

3. MICRO-EXPLANATION¹

In my mother's opinion a husband deserved unquestionable loyalty, and unreserved, full-hearted love. But there was a difficulty: Amina, her mind clogged up with Nadir Khan and insomnia, found she couldn't naturally provide Ahmed Sinai with these things. And so, bringing her gift of assiduity to bear, she began to train herself to love him. To do this she divided him, mentally, into every single one of his component parts, physical as well as behavioural, compartmentalizing him into lips and verbal tics and prejudices and the likes ... she resolved to fall in love with her husband bit by bit.

Salman Rushdie *Midnight's Children*

Micro-explanation is the explanation of the behaviour of macro-systems in terms of the behaviour of their micro-constituents. As elaborated in chapter

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1 its success is taken by microphysicalists to provide an argument for micro-determination, micro-government and micro-causation. In the first part of the present chapter I will distinguish various kinds of micro-explanation – in particular those that pertain to the part-whole-relation from those that concern the relation of two properties of the same system. Given that micro-explanation is taken to support (micro-)physicalism it is important to disentangle these forms of explanation. Whereas micro-explanation concerning the part-whole-relation ought to be taken to provide evidence for micro-physicalism, micro-explanation that relates two properties of the same system may be taken to lend support to identity-physicalism. Running together different forms of micro-explanation seems to be one of the reasons for the failure to distinguish microphysicalism and identity-physicalism.

In the second part of the chapter I will investigate to what extent micro-physicalists can be vindicated in their belief that every physical system's behaviour can be micro-explained.

3.1. Distinctions

The behaviour of a physical system can be split up into the *state* of the system, its *constants* and the *law* that pertains to it (e.g. Hughes 1989: 57/8).

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The quantities of a physical system are either constant or they may vary with time. If we take the example of a single classical particle we can distinguish the constants – in this case the mass – and the changing quantities such as position or momentum. The values of the varying quantities at a particular time are called the *state* of the physical system at this time. The constants and the state of a system do not determine the complete system's behaviour. There are furthermore the laws that describe the connections between the various quantities involved and they describe how the state of the system develops in time.

The explanation of the behaviour of a macro-system in terms of the behaviour of the micro-systems may concern the state of a compound system or its behaviour insofar as a law can describe it. Thus, we may be interested to get to know whether the *state* of a compound system can be explained in terms of the *states* of its constituents. Another question concerns the *laws* involved. Is it possible to explain the *law* that describes the behaviour of a compound system in terms of the *laws* that describe the constituent systems?² The distinction between the micro-explanation of states and micro-explanation of laws is the first distinction to consider.

A second distinction concerns the difference between the explanation of a macro-property³ in terms of what is sometimes called a micro-based prop-

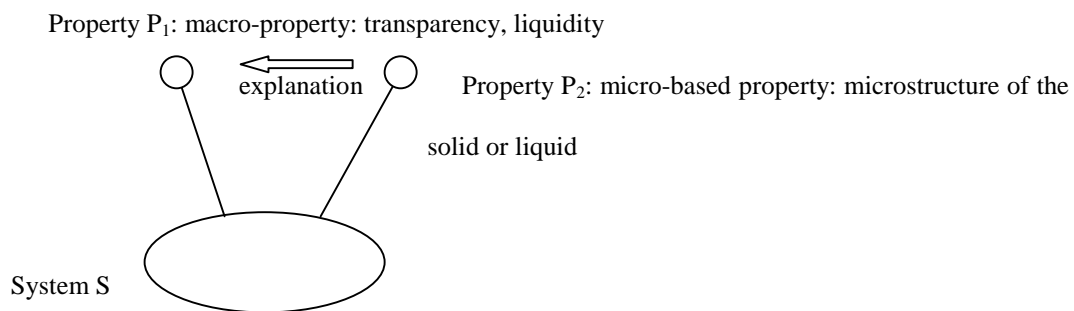
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erty on the one hand, and the explanation of the property of a compound system in terms of the behaviour of its constituents on the other.⁴ The explanation of a macro-property or the macro-behaviour of a system in terms of a micro-based property or the micro-based behaviour of the system concerns two properties or two kinds of behaviour of the same system. We might, for instance, be interested in the transparency of a particular solid or the liquidity of porridge. We might explain these properties by referring to the microstructure of the solid or the porridge. Similarly we might want to explain the fact that a sample of gas has a certain temperature in terms of its mean kinetic energy. In all of these cases the macro-behaviour is explained in terms of the micro-based behaviour. This kind of explanation concerns two properties or two kinds of behaviour of the same system. Often the respective properties are described in terms of different theories and are then said to be linked by bridge-laws. Thus, an ideal gas can be described both by thermodynamics and by statistical mechanics. Both theories attribute certain properties to an ideal gas and we might well ask how these properties that the different theories attribute to the gas are related to one another. Theories of mind and neuro-physiological theories both describe our pain-behaviour. We might ask how pain, a mental property, is related to the firing of C-fibres, a neurophysiological property.

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Micro-explanation in this sense, if successful, provides an explanation of why bridge-laws hold, why a system with a certain microstructure gives rise to a certain temperature or to the transparency of the sample. Successful micro-explanations in this sense explain why the firing of C-fibres gives rise to pain.

Figure 3.1:



Micro-explanations of the first kind concern the relation of Property P₁ and Property P₂, both of which are properties of the same system S.

