately, as if I had long foreboded them." In the following years Primas continued his studies of Jung's works until he began visiting lectures at ETH in 1949.

neutral domain. This general idea has variants though. Five specific features of the conjecture proposed by Pauli and Jung are the following[9]:

- Applying the ontic-epistemic distinction to the Pauli-Jung framework of thinking reflects that the mental and the material are basically regarded as modes of knowledge acquisition about something ontic which is itself not epistemically—i.e. empirically—accessible (compare Sect. 2.2). This is particularly relevant for Jung's notion of archetypal patterns: while archetypes themselves are conceived as structural ordering principles within the psychophysically neutral ontic domain, archetypal patterns and images appear as their mental manifestations, subject to concrete experience.
- At the fundament of the ontic level, reality is undivided, distinction-free (cf. the notion of the "unidived universe" by Bohm and Hiley; see Hiley in this volume). This illustrates why, in the limit of such an *unus mundus*, epistemic access to the ontic is impossible: if there are no distinctions, there are no categories to be distinguished. The move from the *unus mundus* via Jung's collective unconscious to refined mental categories, or via a nonlocal physical reality to physical objects, is *decompositional*. This is different from Russell's neutral monism or Chalmers' naturalistic dualism, where mental and material objects arise due to *compositions* of psychophysically neutral elements.
- The absolute impossibility of epistemic access (a neo-Kantian feature in late Jungian thinking) strictly applies to the undivided *unus mundus* only, not to all unconscious contents in general. Every distinction that is made, even within the unconscious, creates the option of forming categories (e.g. different archetypes), which may be accessed if there are ways to experience them. In this sense, each such level would be ontic relative to more differentiated levels, and epistemic relative to less differentiated ones. The ontic-epistemic distinction becomes relativized (see Sect. 2.4).
- In this spirit, the transition from unconscious activity to fully developed conscious categories is thought of gradually, by the successive creation of distinguishable features, which Pauli (1954) speculated to be analogous to physical measurement (see Sect. 2.3). The process by which unconscious contexts are transformed into consciousness is *active* insofar as it includes a reaction back onto the unconscious,[10] just as measurement in physics changes the measured physical state. This idea is decisive for the application of non-commutative structures to psychology and cognitive science, outlined in Sect. 3.
- The dual aspects in the Pauli-Jung conjecture are understood as *complementary* (see Sect. 3.1). This means that the corresponding epistemic perspectives of the mental and the material exclude one another in the sense of a logical exclusive or

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[9] The notion of the "Pauli-Jung conjecture" emerged in the early 2010s, when it became clear that dual-aspect monism à la Pauli and Jung entails a number of ramifications that have empirically testable consequences (see Atmanspacher and Fach 2013).

[10] Otherwise, the whole purpose of psychotherapy or -analysis as a method to change unconscious roots of conscious symptoms would be pointless. The active backreaction also casts the popular notion of consciousness as a mere filter into doubt.

("either–or"). At the level of the psychophysically neutral, the logical negation of the exclusive or applies ("neither–nor"), because this level does not contain the distinction between the mental and the material. This must not be confused with the logical inclusive or ("both–and").

In a broader picture, Pauli's and Jung's ideas were outstanding in yet another sense: in an intellectual climate of a clear move toward the rejection of ontology and metaphysics in the 20th century, they postulated exactly the opposite: that metaphysical assumptions are mandatory and even useful if one wants to address questions of basic relevance.[11] After the logical empiricism of the Vienna circle, after Bohr's epistemic standpoint in quantum physics, and after the linguistic turn initiated by Wittgenstein, Pauli und Jung suggested that we need a completely new idea of reality, which exceeds our theories about nature in particular and language in general. Jung's emphasis on the "reality of the symbol", very much welcomed by Pauli, may be an important issue in this respect that should be explored further.

4.2 Mental and Physical Time

As much as Hans Primas was interested in dual-aspect monism as an approach toward the psychophysical problem, he was well aware that speculative metaphysical ideas alone will not have the power of transforming a world view. Therefore, he spent much time in his last two decades to explore novel avenues along which one might hope for more concrete insights. His strategic move was to acuminate the psychophysical problem as a whole down to a facet of it that may be restrictive enough to give us hints for where scientific progress toward a better understanding might be possible.

The fact that he identified is itself one of the great problems throughout the history of ideas: the problem of how mental and physical aspects of time are related to one another. In two publications, Primas (2003, 2009) sketched a way in which *temporal entanglement* might be a key to unlock several riddles behind mental and physical time. There is a lot of philosophical literature about them, much of which bases their distinction on the notion of tense.

In physics, the fundamental laws of motion (or their solutions, respectively) are time-translation invariant, time-reversal invariant, and time-scale invariant. These invariances, also called symmetries, mean that physical time at the fundamental level has no privileged instant (present), no preferred direction (past or future), and no intrinsic scale (time unit). The only relation between two instants in physical *tenseless time* is that their values on a time axis are greater or smaller than the other.

