Contextual Emergence from Physics to Cognitive Neuroscience

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Abstract

The concept of contextual emergence has been proposed as a non-reductive, yet well-defined relation between different levels of description of physical and other systems. It is illustrated for the transition from statistical mechanics to thermodynamical properties such as temperature. Stability conditions are shown to be crucial for a rigorous implementation of contingent contexts that are required to understand temperature as an emergent property.

Are such stability conditions meaningful for contextual emergence beyond physics as well? An affirmative example from cognitive neuroscience addresses the relation between neurobiological and mental levels of description. For a particular class of partitions of the underlying neurobiological phase space, so-called generating partitions, the emergent mental states are stable under the dynamics. In this case, mental descriptions are (i) faithful representations of the neurodynamics and (ii) compatible with one another.

1 Introduction

A basic strategy for the scientific description of any system, physical or otherwise, is to specify its state and the properties associated with that state, and then introduce their evolution in terms of dynamical laws. This strategy presupposes that the boundary of a system can be defined with respect to its environment, although such a definition is often problematic. If it can be achieved, there is usually more than one possibility for specifying states and properties. The fact that states and properties can be formally and rigorously defined in fundamental physical theories distinguishes the structure of such theories as particularly transparent. A paradigmatic example for a fundamental theory in present-day physics is quantum theory.

But how about physical theories which are not regarded as fundamental (such as thermodynamics), or how about descriptive approaches beyond physics (such as chemistry, biology or psychology)? For such situations, attempts have been made to relate descriptions of systems which are not fundamental in the sense mentioned above to descriptions which are fundamental in this sense. The usual (and often too simple) framework in which corresponding relations are typically formulated is that of a hierarchy of descriptions. In a hierarchical picture (which can be refined in terms of more complicated networks of descriptions) there are higher-level and lower-level descriptions. More fundamental theories are taken to refer to lower levels in the hierarchy.

In such a simple framework, reduction and emergence are relations between different levels of descriptions of a system, its states and properties, or the (dynamical) laws characterizing their behavior. In the philosophical literature, the usual guiding idea behind reductionist approaches is to "reduce" higher-level features to lower-level features. In contrast, emergentist approaches emphasize higher-level features by stressing the irreducibility of at least some of their aspects to lower levels. In this way, the emergence of features at higher levels[1] is related to the emergence of novelty.

In a recent article (Bishop and Atmanspacher 2006), two selected examples, temperature and chirality, were used to illustrate the sophisticated way in which features at one level of description are often related to features at another level. While strict reductionists would argue that both necessary and sufficient conditions for higher-level features are already embodied at the lower level, this is false in both of these examples, and presumably false in many others as well. An alternative kind of interlevel relation, *contextual emergence*, has been proposed as a less rigid, more appropriate scheme, in which necessary but not sufficient conditions for higher-level features are provided by the lower-level description.

The scheme of contextual emergence is particularly proposed for exploring insufficiently understood interlevel relations beyond physics. Specifically, one may think of relations between different levels of descriptions in brain physiology, where one of

[1]Emergence in the sense of an interlevel relation, as it is addressed in this paper, is always understood synchronically (i.e., as a structural relation) rather than diachronically (i.e., as a dynamical process). For details see Stephan (1999).

the key questions is how properties of neuronal assemblies or populations are related to properties of individual neurons and synapses. However, one may also think of relations between such neurobiological levels of description and their mental correlates at cognitive or psychological levels of description. An interesting candidate for interlevel relations of the latter kind will be presented in this contribution.

We will start with a brief introduction of the idea of contextual emergence and compare it with other kinds of interlevel relations in section 2. Subsequently, in section 3, we recapitulate some details regarding the contextual emergence of temperature (and related thermodynamical properties) from a description in terms of statistical physics. The particularly important role of stability conditions as guiding principles for contextual emergence will be emphasized in section 4. Eventually, section 5 presents an example for the contextual emergence of cognitive features from their underlying neurobiological description: the emergence of compatible psychological descriptions that are consistent with the associated neural description. Section 6 summarizes the basic arguments and results.

