Chapter 17

A closed-system approach to decoherence

Sebastian Fortin and Olimpia Lombardi

17.1. Introduction

Decoherence is a process that leads to spontaneous suppression of quantum interference. The orthodox explanation of the phenomenon is given by the *environment-induced decoherence* approach (see, e.g., Zurek 1982, 1993, 2003), according to which decoherence is a process resulting from the interaction of an open quantum system and its environment. By studying different physical models, it was proved that, when the environment has a huge number of degrees of freedom and for certain interactions, the reduced state of the open system rapidly diagonalizes in a well-defined preferred basis.

The environment-induced approach has been extensively applied to many areas of physics—such as atomic physics, quantum optics and condensed matter—and has acquired a great importance in quantum computation, where the loss of coherence represents a major difficulty for the implementation of the information processing hardware that takes the advantage of superpositions. In the field of the foundations of physics, this approach has been conceived as the key ingredient to explain the emergence of classicality from the quantum world, since the preferred basis identifies the candidates for classical states (see, e.g., Elby 1994, Healey 1995, Paz and Zurek 2002). It has been also considered a relevant element in different interpretations or approaches to quantum mechanics (for a survey, see Bacciagaluppi 2016).

The wide success of the environment-induced approach to decoherence took its difficulties to the background: only few works were devoted to analyze the assumptions and limitations of the orthodox approach. In resonance with this fact, the different approaches to decoherence arisen to face those difficulties were not taken into account with the care that they deserve. In this chapter we will show that there is a different perspective to understand decoherence, a closed-system approach, which not only solves or dissolves the problems of the orthodox approach, but also is in agreement with a top-down view of quantum mechanics that offers a new perspective for the traditional interpretive problems.

With this purpose, the chapter is organized as follows. In Section 2, we will begin by contrasting a bottom-up view versus a top-down view of quantum mechanics. In Section 3, the decoherence resulting from the interaction with the environment will be explained from a closed-system perspective. This will allow us to introduce, in Section 4, a general top-down, closed-system approach to decoherence, in the context of which environment-induced decoherence is a particular case. The paper closes with some final remarks.

17.2. Bottom-up view versus top-down view of quantum mechanics

The idea that nature consists of tiny elemental entities is deeply entrenched in our way of conceiving reality. It finds its roots in ancient Greece with atomism, and reappears in early Modern Age with the corpuscularist philosophy of Robert Boyle, which influenced many contemporary thinkers, including Newton. Since those days, it has taken different forms in chemistry, as in Dalton's atomic theory, and in physics, from the kinetic theory of gases up to the standard model of particle physics. An epistemological strategy becomes natural in the light of this ontological picture: in order to understand nature, it is necessary to decompose it into simple systems. The knowledge about the whole is obtained by first studying the simple systems and then combining them through their interactions. Of course, there are cases in which this analytical strategy leads to descriptions that cannot be solved by formal means. This is the case of the three-body problem in classical mechanics. Nevertheless, even if there is no general closed form solution for the equations describing the many-body system, nobody doubts that the behavior of the whole system is determined by the components and its interactions; precisely for this reason, those problems are commonly solved by numerical methods.

With the advent of quantum mechanics, this ontological picture goes into crisis. The phenomenon of entanglement, which is not a traditional physical interaction, is responsible of correlations that cannot be understood in classical terms. Therefore, in quantum mechanics, the assumption that the better knowledge about the whole is obtained by studying the simple systems and their interactions breaks down: here the state of the composite system is not uniquely determined by the states of the component subsystems. Nevertheless, in spite of this well-known fact, it is usual to begin with quantum systems, represented by Hilbert spaces, which become subsystems when they constitute a composite system. The implicit assumption is the atomistic assumption that there are certain elemental "particles" out of which everything is composed. This assumption has even made explicit by the atomic modal interpretation of quantum mechanics, according to which there is in nature a fixed set of mutually disjoint atomic quantum systems that constitute the building blocks of all the other quantum systems (Bacciagaluppi and Dickson 1999). Good candidates for elemental systems are those represented by the irreducible representations of the symmetry group of the theory.

From this viewpoint, when quantum systems interact, their states may become entangled: "By the interaction the two representatives [the quantum states] have become entangled" (Schrödinger 1935: 555, when coined the term 'entangled'). In this case, it is said that the composite system is an entangled state, because it cannot be obtained as the tensor product of the component's states. Entanglement is, therefore, the responsible for the correlations between the values of the observables of the two subsystems.