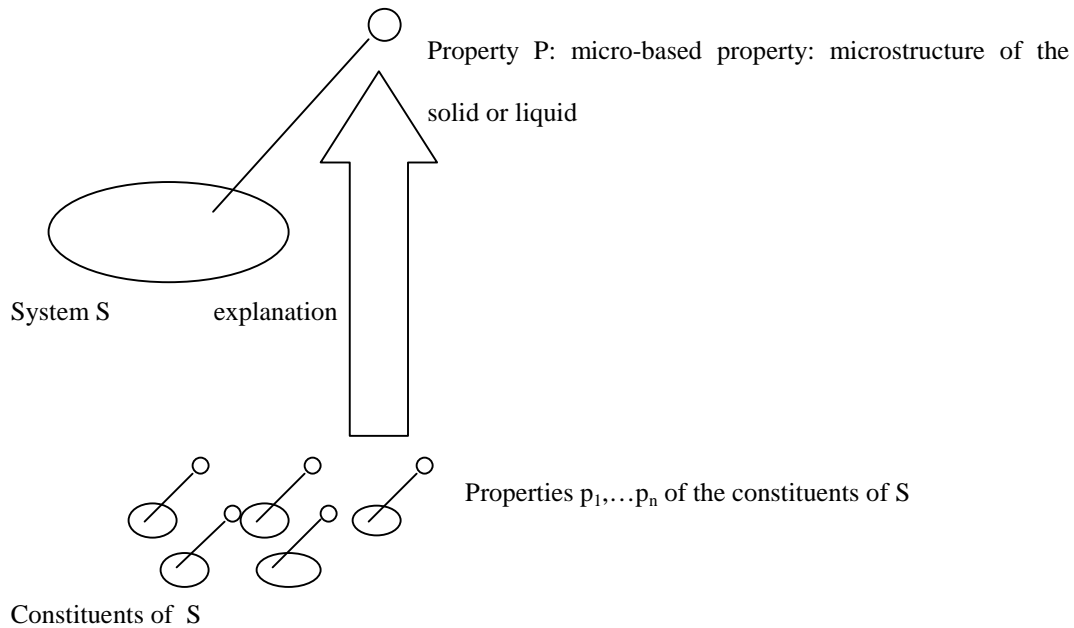
This kind of micro-explanation has to be distinguished from part whole explanations. Take the following example. Before the general theory of relativity compound physical systems were thought to have two distinct properties, gravitational mass and inertial mass. These were thought to be properties of one and the same system (though none of them can reasonably be thought of as a micro-based property if compared to the other). With respect to these properties we might be interested in how they are related (as be-

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fore), e.g. whether they co-vary. However, besides this question we might be interested in a further question. How is the gravitational mass of the compound system related to the gravitational mass of its constituents? There is a law that tells us and it is non-trivial due to energy-mass-conservation. This question does not concern the relation of two properties of the same system but rather the relation between a property of a compound and the properties of the constituents. Micro-explanation in this sense is the attempt to understand nature bit by bit. Similarly we might ask how the micro-based behaviour of the solid that gives rise to the solid being transparent does in turn depend on the properties of the constituents. The micro-based property is a property of the compound system somehow depending on the properties of the constituents. This, again, concerns the part whole relation and not the relation of two properties of the same system. Again, we might try to explain the firing of the C-fibres in terms of the behaviour of the constituents of the C-fibres. So there is, first, the question of how the mental and the neuro-physiological properties are related. Is it possible to explain the mental property in terms of the neuro-physiological property? Then there is, second, the question how the neuro-physiological property, the firing of the C-fibres, can be explained in terms of the constituents of the C-fibres. This latter question is a question about parts and wholes.

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Figure 3.2:



Part-whole-micro-explanations concerns the relation of the Properties p_1, \dots, p_n of the parts or constituents of system S to a property of the whole, i.e. a property of S.

The case of temperature and mean kinetic energy is a little different because the mean kinetic energy of, say, a sample of gas is *defined* to be the (weighted) sum of the kinetic energies of the molecules. Let us, for the sake of the argument, assume it were an empirical matter, as in the case of mass. Then, again, we have two questions that we ought to distinguish.

- a) Is it possible to explain why an ideal gas with a certain mean kinetic energy W_{kin} has a certain temperature T?

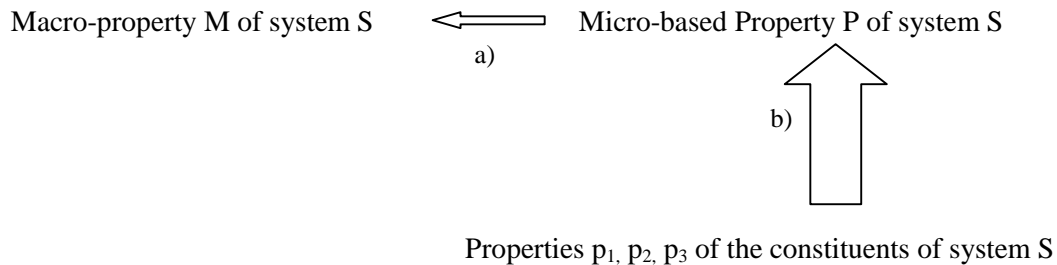
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- b) Is it possible to explain why an ideal gas has a certain mean kinetic energy W_{kin} on the basis of the behaviour of the molecules of the gas?

Question a) concerns two kinds of behaviour of the *same* system, namely of the ideal gas as a whole. It is the question why a system that has a certain kinetic energy at the same time also has a certain temperature. In other words, question a) asks for an explanation of a correspondence rule or a bridge law. Question b), on the other hand, concerns the relation between the behaviour of the components or parts of the ideal gas and the behaviour of the ideal gas as a whole. It concerns the question how the individual kinetic energies add up to the kinetic energy of the whole. The following figure illustrates the two different kinds of questions (and, correspondingly, the different kinds of explanation they ask for).

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Figure 3.3:



Question/explanation a) concerns two properties of the same system.

Question/explanation b) concerns relation between properties of components (p_1, p_2, p_3) of S and property P of S.

The arrows indicate the direction of explanation.

System S has property M (pain, temperature) as well as property P (C-fibre firing, mean kinetic energy). Question a) asks for an explanation of S's having M in terms of S's having P. Question b) asks for an explanation of S's having P (mean kinetic energy, C-fibre firing) in terms of the properties p_1, p_2, p_3 , etc. of the constituents of S (kinetic energies of the molecules of S, properties of the constituents of the C-fibres)

The distinction between these two kinds of questions and *a fortiori* between the ensuing two kinds of micro-explanation is of considerable importance for our project. The microphysicalists' claims, i.e., the theses of micro-determination, micro-government and micro-causation, crucially depend on

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whether the micro-macro-relation is read as concerning bridge-principles or the part whole relation. Interpreting the micro-macro-relation as a relation between properties of the same system gives rise to claims that are completely different if compared to an interpretation of the micro-macro-relation in terms of the part whole relation. According to the first reading micro-explanation might be taken to support identity-physicalism whereas the second reading is relevant for microphysicalism. Separating these claims will be the topic of chapter 4.

Returning to the distinctions I draw at the beginning of this section we can combine the two which yields altogether four kinds of micro-explanation. We have the explanation of the properties of one system in terms of other properties of the same system. Such an explanation may either concern the lawful behaviour of the system (first kind of micro-explanation) or the states of the system (second kind of micro-explanation). These two kinds of micro-explanation pertain to bridge-principles.