2 Reduction and Emergence

Reduction and emergence are used in a variety of senses in the literature. In general terms, both concepts express ways to achieve a better understanding of some feature of a system in terms of other features which are assumed to provide such understanding. For the sake of simplicity, reduction and emergence schemes are typically organized in a hierarchical manner, such that levels of description or levels of reality are related to each other. As mentioned above, an analysis in terms of hierarchical levels often oversimplifies the picture. In general, non-hierarchical frameworks including other notions such as those of domains of description or domains of reality might be more appropriate.

As indicated by the distinction between levels of description and levels of reality, there is a difference between epistemological and ontological frameworks for reduction and emergence. Broadly speaking, descriptive terms are subjects of epistemological discourse while elements of reality are subjects of ontological discourse. Both types of discourse are used in reductionist and emergentist approaches. The concept of reference establishes a connection between descriptive terms and described elements of reality (leaving aside difficult questions about reference itself).

The distinction between epistemological discourse and ontological discourse is not sufficient to exhaust the different ways in which the notions of reduction and emergence are used. In addition, it is also important to distinguish between different types of features which are to be related to others. There are three main categories of relations: theories/laws to other theories/laws, properties to other properties, and wholes to parts. Clearly, relations between theories/laws are predominantly epistemological. The relation between wholes and parts, on the other hand, is primarily discussed ontologically insofar as it refers to elements of reality rather than their description. In the literature on property relations, both epistemological and ontological frameworks can be found. Property relations are sometimes meant ontologically (i.e., regarding properties of elements of reality) and sometimes epistemologically (i.e., regarding descriptive terms referring to properties of elements of reality).

An ontological framework of discussion is usually employed in reductive approaches, where ontic elements are restricted to a fundamental level of description, at which those properties reside to which other properties are regarded reducible and from which other properties are regarded to be exhaustively determined. An alternative idea of a "tiered" ontology, ascribing ontic elements to all levels of description, was proposed originally by Hartmann (1935). Quine (1969) has revitalized this idea with his notion of an ontological relativity. It was adopted by Putnam (1987) when he suggested the idea of internal realism, later denoted pragmatic realism. These philosophical frameworks of thinking were for the first time fleshed out by Atmanspacher and Kronz (1999) from a scientific perspective. The key to this option is the distinction between ontic and epistemic descriptions of the behavior of physical systems, in particular quantum systems, which goes back to Scheibe (1973) and Primas (1990).[2]

Analogous to Quine's ontological relativity, this allows us to conceive ontic elements at each level of description. In addition to Quine's notion, however, it allows us to propose formal techniques with which appropriate interlevel relations (sometimes referred to as "bridge laws") can be designed in detail. In a nutshell, an ontic description at one level serves as the basis for an epistemic description at a higher level, where it can be "ontologized" and then provides the basis for proceeding to another epistemic description at yet another level. (For details see Atmanspacher and Kronz 1999.)

If one wants to have the option of ontic elements at each level of description rather than only at one or a few fundamental levels, a straightforward and strictly reductive scheme for interlevel relations becomes impossible and must be relaxed. The way in which ontic and epistemic descriptions are related to each other motivates contextual emergence as a viable alternative.

In order to clearly distinguish between different concepts of reduction and emergence, it is desirable to have a transparent classification scheme, so that the basic characteristics of these concepts can be discussed coherently. A useful approach toward such a classification is based on the role which contingent contexts play in reduction and emergence. More precisely, the way in which necessary and sufficient conditions are assumed in the relation between different levels of description can be used to distinguish four classes of relations:

(1) The description of features of a system at a particular level of description offers *both necessary and sufficient* conditions to rigorously derive the description of features at a higher level. This is the strictest possible form of *reduction*. It was most popular under the influence of positivist thinking in the mid-20th century.

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[2] A comprehensive recent account, which also addresses the notions of ontological versus ontic and epistemological versus epistemic, can be found in Atmanspacher and Primas (2003).