This bottom-up ontological view leads to first consider two particles, say, a proton *p* and an electron *e*, represented by the Hilbert spaces $\mathcal{H}_p$ and $\mathcal{H}_e$ and in states $\psi_p \in \mathcal{H}_p$ and $\psi_e \in \mathcal{H}_e$, respectively. Then, the state $\psi \in \mathcal{H}_p \otimes \mathcal{H}_e$ of the hydrogen atom as a composite system is said to be entangled when $\psi \neq \psi_p \otimes \psi_e$ for any pair of states ψ_p and ψ_e. This suggests that 'entangled' is a property that applies or no to the state of a composite system. However, the hydrogen atom can also be represented as constituted by two different subsystems, the center-of-mass system $\psi_c \in \mathcal{H}_c$ and the relative system $\psi_r \in \mathcal{H}_r$, such that the state of the hydrogen atom $\psi \in \mathcal{H}_c \otimes \mathcal{H}_r$ can be obtained as $\psi = \psi_c \otimes \psi_r$: now the state of the composite system is not entangled. Although conceiving the hydrogen atom as composed by a proton and an electron seems more natural, there are group reasons that may lead to consider that the decomposition in center-of-mass system and relative system is more fundamental (see Ardenghi, Castagnino, and Lombardi 2009). This means that it cannot be said that a state of a composite system is entangled or not without first deciding which decomposition of the system will be considered.

John Earman stresses this fact by saying:

> [A] state may be entangled with respect to one decomposition but not another; hence, unless there is some principled way to choose a decomposition, entanglement is a radically ambiguous notion. (Earman 2013: 303).

As a consequence, it is necessary to single out the "correct" decomposition, and two positions can be distinguished (Earman 2013: 324-327): for the realist, there are certain subsystems that are ontologically "real" systems, whereas others are merely fictional; for the pragmatist, by contrast, the legitimate criterion for decomposition is empirical accessibility.

Although in certain passages of his article Earman talks of relativity, the stronger idea is that of "*the rampant ambiguity*" of the notion of entanglement (3012: 324, 325, 327). A notion is ambiguous if it has more that one meaning; so, in science and in philosophy ambiguity must be avoided. Therefore, if the notion of entanglement is ambiguous, the need for a clear-cut decision about how to split the composite system into subsystems seems completely reasonable. Nevertheless, a different view is possible: the notion of entanglement is not ambiguous; it is *relative* to the decomposition. The difference between ambiguity and relativity is not irrelevant at all: whereas the first is a conceptual problem to be solved, the second is a common feature of physical concepts. In fact, the concept of velocity is not ambiguous because relative to a reference frame. In the same sense, entanglement is a notion that acquires a precise meaning when relativized to a certain partition of the composite system and, as a consequence, no absolute criterion to select the right decomposition is needed.

The relative conception of entanglement invites to reverse the general approach to quantum mechanics, from the traditional, classically-inspired bottom-up view, to a top-down view that endows the composite system with ontological priority. From this perspective, even if two systems exist independently before interaction, after the interaction their existence is only derivative, they become components of the composite system on a par with other subsystems resulting from any different decomposition. This view finds a significant affinity with the so called '*quantum structure studies*', which deal with the different ways in which a quantum system can be decomposed into subsystems according to different tensor product structures (Harshman and Wickramasekara 2007a,b, Jekniæ-Dugiæ, Arsenijeviæ, and Dugiæ 2013, Arsenijeviæ, Jekniæ-Dugiæ, and Dugiæ 2016, Harshman 2016).

But the top-down view can be generalized a step further. Up to this point, the relation between "top" and "down" was described in terms of decomposing the composite system into its subsystems: the result of decomposition are subsystems, represented by Hilbert spaces; the tensor product of the Hilbert spaces of the subsystems is the Hilbert space of the composite system. But the top-down relationship can also be conceptualized in terms of algebras of observables, in resonance with the algebraic approach to quantum mechanics (Haag 1992). The whole system, represented by its algebra of observables, can be partitioned into different parts, identified by the subalgebras, even when these subalgebras do not correspond to subsystems represented by Hilbert spaces. This perspective, released from the subsystem-dependent view anchored in tensor product structures, was proposed by Howard Barnum and his colleagues (2003), who proposed a generalization of the notion of entanglement to partitions of algebras. This generalized notion becomes the usual notion of entanglement when the partition of the algebra of the whole system defines a decomposition of the system into subsystems (Barnum et al. 2004, Viola et al. 2005; Viola and Barnum 2010). A further characterization of pure entangled states can be given by appealing to the notion of restriction to a subalgebra is a natural algebraic generalization of the partial trace operation (Balachandran et al. 2013a,b). As a consequence, entanglement is not a relationship between systems or states, but between algebras of observables (Harshman and Ranade 2011).

At present, this subsystem-independent view has been formally studied with great detail in many works and is still in development. But the point that we want to stress here is that this view suggests a top-down closed-system ontological picture, according to which the whole closed-system is the only autonomous entity: the sub-entities represented by subalgebras of the whole algebra of observables are only partial perspectives of the closed-system without autonomous existence. In the following section we will show that the phenomenon of decoherence can be explained from this top-down closed-system view, which, in turn, leads to a generalized approach to decoherence.