A further example will help to make the relation between these two kinds of micro-explanation more explicit. Consider a piece of iron. Iron shows a property called ferromagnetism, i.e. it is capable of remaining permanently magnetized. The macro-property of being magnetized can be explained in terms of the micro-structure of the piece of iron. More precisely, the laws

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that characterise the magnetisation of a piece of iron can be explained in terms of laws that pertain to a system of so-called Weiss-domains, each of which is magnetized in a certain direction.⁵ Changes with respect to magnetisation of the piece of iron, e.g. in the hysteresis loop, can be explained in terms of moving domain walls of the micro-structure of the iron. Both, the magnetisation and the structure of the Weiss-domains are properties of the piece of iron. This is the first kind of micro-explanation. Given such an explanation of the lawful behaviour of the magnetisation of the iron, it is furthermore possible to explain why a piece of iron shows a *determinate* magnetisation, an explanation of why it is in a particular *state* of magnetisation. The piece of iron is in a particular state of magnetisation because there is a determinate underlying state of the domain wall-structure. So in this case the state of a system is explained in terms of another state of the same system. This is the second kind of micro-explanation. Both, the first and the second kind of micro-explanation concern the relation of two properties of the same system.

Then we have part-whole micro-explanation. Again, it may either concern the explanation of the lawful behaviour of the compound system in terms of the lawful behaviour of the parts (third kind of micro-explanation) or the explanation of the states of a compound system in terms of the states of its constituents (fourth kind of micro-explanation). In the case of the piece of

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iron part-whole micro-explanation concerns the relation of the micro-structure of the piece of iron (Weiss domains and their walls) and the single iron-atoms. How is it that these atoms give rise to the structure of Weiss-domains? Idealized explanations of the microstructure of a piece of iron in terms of the behaviour of the subsystems typically rely on the so-called Ising model or the Heisenberg model. On the basis of these models, that take into consideration only certain kinds of interaction, one gains an explanation of the lawful behaviour of the compound in terms of the lawful behaviour of the parts (third kind of micro-explanation). Once such an explanation has been given it is furthermore possible to explain the determinate configuration of domain walls in terms of the determinate values for the interaction couplings between the constituents. Thus we have an explanation of the state of a compound system in terms of the states of its parts (fourth kind of micro-explanation). Both, the third and the fourth kind of micro-explanation concern the part-whole relation.

Altogether we have four kinds of micro-explanations:

| | Laws | States |
|---|------|--------|
| Explanation concerning two properties of the same system (bridge-principles) | 1 | 2 |
| Part-whole explanation | 3 | 4 |

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Of these four kinds I will focus on the two types of micro-explanation that attempt to explain laws, i.e. to micro-explanation(1) and micro-explanation(3). Micro-explanation(1) is tied to the explanation of bridge-laws and plays a significant role in contemporary discussions in particular in the philosophy of mind. Micro-explanation(3) is closely connected to C. D. Broads notions of mechanical explanation and emergence. It is central to the interpretation of the microphysicalists' concerns.

3.2. Micro-explanation(1) and the explanation of bridge-laws

Participants in philosophy of mind debates tend to be interested in the explanation of bridge-laws rather than in part whole explanations. In chapter 4 I will argue that this focus is seriously misleading. But let me shortly explain how interest in this question arose.

The notion of supervenience has played a significant role in much of the recent debates on the status of mental states. It was thought to provide us with a physicalistic conception of the mental that nevertheless allows for multiple realisation of mental properties. Supervenience was meant to capture the idea that one set of properties (the physical properties) of a system

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‘in some sense’ determines another set of properties of the same system (the mental properties). Suppose you are looking at the Mona Lisa and are musing about its aesthetic qualities. Let us furthermore assume that an exact replica, a picture that is molecule-for-molecule, indistinguishable from the original Mona Lisa, replaced the picture in front of you. Would this replica which is physically indiscernible from the original, be also indiscernible with respect to its aesthetic qualities? Could the pictures differ in aesthetic respect unless they differed in a physical respect? If the supervenience relation holds we ought to answer ‘yes’ with respect to the first question and ‘no’ with respect to the second. (For the sake of the argument it is assumed that aesthetic properties are intrinsic.)

This can be made more precise in various ways. Let us consider two disjoint sets of properties of one system, say, mental and physical properties. Jaegwon Kim, one of those philosophers who made this concept popular defines *strong* supervenience as follows:

Mental properties supervene on physical properties, in that necessarily, for any mental property M, if any thing has M at time t, there exists a physical base (or subvenient) property P at t, and necessarily anything that has P at a time has M at that time (Kim 1998: 9).

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According to supervenience certain properties of one and the same system are modally correlated. The first half of the definition allows for multiple realisation (it requires *a* physical base). The second half explicates the idea of *P determining M*. Supervenience as defined by Kim is not a relation between parts and wholes – despite the fact that the terminology that is sometimes used, such as ‘mereological supervenience’, suggests that the part whole relation is what is at issue here (Kim 1984b: 54).⁶ Recently Kim explicitly denounced the notion of ‘mereological supervenience’ as a loose way of speaking:

Suppose that we say that a certain property *P* of something *s* supervenes on microphysical properties or facts about *s*. What we mean to say is that the fact that *s* has *P*, or whether or not *s* has *P*, is fixed once the micro-constituents of *s* and the properties and relations characterizing these constituents are fixed. This means that the base property on which *P* supervenes is a micro-based property, the property of having such-and-such proper parts that have such-and-such properties and are configured by such-and-such relations. This is a micro-based property of *s*, not a property that belongs to any of its proper parts. In general, supervenient properties and their base properties are instantiated by the same objects [...] (Kim 1998: 85/86).

Thus, in the philosophy of mind debate supervenience is conceived of as a relation between properties or classes of properties such that if we say that

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one property supervenes on another, these properties are properties of one and the same system. It is usually not considered to be a relation between parts and wholes.

The enthusiasm for supervenience as an independent position in the philosophy of mind debate has clearly waned. It turned out that supervenience is compatible with various metaphysical positions concerning the mind-body relation and thus cannot be taken to explicate a physicalistic conception of the mental. The reason for this is that supervenience does not say anything about *why* the modal pattern holds. What is it that determines the supervenient property given the subvenient base? In the absence of an answer to this question supervenience - with respect to the mind body problem - is compatible with various metaphysical positions such as materialism (physicalism) or psychophysical parallelism. Both of these views imply a modal pattern of covariance in the sense of supervenience, but for different reasons. Whereas materialism holds that when M is instantiated by P, these properties are identical (if there are not any further realisations), psychophysical parallelism according to Leibniz holds that God has associated these properties in the appropriate way.

One way out of this uncomfortable situation was the introduction of a further requirement. What was asked for was no longer the bare supervenience

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relation but also an explanation of why it holds. This has been dubbed ‘superdupervenience’ (Horgan 1993). What is required over and above supervenience is an explanation of why this pattern obtains, i.e., of why a bridge-law holds, e.g., between temperature and mean kinetic energy of an ideal gas.