(2) The description of features of a system at a particular level of description offers *necessary but not sufficient* conditions to derive the description of features at a higher level. This version is called *contextual emergence*, because contingent contextual conditions are required in addition to the lower-level description for a rigorous derivation of higher-level features.

(3) The description of features of a system at a particular level of description offers *sufficient but not necessary* conditions to derive the description of features at a higher level. This version includes the idea that a lower-level description offers multiple realizations of a particular feature at a higher level, which is characteristic of *supervenience*.

(4) The description of features of a system at a particular level of description offers *neither necessary nor sufficient* conditions to derive the description of features at a higher level. This represents a form of *radical emergence* insofar as there are no relevant conditions connecting the two levels whatsoever.

For obvious reasons, class (4) is unattractive if one is interested in explanatory relations between different levels of description. Property dualism à la Davidson (1980) would be an example of radical emergence. By contrast, class (1) is extremely appealing if one is interested in simple explanations. The "received views" of reduction – as Batterman (2002) refers to them – fall into this class (e.g., Nagel 1961, Schaffner 1976). They share particular features with variants of type physicalism.

From a contemporary point of view, classes (2) and (3) are viable alternative schemes for analyzing relationships between different levels of description. Class (3) includes token physicalism, and some kinds of functionalism, together with supervenience relations[3] as extensively discussed on the basis of Kim's proposals (Kim 1993). Interestingly, Kim himself has recently argued that supervenience may be inadequate for capturing relations in the sciences (Kim 1998, 1999). This development has led to an emphasis on realization relations (e.g., Kim 1998, 1999, Crook and Gillett 2001, Gillett 2002), such as the multiple realizability of higher-level states by lower-level states. For instance, Chalmers (2000) defines neural correlates of consciousness as neural systems that may realize conscious mental states in multiple ways and are minimally sufficient for the occurence of those states.

In the remainder of this contribution we will focus our discussion on class (2), contextual emergence, which is less rigid than the strong form of reduction (1) on the one hand and provides more structure for interlevel relations than radical emergence (4) on the other. It should be mentioned that contextual emergence (2) has much in common with a notion of reduction which is different from its standard philosophical meaning and has been distinguished as a "physicist account" of reduction (Nickles

[3]Some versions of supervenience require that changes in lower-level descriptions are both necessary and sufficient to bring about changes in a higher-level description. Such versions are indistinguishable from reduction (Kim 1998) and fall into class (1).

1973, Batterman 2002, pp. 17-19). In addition, particular aspects of contextual emergence resemble aspects of emergent interactionism (Sperry 1969, Stephan 1999, Chap. 16), but there are also crucial differences between the two.

3 Thermodynamic Equilibrium and Temperature

This section describes a physical example of contextual emergence that is detailed enough to see how contexts can be introduced leading to emergent properties via the construction of contextual topologies. It will be shown how necessary conditions for the emergence of novel properties are related to lower-level descriptions, whereas contingent contexts, not available at the lower-level description, serve as sufficient conditions leading to well-defined properties at higher-order levels of description.[4]

Our much discussed example is the reduction or emergence, respectively, of thermodynamic properties such as temperature to or from properties at lower-level descriptions. The lower-level descriptions in this case are statistical mechanics and point mechanics. How are these levels of description related to thermodynamics?

To start with the less controversial issue, the step from point mechanics to statistical mechanics is essentially based on the formation of an ensemble distribution. Particular properties of a many-particle system are defined in terms of a statistical ensemble description (e.g., as moments of a many-particle distribution function) which refers to the state of an ensemble rather than the states of single particles in an individual description.

An example is the mean kinetic energy of a system of N particles, which can be calculated from the distribution of the momenta of all particles. The expectation value of kinetic energy is defined as the limit $N \to \infty$ of its mean value, assuming the applicability of limit theorems such as the law of large numbers. Although a *mean value* can in principle be calculated even for a small number of particles, it is illegitimate to assign an *expectation value* to a system if its number of particles is too small. An expectation value of a property whose definition is based on a statistical ensemble description presupposes (infinitely) many degrees of freedom.