17.3. Environment-induced decoherence from a closed-system perspective

17.3.1. What are the systems that decohere?

The environment-induced-decoherence program quickly became a new orthodoxy in the physicists' community (Bub 1997). Despite this, the program is still threatened by a serious conceptual problem, which is precisely derived from its open-system.

According to the orthodox view, the first step is to split the universe into the degrees of freedom which are of direct interest to the observer, "the system of interest", and the remaining degrees of freedom usually referred to as "the environment". In many models, distinguishing between the system of interest and its environment seems to be a simple matter. This is the case in many typical applications of the decoherence formalism to spin-bath models, devoted to study the behavior of a particle immersed in a large "bath" of many particles (see, e.g., Zurek 1982). But the environment can also be internal, such as phonons or other inside excitations. This is typically the case when the formalism is applied to cosmology: the Universe is split into some degrees of freedom representing the system, and the remaining degrees of freedom that are supposed to be non-accessible and, therefore, play the role of the environment (see, e.g., Calzetta, H and Mazzitelli 2001). The possibility of internal environments leads to the need for a general criterion to distinguish between the system and its environment. The problem consists in that the environment-induced-decoherence program does not provide such a criterion. Wojciech Zurek early recognized this shortcoming of his proposal:

> one issue which has been often taken for granted is looming big, as a foundation of the whole decoherence program. It is the question of what are the "systems" which play such a crucial role in all the discussions of the emergent classicality. This issue was raised earlier, but the progress to date has been slow at best. Moreover, replacing "systems" with, say, "coarse grainings" does not seem to help at all, we have at least tangible evidence of the objectivity of the existence of systems, while coarse-grainings are completely "in the eye of the observer." (Zurek 2000: 338; see also Zurek 1998).

It is quite clear that the problem can be removed from a top-down closed-system perspective as that delineated in the previous section.

In order to explain decoherence from a closed-system perspective, let us begin by recalling the definition of the concept of reduced state, because the environment-induced-decoherence program decides to study the time behavior of the reduced state of the system of interest. The reduced state ρ_1^r of a system S_1, subsystem of a system S, is defined as the density operator by means of which the expectation values of all the observables of S belonging exclusively to S_1 can be computed. As Maximilian Schlosshauer emphasizes, strictly speaking, a reduced density operator is only "*a calculational tool*" for computing expectation values (Schlosshauer 2007: 48). This means that the description of decoherence in terms of the reduced state of the open system is conceptually equivalent to the description in terms of the expectation values of the observables of the open system but viewed from the perspective of the whole closed system. This is the path we will follow here.

17.3.2. The perspective of the closed system

Let us consider a closed system U partitioned as $U = S \cup E$, where S is the open system of interest and E is the environment. Let us call $\mathcal{O}_U$ the space of observables of U, and $\mathcal{O}_S$ and $\mathcal{O}_E$ the spaces of observables of S and E respectively; then $\mathcal{O}_U = \mathcal{O}_S \otimes \mathcal{O}_E$. If ρ_U is the state of U, the reduced state of S can be computed by means of the partial trace as $\rho_S = Tr_E\, \rho_U$. The environment-induced-decoherence formalism proves that, in many physically relevant models with environments of many degrees of freedom, the non-diagonal terms of the reduced state $\rho_S(t)$ rapidly tend to vanish after an extremely short decoherence time t_D:

$$\rho_S(t) \xrightarrow{t \gg t_D} \rho_S^d(t) \qquad (17.1)$$

where $\rho_S^d(t)$ is diagonal in the preferred basis of $\mathcal{O}_S$. The above evolution expresses the following evolution in the expectation values of the observables $O_S \in \mathcal{O}_S$ of the open system S:

$$\langle O_S \rangle_{\rho_S(t)} \xrightarrow{t \gg t_D} \langle O_S \rangle_{\rho_S^d(t)} \qquad (17.2)$$

But, by definition, ρ_S is the density operator by means of which the expectation values of all the observables $O_S \in \mathcal{O}_S$ in the state ρ_S can be computed, that is:

$$\forall \left(O_{US} = O_S \otimes I_E \right) \in \mathcal{O}_U \quad \langle O_{US} \rangle_{\rho_U} = \langle O_S \rangle_{\rho_S} \qquad (17.3)$$

where $I_E \in \mathcal{O}_E$ is the identity of the space of observables of the environment E. Then, it is clear that, even when the task is to describe only S, its reduced state is not indispensable. The physically relevant information about that subsystem can also be obtained by studying the state ρ_U of the whole closed system U and its relevant observables $O_{US} = O_S \otimes I_E$. This means that there is no difference between describing the open system S by means of its reduced state ρ_S and describing it from a closed-system perspective by means of the expectation values of the relevant observables O_{US} of the closed composite system U in the state ρ_U. Therefore, the evolution of eq. (17.3) can be expressed from the viewpoint of the closed system U as:

$$\langle O_{US} \rangle_{\rho_U(t)} \xrightarrow{t \gg t_D} \langle O_{US} \rangle_{\rho_U^d(t)} \qquad (17.4)$$

where $\rho_U^d(t)$ is not completely diagonal, but is diagonal in the preferred basis of $\mathcal{O}_S$.