With respect to mental properties that supervene on physical properties Kim writes:

For it is the explanation of these bridge laws, an explanation of why there are just these mind-body correlations that is at the heart of the demand for an explanation of mentality (Kim 1998: 96).

Kim apparently assumes that explanation has ontological implications that are stronger than the holding of the supervenience relation.

He argues that mental properties can be explained in terms of micro-based properties of the *same* system, given that they can be shown to play the same causal role that the macro-properties play. The important point is that this explanatory project concerns the explanation of one property of a system in terms of another property of the *same* system. It does not concern the relation of the behaviour of the *parts* of a system to the behaviour of the *whole* system.

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Kim hopes that the explanatory requirement helps him to make explicit what it means that the conditions for a physicalistic account of the mental have been met. Whether superdupervenience does any better in this respect than mere supervenience will be discussed in section 3.7.

Let me now turn to the second kind of micro-explanation of laws.

3.3. Micro-explanation(3): C.D. Broad on the relation of parts and wholes

In the 1920s C. D. Broad has rigorously explored what he called mechanistic explanation. Since this notion captures the essence of what I take to be micro-explanation(3), i.e. the explanation of laws that pertain to compounds in terms of the laws of the constituents, I will present his account in some detail.

In the 1920s there was a lively debate concerning the question whether biological systems could be explained solely by reference to their physical constituents. Broad discusses three kinds of theories that try to explain the differences of the behaviour⁷ of living and non-living systems in terms of

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their components. Vitalism claims that there is a *particular* component - an entelechy - that is present in living bodies and nowhere else. It is this component that is responsible for the specific behaviour of living systems. Mechanism and emergentism deny that there is such a specific component in living systems. Both agree that the nature and arrangement of components that can be found elsewhere in nature determine the characteristic behaviour of a system. What they disagree about is whether the behaviour of the complex system can - in principle - 'be deduced from the most complete knowledge of the behaviour of the components, taken separately or in other combinations, and of their proportions and arrangements in this whole' (Broad 1925: 59). Emergentism claims that there are systems with respect to which such an explanation is impossible. Mechanism denies this.

What does it take to explain the behaviour of a complex system on the basis of the behaviour of its components? Such an explanation, according to Broad, has to rely on two independent kinds of information:

- (a) We need to know how the parts would behave separately. And (b) we need to know the law or laws according to which the behaviour of the separate parts is compounded when they are acting together in any proportion and arrangement (Broad 1925: 61).

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Broad is very explicit that information of the behaviour of the isolated components is in *no* case sufficient for determining the behaviour of the complex system.

It is clear that in *no* case could the behaviour of a whole composed of certain constituents be predicted *merely* from a knowledge of the properties of these constituents, taken separately, and of their properties and arrangements in the particular complex under consideration. Whenever this *seems* to be possible it is because we are using a suppressed premise which is so familiar that it has escaped our notice. The suppressed premise is the fact that we have examined other complexes in the past and have noted their behaviour; that we have found a general law connecting the behaviour of these wholes with that which their constituents would show in isolation; and that we are assuming that this law of composition will hold also of the particular complex whole at present under consideration (Broad 1925: 63).

As an example, he mentions the superposition of forces. To know how a force F_1 acts on a particle and to know how a force F_2 acts on the same particle is not sufficient to predict or explain how they will act together. The law of the composition of forces is an independent kind of information that one has to rely on.

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This is an important point because explications of emergence, that is, of the failure of micro-explanation, often neglect this fact. Teller, for example, takes ‘the naked emergentist intuition to be that an emergent property of a whole somehow ”transcends” the properties of the parts’ (Teller 1992: 139). What Broad points to is that properties of wholes *always* transcend the properties of the parts. If one were to take Teller’s intuition seriously this would imply that *every* complex system’s property is emergent.

According to Broad the relevant question is whether or not the kind of ‘transcending’ is *specific* to the kind of system under investigation. This is what distinguishes a mechanistic system and an emergent system. Broad discusses the notion of specificity or uniqueness of laws with respect to the case of silver chloride (He held the behaviour of silverchloride to be a candidate for emergence). For a law that connects the properties of silver chloride with those of silver and chlorine to be specific, Broad requires essentially⁸ that

[i]t is [...] a law which could have been discovered only by studying samples of silver-chloride itself, and which can be extended inductively only to other samples of the same substance (Broad 1925: 65).

And not - one should add - to other substances that contain silver or chlorine as components. This is the condition Broad makes use of, e.g. when he

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refers to clocks as mechanistic systems while relying on the fact that the laws required to explain them are instantiated in systems *other* than clocks. Thus a law is *specific* if its range of application is restricted to the kind of system under investigation.

Broad employs the terminology of wholes and components while explaining the differences between mechanism and emergentism (Broad 1925: 59 – 61). The difference between the two views is not that mechanism claims that in all cases the whole is equal to the sum of its parts whereas emergentism denies this. We can reformulate Broad's position and claim that there are various meanings of 'sum'. There are various possible ways of adding and composing parts to a whole.⁹ Both mechanists and emergentists agree that complex systems in general can be regarded as wholes that are equal to the sum of their parts or components. The relevant difference concerns the question whether or not the summing prescriptions or laws of composition are general or specific. Therefore, an emergentist in the sense of Broad is not a holist, if a holist is someone who defends the claim that the whole is more than the sum of its parts.

What Broad calls 'laws of composition' contains two kinds of information that he separated at other places. On the one hand, information on how sys-

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tems or components combine if there are no interactions present, and on the other hand, information on the effects these interactions will have on the combined systems (Broad 1925: 45).

On the basis of these remarks we are finally able to reconstruct what Broad had in mind when defining the concept of mechanistic and emergent systems. There are two conditions for mechanistic systems. Both mechanistic and emergent systems agree in that the components and their arrangement determine the behaviour of the complex system (the first condition). Mechanistic systems as opposed to emergent systems can be micro-explained (second condition). On the basis of Broad's remarks the notion of micro-explanation has to be spelt out as follows:

(Me) A compound system's behaviour is micro-explainable if it is - at least in principle - possible to deduce (to explain) the behaviour of the compound on the basis of

(i) general laws concerning the behaviour of the components considered in isolation

(ii) general laws of combination and

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(iii) general laws of interaction.¹⁰

Let me mention a few points that are either of importance for the following discussions or which link the present discussion to the previous chapter.

First, all the information that goes into micro-explanation in the Broad-sense is information about *laws*, not about states of physical systems.

Second, laws concerning isolated constituents are not sufficient to explain even the simplest kinds of compound systems. We always need a law of combination (with or without interaction). In this sense the behaviour of wholes always transcends that of the parts.