The more controversial issue in discussing the reduction or emergence of temperature refers to the step from statistical mechanics to thermodynamics (cf. the discussion by Compagner 1989), e.g. from the expectation value of a momentum distribution of a particle ensemble to the temperature of the system as a whole. In many philosophical discussions it is argued that the thermodynamic temperature of a gas *is* the mean kinetic energy of the molecules which constitute the gas. According to Nagel, this leads to a straightforward reduction of thermodynamic temperature to statistical mechanics (Nagel 1961, p. 341-345).

Such a rough picture, however, is a gross mischaracterization, based on a too generous treatment of some important details. First of all, as mentioned above, thermodynamic properties typically require the so-called thermodynamic limit $N \to \infty$ for their definition, as their quantification is related to an expectation value of

[4] See Primas (1998) for more details and for a bunch of illustrative examples.

a statistical ensemble distribution. Second, thermodynamic descriptions presume thermodynamic, or briefly thermal, equilibrium as a crucial assumption which – as will be shown next – is neither formally nor conceptually available at the level of statistical mechanics. Third, the very concept of temperature is *basically* foreign to statistical mechanics and is usually introduced phenomenologically.[5]

Thermal equilibrium is formulated by the zeroth law of thermodynamics: If two systems are both in thermal equilibrium with a third system, then they are said to be in thermal equilibrium with each other. (In this sense, the definition of temperature is relational; this does not contradict the fact that the temperature scale has an absolute zero point.) Based on this equivalence relation, the phenomenological concept of temperature can be introduced in the usual textbook way. Since thermal equilibrium is not defined at the level of statistical mechanics, temperature is not a mechanical property but, rather, emerges as a novel property at the level of thermodynamics.

Popular statements to the effect that temperature corresponds to mean molecular motion are, thus, only correct under the important condition of thermal equilibrium and in the thermodynamic limit. Without these two essential presuppositions, they are meaningless. The standard notion of temperature (and of other thermodynamical observables such as entropy) is undefined far from thermal equilibrium and for single particles.

The concept of thermal equilibrium can be recast in terms of a class of distinguished statistical states, the so-called Kubo-Martin-Schwinger (KMS) states. These states are defined by the KMS condition[6] which characterizes the (structural) stability of a KMS state against local perturbations. Hence, the KMS condition essentially implements the zeroth law of thermodynamics as a *stability criterion* at the level of statistical mechanics. The second law of thermodynamics expresses this stability in terms of a maximization of entropy for thermal equilibrium states. (Equivalently, the free energy of the system is minimal in thermal equilibrium.)

In an algebraic framework (which we cannot explain in detail here), KMS states can be used as reference states for a so-called Gel'fand-Naimark-Segal (GNS) construction. Such reference states induce a new, contextual topology in the state space of statistical mechanics, which is coarser than the original topology, and its associated algebra of observables (i.e. a set of observables obeying some basic algebraic relations). With respect to this new topology, the GNS-construction then gives rise to a new algebra of observables including thermodynamic temperature as a novel property of the system. In this spirit, Takesaki (1970) has shown that temperature emerges as a classical observable from an underlying quantum statistical description.

Because mechanical descriptions are given by a type of algebra different from the contextual algebra of thermodynamic observables, temperature cannot be an ele-

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[5]Similarly, phenomena accounted for in geometrical optics (such as light rays or shadows) or in electric network theory (such as inductances, capacitances, resistances) are *basically* foreign to Maxwell's electrodynamics and require considering short- and long-wavelength limits, respectively.

[6]For more details concerning the significance of the KMS condition see Sewell (2002, chap. 5).

ment of a mechanical description (Primas 1998). Hence, temperature is not reducible to statistical mechanics in any straightforward sense. Thermodynamic temperature is an example of a contextually emergent property, which is neither contained in nor predicted by the lower-level mechanical description alone. However, given the lower-level mechanical description and an appropriate contextual topology based on the KMS state, thermodynamic properties can be rigorously derived. The contextual topology is implied by contingent contexts given in the higher-level thermodynamic description where the notions of thermal equilibrium and thermodynamic limit are applicable.