17.3.3. The emergence of classicality

The emergence of classicality through decoherence can strictly explained in terms of expectation values. The general idea is that the expectation value of an observable O when the system is in the certain state ρ can be expressed as:

$$\langle O \rangle_\rho = \sum_i O_{ii}\, \rho_{ii} + \sum_{i \neq j} O_{ij}\, \rho_{ij} \qquad (17.5)$$

where the ρ_{ii} and the O_{ii} are the diagonal components, and the ρ_{ij} and the O_{ij} are the non-diagonal components of ρ and O, respectively, in a certain basis. The second sum of eq. (17.5) represents the specifically quantum interference terms of the expectation value. If those terms vanished, the expectation value would adopt the structure of a classical expectation value, where the O_{ii} might be interpreted as possible values and the ρ_{ii} might play the role of probabilities since positive numbers that are less than or equal to one and sum to one.

In the light of this idea, the process of decoherence described by the evolution of eq. (17.2) leads to a classical-like expectation value, since $\rho_S^d(t)$ is diagonal in the preferred basis of $\mathcal{O}_S$:

$$\langle O_S \rangle_{\rho_S(t)} \xrightarrow{t \gg t_D} \langle O_S \rangle_{\rho_S^d(t)} = \sum_i O_{Sii}\, \rho_{Sii}^d(t) \qquad (17.6)$$

where the ρ_{Sii} and the O_{Sii} are the diagonal components of ρ_S and O_S, respectively, in the preferred basis.

However, the same move cannot be applied to the evolution as expressed in eq. (17.4), because $\rho_U^d(t)$ is not completely diagonal: it is diagonal only in the components corresponding to the preferred basis of $\mathcal{O}_S$. Nevertheless, decoherence can be described from the closed-system perspective analogously to eq. (17.6) if a coarse-grained state $\rho_G(t)$ of the closed system U is defined as the operator such that:

$$\forall \left(O_{US} = O_S \otimes I_E\right) \in \mathcal{O}_U \quad \langle O_{US} \rangle_{\rho_U(t)} = \langle O_{US} \rangle_{\rho_G(t)} \qquad (17.7)$$

The density operator ρ_G represents a coarse-grained state because it can be obtained as $\rho_G = \Pi \rho_U = \Pi \Pi \rho_U$. The projector Π performs the following operation:

$$\Pi \rho_U = \left(Tr_E\, \rho_U\right) \otimes \tilde{\delta}_E = \rho_S \otimes \tilde{\delta}_E \qquad (17.8)$$

where $\tilde{\delta}_E \in \mathcal{O}_E$ is a normalized identity operator with coefficients $\tilde{\delta}_{E\alpha\beta} = \delta_{\alpha\beta} / \sum_\gamma \delta_{\gamma\gamma}$ (see Fortin and Lombardi 2014). Now, the process of decoherence can be expressed as

$$\langle O_{US} \rangle_{\rho_U(t)} \xrightarrow{t \gg t_D} \langle O_{US} \rangle_{\rho_G^d(t)} \qquad (17.9)$$

where $\rho_G^d(t)$ remains completely diagonal for all times $t \gg t_D$. Now it can be said that the expectation value acquires a classical form also from the closed-system perspective since:

$$\langle O_{US} \rangle_{\rho_U(t)} \xrightarrow{t \gg t_D} \langle O_{US} \rangle_{\rho_G^d(t)} = \sum_i O_{USii}\, \rho_{Gii}^d(t) \qquad (17.10)$$

where the ρ_{Gii}^d and the O_{USii} are the diagonal components of ρ_G^d and O_{US}, respectively, in the basis of decoherence. It is quite clear that ρ_G, although operating onto $\mathcal{O}_U$, is not the quantum state of U: it is a coarse-grained state of the closed system that disregards certain information of its quantum state. However, ρ_G supplies the same information about the open system S as the reduced state ρ_S, but now from the viewpoint of the composite system S. In fact, if the degrees of freedom of the environment are traced off, the reduced state ρ_S is obtained:

$$Tr_E\, \rho_G = \rho_S \qquad (17.11)$$

Therefore, the reduced density operator ρ_S can also be conceived as a kind of coarse-grained state of U, which disregards certain degrees of freedom considered as irrelevant.