Third, micro-explanation refers to counterfactual situations. It relies on how the components would behave if they were isolated. They do not rely on how the parts that go into the whole behave while they are in the whole.

Fourth, in micro-explanation we consider the *subsystems'* behaviour in abstraction – as if they were isolated. But this is not the only abstraction involved. The compound system we are about to micro-explain is considered

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in abstraction as well, as though it were isolated. The behaviour is explained entirely in terms of the behaviour of the parts. That of course presupposes the absence of any external disturbing factors. By contrast, in causal explanation the external disturbing factor does all the explanatory work.

Fifth, even though Broad's conception of mechanistic explanation is obviously shaped classical mechanics the criterion he employs in order to distinguish emergent and non-emergent behaviour is independent of the particular laws and examples he considers. The relevant question is whether or not the laws employed are specific or general.

3.4. Micro-explanation(3) at work

In classical mechanics its path in six-dimensional phase-space specifies the complete behaviour of a one-particle system. The six dimensions are due to three spatial co-ordinates plus three co-ordinates for the momentum (or for velocity). A point in phase-space represents a state of such a system. Its time-evolution and thus its path in phase-space are determined by the Hamilton equations which in turn depend essentially on the classical Hamilton-function.¹¹ Given this structure as a background we may say that the lawful

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behaviour of the isolated particle can be described by a classical Hamilton-function of the form $H = \mathbf{p}^2/2m$, where \mathbf{p} is the momentum and m the mass of the particle in question. This is the law that determines the lawful behaviour of an isolated particle provided there are no forces present (See e.g. ter Haar 1971: chap. 5).

If we now turn to a non-interacting *two*-particle system we describe it by first specifying two six-dimensional phase-spaces, one for each of the particles and a classical Hamilton-function of the above form for each of them. That on its own is not yet a description of a two-particle system. It is a description of two separate one-particle systems. What we furthermore need is a law of composition.

Laws of composition and the part whole relation

Laws of composition tell us how the descriptions of the behaviour of subsystems have to be combined in order to gain descriptions of the lawful behaviour of the compound system. These laws are not at all trivial. In particular, classical mechanics and quantum mechanics have different laws of composition.

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According to the general law of composition in classical mechanics the phase space for the compound system is the Cartesian product of the phase spaces of the subsystems. In the case at hand the phase space for the two-particle system is the Cartesian product of the two six dimensional phase spaces, i.e. a twelve dimensional phase space.

Laws of composition specify the relation of parts and wholes. These parts need not be thought of as spatial parts of wholes. Rather, as will become particularly clear in the case of quantum mechanics, laws of composition describe how the contributions of degrees of freedom¹² add up to the behaviour of a compound system.

This general law of composition leaves room for more specific laws of composition for the physical magnitudes, depending on whether the latter are considered to be scalars, vectors or tensors. Mass and the Hamilton-function, for instance, are scalars. The law of composition for scalars – in the absence of effects of interactions – is the direct sum of the magnitudes for the subsystems. Thus the Hamilton-function for the compound system is the direct sum of the Hamilton-functions for the isolated particles. In our case the lawful behaviour of the system of two non-interacting particles in classical mechanics is described by a Hamilton-function of the form: $H = \mathbf{p}_1^2/2m_1 + \mathbf{p}_2^2/2m_2$. The laws of composition for vectorial or tensorial mag-

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nitudes are more complicated. However, I do not have to present the details of these laws. The essential point is that the general law of composition (cartesian product of phase spaces) leaves room for more specific composition laws.

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Up to this point I have described how to construct a description for a compound system given those for the subsystems. In a micro-explanation the procedure is exactly the reverse of this synthetic method. We start with the description of a compound system and we analyse it into contributions of subsystems: In a first step the complex physical system is split up conceptually into subsystems. In a second step these subsystems are treated as if they were isolated; their lawful behaviour in isolation is determined. Finally the contributions of the subsystems are added up so as to determine the behaviour of the complex system. It is taken for granted that the contributions add up to the behaviour of the compound. The laws of composition, however, according to which these contributions are added up are hardly ever made explicit.

Let me now draw attention to some of the features of micro-explanation mentioned at the end of the last section. First, the explanation relies on how

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each of the particles would behave if it were isolated. Asking for the *contribution* of a subsystem is tantamount to determining the behaviour of the isolated subsystem and then adding it to the other subsystems according to the laws of composition. Second, the behaviour of the compound transcends that of the parts, even in a case as simple as this. The description of the particles by themselves is not sufficient for the description of the compound system. More is needed: A law of composition. It was already Broad who pointed out that the behaviour of two subsystems is not equivalent to the behaviour of the compound. Third, micro-explanation in the Broad-sense concerns *lawful* behaviour. Nothing has been said about the *state* the compound system is in. Neither the state the compound system is in nor the states the parts are in play a role in micro-explanation in the sense of Broad.¹³

In the presence of interactions we have to introduce a further term into the Hamiltonian, e.g., a term for gravitational interaction such as $-Gm_1m_2/r$, where G is the gravitational constant and r the distance between the two particles. In such a case there are two options of describing what an explanation in terms of the behaviour of the subsystems might mean. According to the first option the relevant subsystems are the isolated particles in the absence of any forces acting on them. In order to explain the compound's behaviour in terms of *these* subsystems' behaviour we do not simply have

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to add the general law of composition so as to generate the twelve dimensional phase-space. Furthermore the term for the gravitational field potential has to be added. One may think of it as an addition to the law of composition for the Hamilton-function. The Hamilton-functions $H_1 = \mathbf{p}_1^2/2m_1$ and $H_2 = \mathbf{p}_2^2/2m_2$ have to be summed up not simply according to ordinary addition but according to a modified rule so that

$$H_{1+2} = \mathbf{p}_1^2/2m_1 + \mathbf{p}_2^2/2m_2 - Gm_1m_2/r.$$

As in the non-interacting case it is an explanation that relies on isolated particles (as subsystems). As before, the descriptions of these subsystems is not sufficient to characterise the system as a whole.

According to the second option the subsystem in question are not the particles on their own, but rather the particles in the field generated by the other particle. The other particle itself is not part of the subsystem. Thus, the first subsystem consists of the first particle in an external gravitational field generated by the second particle. The second subsystems is described analogously. The two subsystems behave according to the Hamilton equations with the following Hamilton functions:

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$$H_1 = \mathbf{p}_1^2/2m_1 - (Gm_1m_2/r) |_1$$

$$H_2 = \mathbf{p}_2^2/2m_2 - (Gm_1m_2/r) |_2$$

'|_i' indicates that the function (Gm_1m_2/r) is restricted to the phase-space of particle i.