4 Stability as a Guiding Principle for Contextual Emergence

After the detailed discussion of thermodynamic properties as examples for contextual emergence, it is worthwhile to step back and look at its general principles. Repeating the characterization of contextual emergence as given in section 2, the description of features of a system at a particular level of description offers *necessary but not sufficient* conditions to derive features at a higher level of description. In logical terms, the necessity of conditions at the lower level of description means that higher-level features *imply* those of the lower level of description. The converse – that lower-level features also *imply* the features at the higher level of description – does not hold in contextual emergence. This is due to the absence of sufficient conditions at the lower level of description. Contingent contexts for the transition from the lower to the higher level of description are required in order to provide such sufficient conditions.

In the example of temperature, the notion of thermal equilibrium represents such a context. Thermal equilibrium is not available at the level of description of Newtonian or statistical mechanics. Implementing thermal equilibrium in terms of the KMS condition and considering the limit $N \to \infty$ at the level of statistical mechanics, temperature can be obtained as an emergent property at the level of a thermodynamical description. It is of paramount importance for this procedure that KMS states satisfy a *stability condition* that is imported from the level of thermodynamics onto the level of statistical mechanics.

Since the Newtonian and statistical mechanical levels of description are necessary to derive the higher-level property of temperature, principles or laws at these levels of description cannot be violated by any higher-level description incorporating temperature. That the Newtonian and statistical mechanical levels of description alone are not sufficient is formally recognized by the fact that they do not give rise to an algebra of observables including temperature unless additional contingent conditions are implemented.

The significance of contextual emergence as opposed to strict reduction in this example is clear. Of course, it would be interesting to extend the general construction scheme for emergent properties to other cases. More physical examples are indicated and discussed, for example, in Primas (1998) and Batterman (2002). We propose the concept of stability, in the sense of stability against perturbations or fluctuations, as a key principle for the construction of a contextual topology and an associated algebra of contextual observables in examples even beyond physics.

One possible, and ambitious, case refers to emergent features in the framework of cognitive neuroscience. A particularly active field of research here is concerned with the emergence of new features at the level of neuronal assemblies from lower-level features of individual neurons. Particular interest in this issue derives from the fact that cognitive capabilities are usually correlated with the activity of neuronal assemblies, but detailed neurobiological knowledge refers mainly to the properties of individual neurons. Closing the gap in our understanding of the relation between neuronal assemblies and individual neurons could contribute significantly to understanding neurobiological correlates of consciousness.

As a possible framework for research in this area, the scheme of contextual emergence might be fruitfully applied as follows. Novel features at the (higher) level of neuronal assemblies would have necessary but not sufficient conditions at the (lower) level of neurons. In order to identify contexts providing such sufficient conditions, those among the many possible assembly features which are relevant or interesting as emergent features must first be identified. Assuming that stability criteria play a role analogous to physical examples, techniques of nonlinear dynamics for modeling assemblies in terms of attractors with particular stability properties and corresponding relaxation times or escape times suggest themselves. This can be implemented easily for powerful modeling tools such as neural networks (Anderson and Rosenfeld 1989) or coupled map lattices (Kaneko and Tsuda 2000).

Contextual emergence might even be a viable scheme to address relations between the neurobiology of the brain at various levels on the one hand and cognitive or psychological features – in other words: to address the relation between material (brain) and mental (consciousness) features. In the following section we indicate a concrete scenario which was recently elaborated in detail by Atmanspacher and beim Graben (2006).

5 Contextual Emergence of Compatible Psychological Descriptions

It is an old and much discussed question to which degree psychology could become a unified science, integrating the many approaches and models that constitute its contemporary situation. It is sometimes argued that the largely fragmented appearance of psychology (and cognitive science as well) is due to the fact that psychology is still in a preparadigmatic, “immature” state. Some have even argued that this situation is unavoidable (e.g., Koch 1993, Gardner 1992) and should be considered as the strength of psychology (e.g., Viney 1989, McNally 1992) rather than an undesirable affair.