17.3.4. The applications of the closed-system approach

The closed-system approach was presented from different perspectives, from the more conceptual (Castagnino, Laura, and Lombardi 2007, Lombardi, Fortin, and Castagnino 2012), to the more technical (Castagnino and Lombardi 2005, Castagnino and Fortin 2011, Fortin, Lombardi, and Castagnino 2014). It was also applied to a generalization of the spin-bath model (Castagnino, Fortin, and Lombardi 2010): a generalized spin-bath model of $m+n$ spin-1/2 particles, where the m particles interact with each other and the n particles also interact with each other, but the particles of the m group do not interact with those of the n group. The study of the model shows that there are definite conditions under which all the particles decohere, but neither the system composed of the m group nor the system composed of the n group decoheres.

Once decoherence is understood from this new perspective, the defining-system problem, that is, the problem that there is no criterion to distinguish between the system and the environment, dissapears. In fact, the same closed system can be decomposed in many different ways. Since there is no privileged or "essential" decomposition, there is no need of an unequivocal criterion to decide where to place the cut between "the" system and "the" environment. If all the ways of selecting the system of interest are equally legitimate, decoherence is *relative* to the decomposition of the whole system (Lombardi, Fortin and Castagnino 2012, see also Lychkovskiy 2013). In other words, Zurek's "looming big" problem is not a real threat to the environment-induced-decoherence approach: the supposed challenge dissolves once it is understood that decoherence is not a yes-or-no process but a relative phenomenon.

17.4. The top-down approach to decoherence

17.4.1. The formalism

In the previous section, the closed-system approach to decoherence was still discussed in terms of the possibility of different tensor product structures: decoherence is relative to the particular decomposition of the composite system into subsystems. In this section, the generalization will be taken a step further from the algebraic viewpoint, by admitting that a closed system be partitioned into parts that do not constitute subsystems.

The starting point of the algebraic approach to quantum mechanics (Haag 1992; see also Bratteli and Robinson 1987) is the *algebra of observables* $\mathfrak{A}(\mathcal{O})$, which is the algebra spanned by a certain set $\mathcal{O}$ of observables O represented by self-adjoint operators mapping a suitable Hilbert space $\mathcal{H}$ onto itself. When the algebra $\mathfrak{A}(\mathcal{O})$ identifies a quantum system, the *quantum state* ω of the system is a prescription of the expectation values of the observables, and it is formalized as an expectation value functional from the observables to the unit interval, $\omega : \mathfrak{A}(\mathcal{O}) \to [0,1]$. A quantum state is said to be normal when there is an associate density operator ρ_ω (with $\rho_\omega \geq 0$ and $Tr\,\rho_\omega = 1$) acting on the same Hilbert space $\mathcal{H}$ and such that $\omega(O) = Tr(O\rho_\omega)$. The *expectation value* $\omega(O)$ gives the expected value if one measures the observable O when the system is in the state ω, and the equation '$\omega(O) = Tr(O\rho_\omega)$' is essentially the Born rule extended to mixed states.

The above algebraic notions are sufficient to formulate a top-down approach to decoherence that is independent of the tensor product structures of the Hilbert spaces. Let us consider a closed system U identified by its algebra of observables $\mathfrak{A}(\mathcal{O}_U)$, and its state, represented by the density operator ρ_U. Now U is not decomposed into subsystems, but a certain set of relevant observables $\mathcal{O}_R$ is selected. It is interesting to notice that this move agrees with the approaches of the first period in the historical development in the general program of decoherence (see Fortin, Lombardi, and Castagnino 2014), when the aim was to understand how classical macroscopic properties emerge from the quantum microscopic evolution of a closed system. In this first period, the approach to equilibrium of quantum systems was studied through the behavior of certain observables that supposedly should behave classically, because accessible from the macroscopic viewpoint: "gross observables" (van Kampen 1954), "macroscopic observables of the apparatus" (Daneri, Loinger, and Prosperi 1962). In the present case, no restriction is imposed on the selection of the relevant observables: any set of observables can be selected. In any case, the *algebra of the relevant observables*, subalgebra of $\mathfrak{A}(\mathcal{O}_U)$, will be considered: $\mathfrak{A}(\mathcal{O}_R) \subseteq \mathfrak{A}(\mathcal{O}_U)$.