Mental time, on the other hand, features the tenses—past, present, and future—as key notions. So, at least time-translation symmetry and time-reversal symmetry are broken by mental *tensed time*. Moreover, the phenomenological experience of

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[11] In this context, Primas liked to cite Carl Friedrich von Weizsäcker (in personal conversation): "Every scientist works with metaphysical assumptions, and those who deny this most usually work with the poorest ones."

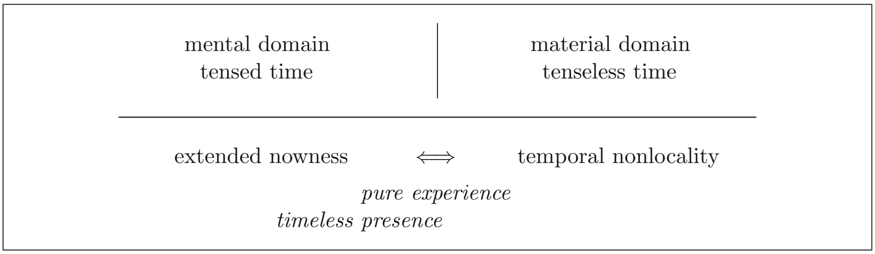

Fig. 4 Restriction of dual-aspect monism to mental and physical time as suggested by Primas. From the mental the neutral reality is approached via the experience of "extended nowness", from the material it is approached via the concept of "temporal nonlocality"

time suggests that the present is not an extensionless instant between past and future but has internal duration, an extended nowness as it were. Philosophers have coined concepts such as the "specious present" (James) or "actual occasion" (Whitehead) to take this into account (Fig. 4).

It is plausible to consider the experience of an extended nowness as the most elementary kind of phenomenal content (quale) of a mental state, without which no other qualia experience can possibly be made. In this sense, nowness is the basis of all experience. James' notion of "pure experience", his way of addressing the psychophysically neutral, resonates with this fundamental mode of the experience of presence in the present.[12]

The physicist's way to enter the domain of psychophysically neutral nowness proceeds via temporal nonlocality as referred to at the end of Sect. 3.2. The idea here is that pieces of nowness exist between successive elementary events, say e_1 and e_2, so that nothing in the interval between them could be used to define any time ordering or, for the same reason, causal relations within this interval. For the level of the *unus mundus* this implies a completely timeless presence, because there are no distinguishable events at all.

George Sudarshan, who together with Gustafson and Misra pioneered the quantum Zeno effect indicated in Sect. 3.2, once posed the question of whether we can "perceive a quantum system directly", and speculated about a mode of awareness in which (Sudarshan 1983)

> sensations, feelings, and insights are not neatly categorized into chains of thoughts, nor is there a step-by-step development of a logical-legal argument-to-conclusion. Instead, patterns appear, interweave, coexist; and sequencing is made inoperative. Conclusion, premises, feelings, and insights coexist in a manner defying temporal order.

The visionary outlook of Hans Primas relates all these ideas to the framework of thinking developed by Pauli and Jung. It does so in his typical manner, heavily relying on mathematical concepts couched in algebraic and group theoretical language and

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[12] "Pure experience" is an ambiguous term, however, since it triggers a mental understanding, similar to Jung's term "archetypal image" if it were used for the psychophysically neutral.

based on his expert knowledge of engineering mathematics. In his first explicit text about time entanglement he states (Primas 2003):

> Our point of departure is the hypothesis that there is a timeless holistic reality which can be described in the non-Boolean logical structure of modern quantum theory. Neither time, nor mind, nor matter and energy, are taken to be a priori concepts. Rather it is assumed that these concepts emerge by a contextual breaking of the holistic symmetry of the unus mundus.

In his final publication (Primas 2009), which Primas saw as an essential refinement of the 2003 paper, he introduces the affine Weyl-Heisenberg group to implement the three time symmetries and their breakdown. The resulting subgroups lead into the domains of tensed mental time and tenseless physical time (often called "A-time" and "B-time" in the philosophical literature):

> The traditional difficulties with the concepts "A-time" and "B-time" arise because they cannot be captured within a single Boolean description. But they can be conceived in terms of a non-Boolean description generated by the affine Weyl-Heisenberg symmetry group. Epistemically accessible partial descriptions can then be generated by an epistemic breaking of the full temporal symmetry. The two affine subgroups of the affine Weyl-Heisenberg group are complementary in a mathematically well-defined sense and allow a precise description of A-time and B-time, respectively. It follows that both A-time and B-time are necessary but none of them has a privileged status, none of them can replace the other.

In the years before he died in 2014, Primas continued to revise and expand his views and ideas on time, mind and matter in a 600-pages manuscript that he left in a fairly complete but unedited state. This manuscript will soon be published under the title *Knowledge and Time*. One could not think of a better testimony for a scholar who spent his scientific life on an avenue so unusual, and at the same time so coherent, as the path of Hans Primas: from engineering and chemistry to the foundations of physics and to the metaphysics of consciousness—stimulation and inspiration for everyone who has the thirst for insight and the intellectual freedom to follow.

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