From the perspective of the philosophy of mind, arguments against the possibility of a unified science of psychology have been presented as well. Most prominent are the accounts of Kim (1992) and Fodor (1997), both using the scheme of multiple realization in the framework of supervenience to reject unification. Shapiro (2006) has recently pointed out particular weak points in their arguments.

On the other hand, there is a growing interest in articulating visions for a unified science of psychology, and of cognitive science as well (see, e.g., Newell 1990, Anderson 1996). Recently, various approaches have been proposed to reach a degree of coherence comparable to established sciences as, e.g., physics with well-defined relations between its different disciplines. Examples are the "information processing" paradigm (Lachmann et al. 1979, Dawson 1998), "psychological behaviorism" (Staats 1996, 1999), "unified psychology" (Sternberg and Grigorenko 2001, Sternberg *et al.* 2001), and the "tree of knowledge" system (Henriques 2003). Similar visions are currently being explored for a unified science of consciousness. A key feature in the latter program is the *commensurability*, i.e. comparability, of competing approaches in psychology, explicated by Yanchar and Slife (1997) and Slife (2000).

This section presents a way in which the notion of commensurable models can be implemented formally. A suitable way to formulate commensurability in technical terms is given by the concept of *compatibility*. Briefly speaking, two models are considered as commensurable if they are compatible in the sense that there exist well-defined mappings between their key terms. If this is not the case, they are incompatible.[7] It turns out that the scheme of contextual emergence provides some detailed and clarifying insights on how to proceed in this regard. The two levels of description whose interlevel relations are significant for this purpose are those of neurobiology and psychology, or of neurobiology and cognitive science, respectively. Compatible and incompatible implementations of symbolic representations of cognitive states, briefly cognitive symbol systems, have recently been discussed by beim Graben (2004).

As mentioned above, a basic way in which systems at any level are described starts with the specification of their states, their observables, and their dynamics. An appropriate representation of these basic elements is usually given in terms of a state space. The state of a system at a given time is represented by a more or less refined subset of that space, the values of its associated observables are the projections of that subset onto the state space coordinates, and the dynamics is represented by the motion of the state as parametrized by time.

Let us assume a neurobiological state space X with fairly fine-grained states x, ideally represented pointwise in X, and with observables X_i, $i = 1, ..., n$, for n degrees of freedom. Typical examples for neurobiological observables are electroencephalogram (EEG) potentials at the macroscopic level, local field potentials at the mesoscopic level, or spike trains of neurons at the microscopic level of the brain. These observables are usually obtained with much higher resolution than observ-

[7]Note that this notion of incompatibility is more subtle than a "logical incompatibility" (Slife 2000) in the sense that two models are simply negations of each other. In particular, our framework includes complementary models as maximally incompatible models. See further discussion below.

ables at a psychological level of description. We assume that the dynamics can be considered as (quasi-) continuous as a function of time.

The construction of a mental (i.e., psychological or cognitive) state space Y from X can be based on some coarse-graining of X, reflecting that a mental state is multiply realized by a variety of neural states. That is, the state space X must be partitioned such that cells of finite volume in X emerge, which can be used to represent mental states in Y. Often, such discrete states are denoted by alphabetic symbols $A, B, C, ...$, where each symbol represents an equivalence class of neurobiological states. In contrast to the dynamics of states x in a continuous state space X, the symbolic dynamics (Lind and Marcus 1995) in Y is a discrete sequence of symbols as a function of time.

A coarse-grained partition on X implies neighborhood relations between states in Y that are different from those in the original space X; in this sense it implies a change in topology. (For instance, neural states that are distant in X can belong to the same mental state in Y, and neural states that are nearby in X can belong to different mental states in Y.) Also, the definition of observables Y_i for Y leads to an algebra of mental observables that is different from that of neurobiological observables. Obviously, these two differences depend essentially on the choice of the partition of X. We will now show that a particular concept of stability is crucial for a "proper" choice of such a partition and, thus, crucial for a "proper" mapping from X to Y.