Once the relevant observables are selected, the second step consists in computing the expectation values of the observables of the relevant algebra $\mathfrak{A}(\mathcal{O}_R)$:

$$\forall O_R \in \mathfrak{A}(\mathcal{O}_R) \quad \langle O_R \rangle_{\rho_U(t)} \qquad (17.12)$$

Then, a coarse-grained state $\rho_G(t)$ is defined, such that:

$$\forall O_R \in \mathfrak{A}(\mathcal{O}_R) \quad \langle O_R \rangle_{\rho_U(t)} = \langle O_R \rangle_{\rho_G(t)} \qquad (17.13)$$

Now, the non-unitary evolution (governed by a master equation) of this expectation values is computed. Decoherence occurs when, after an extremely short decoherence time t_D, the expectation acquires a particular form:

$$\langle O_R \rangle_{\rho_U(t)} = \langle O_R \rangle_{\rho_G(t)} \xrightarrow{t \gg t_D} \langle O_R \rangle_{\rho_G^d(t)} \qquad (17.14)$$

where $\rho_G^d(t)$ remains diagonal in the preferred basis for all times $t \gg t_D$. This means that, although the off-diagonal terms of $\rho_U(t)$ never vanish through its unitary evolution, it might be said that the system decoheres *relatively to the observational point of view* given by any observable belonging to the algebra of the relevant observables $\mathfrak{A}(\mathcal{O}_R)$.

17.4.2. Classically-behaving observables

Let us recall that decoherence has been considered the essential element to explain the emergence of classicality from the quantum world. But if decoherence is a relative phenomenon, classicality seems to be also relative: the fact that a system behaves classically or not cannot seems to depend on the way in which the observer decides to split the original closed system into relevant and irrelevant observables. This situation also challenges the orthodox open-system approach: in certain situations the fact that classicality emerges in an open system or not depends on what composite system that open subsystem is embedded in. More precisely, given two partitions of a closed system U, $U = S_1 \cup E_1$ and $U = S_2 \cup E_2$, it may be the case that S_1 and S_2 decohere and behave classically, but $S_1 \cup S_2$ does not decohere and, so, classicality does not emerge in it (see the model in Castagnino, Fortin, and Lombardi 2010). This is a difficulty if one considers that the classical world is objective, independent of any observer's decision: recall Zurek's rejection of any solution of the defining-system problem that relies on "the eye of the observer" (Zurek 2000: 338).

Despite what it seems, the top-down view of decoherence based on the algebraic approach is not affected by that difficulty. Given the closed system U, saying that it decoheres from the perspective of the relevant observables $O_R \in \mathfrak{A}(\mathcal{O}_R)$ amounts to saying that, after a very short decoherence time, the interference terms of the expectation values of those observables tend to vanish with the unitary time-evolution of the state ρ_U of U. But the vanishing of the interference terms of the expectation values of an observable is not a relative fact that depends on the observer: what depends on the observer is the selection of the relevant observables with the purpose to see if the closed system decoheres relative to it or not.

When this fact is understood, it turns out to be clear that the all observables of the closed system U can be considered one by one, their trivial algebras can be defined, and the decoherence of the system U relative to each one of those algebras can be studied. As the result, one is in a position to know the set of all the observables of U that behave classically after a certain time, with neither ambiguity nor relativity.

Another difficulty of the orthodox approach is that usually not stressed is that certain systems have a classical behavior with respect to certain observables and a quantum behavior with respect to others. For instance, a transistor behaves classically with respect to its center of mass when it falls off the table, but also has the quantum behavior characteristic of its specific use. When decoherence is conceived as a phenomenon that occurs or not to a quantum system, these common situations cannot be accounted for. By contrast, the top-down approach that relies on the subalgebras of observables can easily explain how a single system may combine classical and quantum behaviors of its different observables.

In summary, according to the explanation of the emergence of the classical world given by the top-down algebraic approach just proposed, strictly speaking classicality is not a property of systems: thinking in systems that become classical in their whole leads to the above mentioned difficulties. The difficulties can be overcome once it is recognized that *classicality is a property of observables*. The emergent classical world is, then, the world described by the observables that behave classically with respect to their expectation values.

17.5. Concluding remarks

In this chapter we have proposed a closed-system approach to decoherence which, at first sight, seems to be a rival of the orthodox open-system approach. However, as we have argued, our proposal is compatible with the environment-induced-decoherence view, but generalizes it by including the treatment of situations that could not be studied with that orthodox view.

As already explained, this closed-system approach is in resonance with a top-down view of quantum mechanics, usually based on the algebraic formalism, which is gaining ground in the physics community. It is interesting to notice also that understanding decoherence from the viewpoint of a closed system represented by its algebra of observables stands in close agreement with the modal-Hamiltonian interpretation of quantum mechanics (Lombardi and Castagnino 2008, Ardenghi, Castagnino and Lombardi 2009, Lombardi, Castagnino and Ardenghi 2010; see also Chapter 2 of this volume), also developed in our research group. This interpretation, also based on the algebraic approach, makes the rule that selects the definite-valued observables to depend on the Hamiltonian of the closed system. Moreover, the definition of the system in terms of its algebra of observables leads to an ontological picture where quantum systems are bundles of properties without individuality (da Costa, Lombardi and Lastiri 2013, da Costa and Lombardi 2014, Lombardi and Dieks 2016). In summary, the general view that endows closed systems with ontological priority has different but converging manifestations, in the light of which it deserves to be further developed.