Again, what we have is the description relying on two isolated systems (though not on two isolated *particles*). Each of these systems (particle plus field) is described as though it were the whole world. The description of the two subsystems does not yet yield the description of the compound, we need to know the contributions add up. We need a law of composition for the phase-spaces as well as for the Hamilton functions.

In quantum mechanics a vector in Hilbert-space represents the state of a physical system at a time t . The time-evolution of this state-vector (the law-governed part of its behaviour) is described by the Schrödinger-equation which in turn requires the quantum-mechanical Hamiltonian to be specified. In the case of an isolated one-particle-system the quantum mechanical Hamiltonian is defined as $H = \frac{1}{2} \mathbf{P}^2/m$, where \mathbf{P} is the momentum operator of the particle. When we turn to a system of two non-interacting particles

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the procedure is analogous to the classical case. We rely on a quantum-mechanical law of composition of the following form:

With the notion of the direct product of spaces we can formulate the basic assumption about the physical combination of two quantum mechanical systems:

IVa. Let one physical system be described by an algebra of operators, A_1 , in the space R_1 , and the other physical system by an algebra A_2 in R_2 . The direct-product space $R_1 \otimes R_2$ is then the space of physical states of the physical combinations of these two systems, and its observables are operators in the direct-product space. The particular observables of the first system alone are given by $A_1 \otimes I$, and the observables of the second system alone are given by $I \otimes A_2$ ($I =$ identity operator).

We reemphasize that IVa is a basic assumption of quantum mechanics and can only be justified by the fact that such physical systems exist (Bohm 1986: 147).

This law of composition essentially requires that we take the tensor-product of the two Hilbert-spaces so as to gain a new Hilbert-space in which the two-particle system can be represented. As a consequence, the Hamiltonian for the combined system is a direct sum of those for the isolated subsystems.¹⁴

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This presentation of a simple example of a micro-explanation in quantum mechanics suggests that not much has changed while turning from classical mechanics to quantum mechanics. That is indeed what I maintain – as long as we confine ourselves to micro-explanation in the Broad-sense, i.e., as long as we confine ourselves to the micro-explanation of the lawful behaviour of compound systems. (Alleged counterexamples will be discussed in section 3.8 and 3.9) The laws that govern the behaviour of compound quantum mechanical systems can be explained in terms of those laws that would govern the isolated components plus the laws of combination (plus interaction laws).

The micro-explanation of more complicated cases of compound systems does not differ in principle from the simple case outlined above. For instance, in calculating the specific heat of a metal you determine the contribution of the crystalline structure, i.e. the expression that goes into the Hamiltonian, and those of the electrons separately and then add them up. Another example is the calculation of so-called critical exponents that characterise the behaviour of quantum-mechanical systems that undergo phase-transitions. Even though this is a considerably more complicated case the general strategy remains the same. The essential point is to know how the particles that constitute the system in question would behave in isolation, to know what interactions are present and then to sum up the contributions of

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all of these into a single Hamiltonian (thereby relying on a law of composition). To what extent micro-explanation(3) in quantum mechanics is affected by quantum entanglement will be discussed in section 3.9.

3.5. Micro-explanation(2) and micro-explanation (4): explaining the *states* of compound systems

Hitherto we have considered two kinds of micro-explanation that pertain to laws. It has already been pointed out that we might also want to explain macro-*states* in terms of micro-*states*. There are, again, two kinds of explanations of this kind. First, we might try to explain why an ideal gas is in a certain *state* by referring to the micro-*state* of the system. The ideal gas has the determinate temperature T^* because the ideal gas has the determinate kinetic energy value W_{kin}^* . This is not an explanation of a bridge-law, it is rather an explanation that presupposes the existence of a bridge-law. In the absence of a bridge-law there would be no determinate relation between the macro-state and the micro-state. This kind of micro-explanation of a state of a compound system (micro-explanation(2)) is the explanation of why a system's determinable property (temperature) has a determinate value (T^*) in terms of the determinate value of another determinable property *of the same system* (mean kinetic energy).

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Micro-explanation(4) is the explanation of the state of a compound system on the basis of the part whole relation. We might want to explain a compound system's state (the determinate value of a determinable property) in terms of the states of the constituents (the determinate values of the determinable properties of the constituents). Thus, we might explain why a compound has the determinate energy value E^* (the macro-state) by pointing out that the constituents have the determinate energy values E^1 to E^n (the micro-states). This kind of micro-explanation of states presupposes laws of composition to hold. Otherwise there would be no determinate relation between the state of the constituents and the state of the compound. There is no micro-explanation of states without either bridge-laws or laws of composition.

In what follows micro-explanation(2) and micro-explanation(4) will not play a major role. However, micro-explanation(4) (explanation of the states of compounds in terms of states of the parts) is an interesting case because an often quoted counter-example to micro-explanation *in general* is a counter-example to part whole micro-explanation of states – but not to any other kinds of micro-explanation.

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The counter-example to the micro-explanation of the states of compound systems in terms of the states of their parts is a feature of quantum mechanics. In classical mechanics there is no such problem. The states of two separate one-particle-systems in classical mechanics are represented by two points in the respective phase-spaces, i.e., by two six-dimensional vectors. The state of a compound two-particle-system is represented by a point in its phase-space, i.e., by a twelve-dimensional vector. It is due to the law of composition that we are able to explain the state of the compound in terms of the states the constituents would have if they were isolated.

3.6. Micro-explanation and emergence

The concept of emergence is tied to a lot of other notions such as novelty, holism etc.¹⁵ I am interested in emergence as defined by Broad: emergence as the non-availability of micro-explanation.¹⁶ If there are clear-cut examples of emergence in this sense, i.e. the principled failure of micro-explanation, the microphysicalists' assumption that the success of micro-explanation provides evidence for their position is seriously threatened.

Since there are four different kinds of micro-explanation there are at least four different kinds of failures of micro-explanations. That in turn gives rise

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to four different kinds of emergence. I will discuss all of these in turn but will focus on the question whether there are emergent properties that would undermine the microphysicalist thesis (emergence with respect to the part-whole-relation).

3.7. Failure of micro-explanation(1): emergence in the sense of Kim

As we have seen in section 3.2. Kim and others ask for the explanation of bridge laws. Traditionally bridge laws played a role in theory reduction according to the model presented by Nagel. If the theory to be reduced and the reducing theory are couched in different vocabularies, bridge laws provide links between the predicates of the two theories. Commonly they were understood to be of biconditional form (e.g.: $M \leftrightarrow P$), linking one predicate (or the property it refers to) to another predicate (or the property it refers to) coextensively and with either nomic or logical necessity.