First of all, it should be required that a proper partition leads to mental states in Y that are empirically plausible. For instance, a plausible formation of basic equivalence classes of neurobiological states is due to the distinction between wakefulness and sleep – two evidently different psychological states.[8] However, an important second demand is that these equivalence classes be stable under the dynamics in X. If this cannot be guaranteed, the boundaries between cells in Y become blurred as time proceeds, thus rendering the concept of a mental state suboptimally defined. Although concepts or categories in psychology are typically fuzzy rather than sharp (cf., e.g., Smith and Medin 1981), they can be less well defined than possible, even if one takes an unavoidable extent of fuzziness for granted.

In a recent contribution, Atmanspacher and beim Graben (2006) have shown in detail that a particular type of partition is needed for a proper definition of stable symbols in Y based on cells in X. These partitions are called generating partitions. They exist for chaotic systems and provide the supremum of the dynamical entropy of such systems (over all possible partitions), the so-called Kolmogorov-Sinai entropy (see Atmanspacher (1997) for an annotated introduction).[9] This is equivalent

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[8]A recent empirically based study concerning the relation between neurobiological and mental state space representations for wakefulness versus sleep and other, subtler examples (selective attention, intrinsic perceptual selection) is due to Fell (2004). For alternative state space approaches see Wackermann (1999) and Hobson *et al.* (2000).

[9]Markov partitions, a special case of generating partitions, create a Markov process for the symbolic dynamics in Y. Evidence for chaotic brain processes has often been reported (cf. Kaneko and Tsuda 2000, and references therein).

with the minimization of correlations between their cells as caused by the chaotic dynamics in X (cf. Cornfeld et al. 1982). This in turn minimizes the fuzziness of symbolic states in Y, thus providing a stable definition of such states, whose dynamics is then a faithful representations of the underlying neurodynamics. However, generating partitions are notoriously difficult to construct, and they are explicitly known for only a few examples.

It should be noted that it is possible to specify some "optimal" partition in X even in case of multiple attractors at the neural level. If there are many attractors coexisting, such a partition can be approximately determined by the boundaries between the coexisting basins of attraction. Froyland (2005) and Gaveau and Schulman (2005) have recently proposed procedures how to achieve this in case of multiple fixed points.

Insofar as generating partitions are in principle defined by the dynamics in X, they reflect the behavior of the system at the corresponding (lower) level of description. The reason for using them for the construction of states in Y is basically that these states are multiply realized in X, so that an equivalence class of states in X must be formed in order to define a state in Y. The generating partition is a tool to do this in a proper way. The contingent contexts at the level of Y, which are mandatory for contextual emergence, are for instance given by the choice of a "phenomenal family" (Chalmers 2000) to which the states of interest in Y belong. The fact that contextual emergence does not work without specifying these higher-level contexts prompts us to question the impulse, exhibited by many neuroscientists, of reducing mental states to "nothing but" the activity of neural states.

A key result of the work by beim Graben and Atmanspacher (2006) is that a non-generating partition is incompatible with any other partition (even if this is generating) in the sense that there is no well-defined mapping between the partitions. As a consequence, models based on such partitions are incompatible as well. Since any *ad hoc* chosen partition is quite unlikely to be generating, it may be suspected that the resulting incompatibility of models based on such partitions is the rule rather than the exception. While incompatibility may admit the possibility of "partially coherent" models, the case of maximal incompatibility, also called complementarity, excludes any coherence between different models completely.

This represents a significant limit to the vision of a unified or integrative science of psychology. Or, turned positively, such a unification will be strongly facilitated if the approaches to be unified are based on compatible, i.e. generating, partitions providing dynamically stable, well-defined mental states. As mentioned, it is a tedious task to identify such generating partitions. Nevertheless, the necessary formal and numerical tools are available today.