Acknowledgements

We are grateful to the participants of the workshop, *Identity, indistinguishability and non-locality in quantum physics*, Buenos Aires, June 2017, for their interesting comments. This article was made possible through the support of Grant 57919 from the John Templeton Foundation and Grant PICT-2014-2812 from the National Agency of Scientific and Technological Promotion of Argentina.

References

Ardenghi, J. S., Castagnino, M., and Lombardi, O. (2009). "Quantum mechanics: modal interpretation and Galilean transformations," *Foundations of Physics*, **39**: 1023-1045.

Arsenijeviæ, M., Jekniæ-Dugiæ, J., and Dugiæ, M. (2016). "A top-down versus a bottom-up hidden-variables description of the Stern-Gerlach experiment," pp. 469-484 in R. E. Kastner, J. Jeknić-Dugić, and G. Jaroszkiewicz (eds.), *Quantum Structural Studies: Classical Emergence from the Quantum Level*. Singapore: World Scientific.

Bacciagaluppi, G. (2016). "The role of decoherence in quantum mechanics," in E. N. Zalta (ed.), *The Stanford Encyclopedia of Philosophy* (Fall 2016 Edition). URL = <https://plato.stanford.edu/archives/fall2016/entries/qm-decoherence/>.

Bacciagaluppi, G. and Dickson, M. (1999). "Dynamics for modal interpretations," *Foundations of Physics*, **29**: 1165-1201.

Balachandran, A. P., Govindarajan, T. R., de Queiroz, A. R., and Reyes-Lega, A. F. (2013a). "Algebraic approach to entanglement and entropy," *Physical Review A*, **88**: #022301.

Balachandran, A. P., Govindarajan, T. R., de Queiroz, A. R., and Reyes-Lega, A. F. (2013b). "Entanglement and particle identity: A unifying approach," *Physical Review Letters*, **110**: "080503

Barnum, H., Knill, E., Ortiz, G., Somma, R., and Viola, L. (2003). "Generalizations of entanglement based on coherent states and convex sets," *Physical Review A*, **68**: #032308.

Barnum, H., Knill, E., Ortiz, G., Somma, R., and Viola, L. (2004). "A subsystem-independent generalization of entanglement," *Physical Review Letters*, **92**: #107902.

Bratteli, O., and Robinson, D. W. (1987). *Operator algebras and quantum statistical mechanics 1* (2nd ed.). New York: Springer.

Bub, J. (1997). *Interpreting the Quantum World*. Cambridge: Cambridge University Press.

Calzetta, E., Hu, B. L., and Mazzitelli, F. (2001). "Coarse-grained effective action and renormalization group theory in semiclassical gravity and cosmology," *Physics Reports*, **352**: 459-520.

Castagnino, M. and Fortin, S. (2011). "New bases for a general definition for the moving preferred basis," *Modern Physics Letters A*, **26**: 2365-2373.

Castagnino, M., Fortin, S. and Lombardi, O. (2010). "Suppression of decoherence in a generalization of the spin-bath model," *Journal of Physics A: Mathematical and Theoretical*, **43**: #065304.

Castagnino, M., Laura, R. and Lombardi, O. (2007). "A general conceptual framework for decoherence in closed and open systems," *Philosophy of Science*, **74**: 968-980.

Castagnino, M. and Lombardi, O. (2005b). "Decoherence time in self-induced decoherence," *Physical Review A*, **72**: #012102.

Da Costa, N. and Lombardi, O. (2014). "Quantum mechanics: ontology without individuals," *Foundations of Physics*, **44**: 1246-1257.

Da Costa, N., Lombardi, O., and Lastiri, M. (2013). "A modal ontology of properties for quantum mechanics," *Synthese*, **190**: 3671-3693.

Daneri, A., Loinger, A., and Prosperi, G. (1962). "Quantum theory of measurement and ergodicity conditions," *Nuclear Physics*, **33**: 297-319.

Earman, J. (2014). "Some puzzles and unresolved issues about quantum entanglement," *Erkenntnis*, **80**: 303-337.

Elby, A. (1994). "The 'decoherence' approach to the measurement problem in quantum mechanics," *Proceedings of the of the 1994 Biennial Meeting of the Philosophy of Science Association*, **1**: 355-365.

Fortin, S. and Lombardi, O. (2014). "Partial traces in decoherence and in interpretation: What do reduced states refer to?," *Foundations of Physics*, **44**: 426-446.