In the last decades it has been doubted that universal bridge-laws are as widespread as it must be assumed for Nagel-reductions to do any work. According to the multiple realisation argument many properties can be multiply realized. There is, for example, no universal bridge law for tooth-pain

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because tooth-pain is realized differently in humans and in, say, elephants. At best there are *localized* bridge laws – bridge laws that are relative to species, for instance. It is these local bridge laws that Kim attempts to explain. He tries to answer the question, why it is the case that C-fibre-firing gives rise to pain (in human beings). How is it that the subvenient property gives rise to the supervenient property? Explaining local bridge laws is tantamount to an explanation of the correlations between subvenient and supervenient properties (Kim 1998: 96).

What does such an explanation look like? Kim takes the possibility of functionalization to be the key to the explanation of bridge laws (Kim 1997: 289/90 and Kim 1998: 25ff). Given the function or causal role of a macro-property, the micro-(based-)property is said to explain the macro-property if it can be shown that the micro-property has exactly the same function or fills the causal role in question. He discusses the following example of an explanation of bridge-laws according to his model:

To reduce temperature we must first stop thinking of it as an intrinsic property but construe it as an extrinsic property characterised relationally, in terms of causal/nomic relations, perhaps something like this: it is that magnitude of an object that increases (or is caused to increase) when the object is in contact with another with a higher degree of it, that, when high, causes a ball of wax in

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the vicinity to melt, that, when extremely low can make steel brittle, that, when extremely high, can turn steel into a molten state [...]. We then find properties or mechanisms, often at the micro-level, that satisfy these causal/nomic specifications and thereby fill the specified causal role (Kim 1998: 25).¹⁷

Given this functional model of the explanation of bridge-laws it may be asked whether such explanations are available. There are at least two ways to answer this question. On the one hand we might be interested in what counts as an adequate micro-explanation of, say, the transparency of glass, within an ordinary scientific context. I will not have to say much about criteria for successful explanations in this sense. As Kim himself points out, it is a necessary condition that the property to be explained is characterizable in terms of its function or causal role. Whether or not all higher order properties can be functionalized is ultimately an empirical matter. There seems to be a widespread consensus that qualia, i.e., properties of conscious experience, very likely they turn out to be recalcitrant with respect to functionalization. Thus, even if we are ever going to find correlations between qualia on the one side and physical properties of the others, such correlations or bridge laws cannot be explained on the basis of the physical property or properties. *A fortiori* qualia would turn out to be emergent, given this conception of explanation. In other cases such as the liquidity or the

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transparency of water or other substances it is very likely that explanations that live up to the requirements mentioned so far can be given.

I agree with Kim that this model of explanation (or reduction, as he prefers to call it) accords well with how within science higher order properties are explained in terms of micro-based properties (Kim 1998: 24). However, admitting that this model is reasonable in the light of the scientific explanatory practice is one thing. Quite another thing is the question whether explanations of the above kind explain bridge laws in the sense Kim and others want to have them explained. In order to deal with this point it is essential to focus on what exactly is asked for when the question arises why C-fibre-firing gives rise to pain. This will lead to a second answer to question whether adequate explanations of bridge laws are available.

Terence Horgan introduces the demand for explanations of the kind under discussion in the context of supervenience. As we have seen in section 3.2. mere supervenience is compatible not only with physicalism but also with, for example, parallelism. The demand for an explanation of the bridge laws or supervenient correlations is introduced in order to be able to formulate a viable physicalistic or materialistic conception of the mind-body-relation or inter-level relations in general. Thus, Horgan concludes that

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the sort of inter-level relation that would confer materialistic ‘respectability’ on higher order properties and facts would be not bare ontological supervenience, but superdupervenience – ontological supervenience that is robustly explainable in a materialistically acceptable way (Horgan 1993: 577).

Horgan claims that we have some examples for such a robust explanation in a materialistically acceptable way. He mentions the explanation of liquidity.

What needs to be explained is the following:

Thus, explaining why liquidity supervenes on certain microphysical properties is essentially a matter of explaining why any quantity of stuff with these microphysical properties will exhibit those macro-features (Horgan 1993: 579).

Horgan seems to think that explanations of bridge-laws together with the supervenience relation enable us to give a materialistically adequate theory of the relation of the properties of different levels such as the mental and the physical – a theory that bare supervenience was unable to deliver.

Kim asks for the explanation of supervenience as well. But he is less clear than Horgan what would fit the bill. At various points Kim suggests that we need a *metaphysical* explanation of why supervenience holds. It seems that what is asked for is an ontological relation that explains why subvenient and supervenient properties co-vary. The metaphysical view he favours,

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physical realizationism, i.e., the claim that mental properties are realized by physical properties, provides such an explanation. Physical realizationism entails supervenience (Kim 1998: 23). According to this conception the explanations of why *particular* bridge-laws hold count as evidence for the truth of physical realizationism. This evidence does not have to be decisive for physical realizationism and against other metaphysical standpoints.

At other points, however, it seems that the explanations of particular bridge laws are meant to do the whole work that supervenience on its own is unable to do. Thus, Kim contrasts his model of reduction with Nagel's. He claims that the latter's poverty is manifest because it is compatible with e.g. epiphenomenalism or preestablished harmony (Kim 1998: 97). Apparently he assumes that his own, functional, model of reduction (of the explanation of bridge laws) would not work if psycho-physical parallelism, for instance, were true.

What this suggests is that both Kim (at some places) and Horgan seem to think that an adequate explanation of bridge-laws has to be able to *rule out* non-materialist theories of mind such as parallelism (or non-reductionist theories of the biological *vis à vis* the physical). It is, however, not easy to see how an explanation of bridge laws can live up to *this* standard. It seems

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that – *given this standard* – micro-explanations in the sense of Kim are bound to fail, i.e., to give rise to emergence in the sense of Kim. There is no reason why Kim's explanatory strategy would not work in a world in which pre-established harmony was true. If, say psycho-physical parallelism was true we would be able to specify the functional role of tooth pain and presumably we would be able to explain its functional role on the basis of neurophysiological properties that God has correlated with toothpain. Given that materialism and parallelism are theories that are compatible with the same bodies of evidence it is hard to see why an explanation that relies on empirical laws should rule out the one but not the other.

Let me add that the question at stake is not whether parallelism is a better account of the phenomena than, say, physical realizationism. The question under discussion is whether explanations according to the functional model *rule out* parallelism. This is what Horgan and Kim (at some places) expects such explanations to do.