If there is a good deal of empirical plausibility for a particular partition, one might hope that this implies that such a partition is generating (at least in an approximate sense) and, thus, that the corresponding mental states are stable. However, there may be cases of conflict between the empirical and the theoretical constraint on a proper partition. In such cases, one has to face the possibility that the "empirical plausibility" of mental states may be unjustified, e.g. based on questionable prejudices. If mental states turn out to be dynamically unstable, the theoretical argument against their adequacy is very strong indeed.

Compatible partitions and, consequently, compatible psychological models show another important feature that is occasionally addressed in current literature: the topological equivalence of representations in neurobiological and mental state spaces (cf. Metzinger 2003, p. 619, and Fell (2004) for empirically based examples). Topological equivalence ensures that the mapping between X and Y is faithful in the sense that the two state space representations yield equivalent information about the system. Non-generating, incompatible partitions do not provide representations in Y that are topologically equivalent with the underlying representation in X.

As a consequence, compatible psychological (or cognitive) models that are topologically equivalent with their neurobiological basis emerge if they are constructed from generating partitions. The relevant context for this construction at the psychological level is given by the requirement of stable mental states, related to the dynamical stability of generating partitions. Without this sufficient condition for compatibility and topological equivalence, the neurobiological level of description provides only necessary conditions for psychological descriptions which will generally be incompatible.

In supervenience, the notion of sufficiency takes into account that different neural states can be correlated with the same mental state (multiple realization). Our notion of contextual emergence addresses the different question of how it can be understood that neural states are correlates of mental states. Contextual emergence tries to elucidate principles which allow us to understand the relationship between mental and neural states, even in individual instantiations, in a more profound manner. In this way, supervenience and contextual emergence complement rather than contradict each other. Applying both concepts together may, thus, provide novel insight into the nature of mind-brain relations.

6 Summary

The goal of reduction is to derive the description of higher-level features e.g., properties, of a system exhaustively in terms of the description of features at a lower level. The implicit assumption in this program is that the description of all features which are not included at the lower level can be constructed or derived from this level without additional input. However, many physical examples pose serious difficulties for this program. For instance, temperature is a novel property emerging from a lower-level statistical mechanical description, but it is not derivable from this lower-level description alone.

The concept of contextual emergence addresses such situations properly. Contextual emergence is characterized by the fact that a lower-level description provides necessary, but not sufficient conditions for higher-level descriptions. The presence of necessary conditions indicates that the lower-level description provides a basis for higher-level descriptions, while the absence of sufficient conditions means that higher-level features are neither logical consequences of the lower-level description nor can they be rigorously derived from the lower-level description alone. Hence, the notion of strong reduction is inapplicable in these cases.

Sufficient conditions for a rigorous derivation of higher-level features can be introduced through specifying contexts reflecting the particular kinds of contingency in a given situation. These contexts can be implemented as a stability criterion in the lower-level description and induce a change in the topology of the corresponding state space (e.g., due to coarse-graining). There is, then, a mathematically well-defined procedure for deriving higher-level features given the lower-level description plus the contingent contextual conditions.

Contextual emergence and the associated identification of appropriate stability conditions may have applications in other domains such as biology and psychology, and, ultimately, for the relationship between the physical and the mental. A concrete example for contextual emergence in cognitive neuroscience demonstrate its viability in this regard. Note that the scheme of contextual emergence is here understood as complementing (rather than opposing) adequate supervenience relations.

Compatible descriptions at the psychological level, which are topologically equivalent, i.e. consistent, with the underlying neurobiological description, emerge only if the mental states defined at the psychological level are dynamically stable. If the neural dynamics is sufficiently complex, e.g. chaotic, this requires that the partition providing these states be generating. Generating partitions are defined by the dynamics of the neural states and give rise to particular, dynamically stable equivalence classes of neural states that can be re-defined symbolically as mental states. A unified science of psychology, with mutually compatible domains of description, becomes problematic if those descriptions are not based on generating partitions.

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