Fortin, S., Lombardi, O., and Castagnino, M. (2014). "Decoherence: a closed-system approach," *Brazilian Journal of Physics,* **44**: 138-153.

Haag, R. (1992). *Local Quantum Physics: Fields, Particles, Algebras*. Berlin: Springer.

Harshman, N. (2016). "Symmetry and natural quantum structures for three-particles in one-dimension," pp. 373-400 in R. E. Kastner, J. Jeknić-Dugić, and G. Jaroszkiewicz (eds.), *Quantum Structural Studies: Classical Emergence from the Quantum Level*. Singapore: World Scientific.

Harshman, N. and Ranade, K. (2011). "Observables can be tailored to change the entanglement of any pure state," *Physical Review A*, **84**: #012303.

Harshman, N. and Wickramasekara, S. (2007a). "Galilean and dynamical invariance of entanglement in particle scattering," *Physical Review Letters*, **98**: #080406.

Harshman, N. and Wickramasekara, S. (2007b). "Tensor product structures, entanglement, and particle scattering, *Open Systems & Information Dynamics*, **14**: 341-351.

Healey, R. (1995). "Dissipating the quantum measurement problem," *Topoi*, **14**: 55-65.

Jekniæ-Dugiæ, J., Arsenijeviæ, M., and Dugiæ, M. (2013). *Quantum Structures: A View of the Quantum World*. Saarbrücken: Lambert Academic Publishing.

Lombardi, O. and Castagnino, M. (2008). "A modal-Hamiltonian interpretation of quantum mechanics," *Studies in History and Philosophy of Modern Physics*, **39**: 380-443.

Lombardi, O., Castagnino, M., and Ardenghi, J. S. (2010). "The modal-Hamiltonian interpretation and the Galilean covariance of quantum mechanics," *Studies in History and Philosophy of Modern Physics*, **41**: 93-103.

Lombardi, O. and Dieks, D. (2016). "Particles in a quantum ontology of properties," pp. 123-143 in T. Bigaj and C. Wüthrich (eds.), *Metaphysics in Contemporary Physics*. Leiden: Brill-Rodopi.

Lychkovskiy, O. (2013). “Dependence of decoherence-assisted classicality on the way a system is partitioned into subsystems,” *Physical Review A*, **87**: #022112.

Lombardi, O., Fortin, S. and Castagnino, M. (2012). “The problem of identifying the system and the environment in the phenomenon of decoherence,” pp. 161-174 in H. W. de Regt, S. Hartmann and S. Okasha (eds.), *Philosophical Issues in the Sciences Volume 3*. Berlin: Springer.

Paz, J. P. and Zurek, W. H. (2002). “Environment-induced decoherence and the transition from quantum to classical,” pp. 77-148, in D. Heiss (ed.), *Fundamentals of Quantum Information: Quantum Computation, Communication, Decoherence and All That*. Heidelberg-Berlin: Springer.

Schlosshauer, M. (2007). *Decoherence and the Quantum-to-Classical Transition*. Berlin: Springer.

Schrödinger, E. (1935). “Discussion of probability relations between separated systems,” *Proceedings of the Cambridge Philosophical Society*, **31**: 555-563.

Van Kampen, N. G. (1954). “Quantum statistics of irreversible processes,” *Physica*, **20**: 603-622.

Viola, L. and Barnum, H. (2010). “Entanglement and subsystems, entanglement beyond subsystems, and all that,” pp. 16-43 in A. Bokulich and G. Jaeger (eds.), *Philosophy of Quantum Information and Entanglement*. Cambridge: Cambridge University Press.

Viola, L., Barnum, H., Knill, E., Ortiz, G., and Somma, R. (2005). “Entanglement beyond Subsystems,” *Contemporary Mathematics*, **381**: 117-130.

Zurek, W. H. (1982). “Environment-induced superselection rules,” *Physical Review D*, **26**: 1862-1880.

Zurek, W. H. (1993). “Preferred states, predictability, classicality and the environment-induced decoherence,” *Progress of Theoretical Physics*, **89**: 281-312.

Zurek, W. H. (1998). “Decoherence, einselection, and the existential interpretation,” *Philosophical Transactions of the Royal Society A*, **356**: 1793-1820.

Zurek, W. H. (2000). “Decoherence and einselection,” pp. 309-342 in P. Blanchard, D. Giulini, E. Joos, C. Kiefer and I.-O. Stamatescu (eds.), *Decoherence: Theoretical, Experimental, and Conceptual Problems*. Berlin-Heidelberg: Springer-Verlag.

Zurek, W. H. (2003). "Decoherence, einselection, and the quantum origins of the classical," *Reviews of Modern Physics*, **75**: 715-776.