Given *this* standard (an empirical explanation that rules out parallelism), micro-explanation in the sense of Kim *is bound* to fail. Supervenient properties are emergent if the above criteria for explanation are accepted. Superdupervenience (supervenience plus explanation of bridge-laws) yields superduper-emergence.

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Let me add that this is not a very interesting conception of emergence. The failure of micro-explanation in the sense of Kim is entirely due the unreasonably high standards Horgan and Kim (at some places) are bound to set for the explanations to do the work they are supposed to do.

Be that as it may, one does not have to accept this standard for adequate explanations. By ordinary scientific standards, one might argue, the explanations of the transparency of water or of the boiling of water are successful explanations. I agree. It is, however, important to point out that the explanations of bridge laws according to the functional model piggy-back on micro-explanations in the sense of Broad, i.e. on part whole micro-explanations. Consider the example of the boiling of water. The bridge-law links the boiling of water and the phase-transition of H₂O-molecules. An explanation of the bridge-law contains essentially two ingredients. First, information about the empirical correlation of water and H₂O as well as about the correlation of the boiling of the water and the phase-transition of an ensemble of H₂O-molecules. Second, a story about why the ensemble of H₂O-molecules undergoes a phase-transition. This second ingredient does most of the explanatory work and it does this by relying on a micro-explanation(3), i.e. on an explanation that invokes laws concerning the part-whole relation. Thus, if micro-explanation of bridge-laws is thought to pro-

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vide evidence for some kind of physicalism, it ought to be kept in mind that it is evidence in virtue of underlying part whole micro-explanations.

3.8. The failure of micro-explanation(3): emergence in the sense of Broad

When it comes to the question whether the behaviour of compound systems can be explained in terms of that of its parts the most prominent counter-example is quantum-entanglement. That will be discussed in a separate section (3.9). Here I will discuss two further candidates for emergence. These candidates will turn out not be examples of emergent behaviour. The behaviour of the compounds in question can be micro-explained – at least there is not the slightest evidence to the contrary. These cases are therefore no warrant against the microphysicalists' claim that micro-explanation are always possible.

The first example concerns so-called chaotic behaviour of some physical systems. It has been argued that chaotic systems provide examples of emergent systems. Fairly recently this claim has been based on the observation that '[w]e can only make finite precision measurements and specifications or descriptions of physical systems' (Newman 1996: 252). Therefore, our

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knowledge of the behaviour of the parts never suffices to explain the behaviour of the compound system.

Emergence as we have discussed it here is an ontological concept. It concerns the question whether the behaviour of a whole can be taken to be ontologically independent of the behaviour of the parts. The difficulty consists in spelling out what is meant by ‘ontological independence’. Usually, epistemological concepts such as our ability to explain are referred to in order to mark ontological distinctions such as those between emergent systems and what Broad called mechanistic systems.

The rationale behind this strategy can be made more explicit by taking a look at one of Leibniz’s arguments against Clarke. Leibniz argued that two states of the universe are identical if it is in principle impossible to observe a difference between them. The idea is that the impossibility of an epistemic procedure reflects an ontological fact. Similarly, if it is *impossible* to deduce, predict, or explain the behaviour of some entity A on the basis of the complete knowledge of the behaviour of entity B, then there is no ontological connection between the behaviour of B and the behaviour of A.

It is important that Leibniz has to refer to an *ideal* observer. Leibniz’s argument would not work if the impossibility of observing a difference were

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to refer to human beings with their epistemic limitations. It is for this reason that Broad mentions a mathematical archangel that is supposed to do the explanation, deduction, or prediction (Broad 1925: 70).

If we take emergence to be an ontological notion candidates for emergence that depend on the epistemological inaccessibility of explanations to human beings (as opposed to mathematical archangels) cannot be accepted as genuine examples of systems showing emergent behaviour.

It is the misconstrual of the impossibility-claim with respect to micro-explanation that makes chaotic systems come out emergent. From the perspective of a mathematical archangel, which is relevant for an ontological perspective, chaotic behaviour is very well predictable or deducible, because we are dealing with deterministic systems. Deterministic chaos is thus not an example of emergent behaviour.

A second candidate that is sometimes mentioned is the phenomenon of phase transitions (Anderson 1972 and Liu 1999). Physical systems can exist in different phases. Water, for example can exist in the solid, liquid or gaseous phase. Ferromagnets exist in a magnetic phase below the so-called Curie temperature and are demagnetized above. The alleged emergent be-

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behaviour occurs when a system undergoes a phase-transition. These phase-transitions are uncontroversial phenomena as regards their mere existence. Whenever your coffee water starts to boil we are confronted with an instance of a phase-transition. Within statistical mechanics the occurrence of phase transitions is somewhat problematic. They are defined to occur in the so-called thermodynamic limit, i.e., under the assumption that the system in question consists of an infinite number of subsystems. Finite systems – and among them all real systems such as the boiling coffee water – will, it seems, never be able to undergo a phase-transition. Those phase-transitions we observe can – to all appearances – not be explained on the basis of rules of composition and the behaviour of the finitely many subsystems.

This argument relies on an equivocation, though. Two different senses of ‘phase-transition’ occur in the above argument. On the one hand we have defined within statistical mechanics the notion of *phase transitions in the mathematically rigorous sense*. On the other hand we have a real-life concept of phase transitions. We can calculate how a system with a finite – albeit enormous – number of components behaves – so-called finite-size-calculations. It turns out that the behaviour of real systems with a finite number of components deviates slightly from *phase transitions in the mathematically rigorous sense*. *Phase transitions in the mathematically rigorous sense* occur instantaneously, real transitions take a little time. The

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differences are so small that they usually cannot even be observed (Goldenfeld 1992: 30/1). The upshot is, that the mathematically rigorous description is an idealisation. We have good reason to believe that what we observe is not phase transitions in the mathematically rigorous sense but merely a watered down kind of phase transition, which is for all practical purposes indistinguishable from the mathematically rigorous case. Those phase transitions that occur in real physical systems therefore fail to be examples of emergent behaviour. These transitions can be explained on the basis of finite size calculations.¹⁸

Let me, finally, mention a slightly peculiar feature of Broad's explication of micro-explanation and thus of emergence. It concerns his use of 'general'. It is only general laws that go into such an explanation. If we were allowed to use specific laws we could make one up just for the occasion. Now, consider the following. In section 3.4. I have mentioned the general quantum mechanical law of composition. This applies only if the particles or parts that make up the compound differ in some respect. If they don't, i.e. if they are so-called indistinguishable or identical particles, another law applies.

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IVb. The space of physical states of N identical quantum-mechanical systems (particles) is H_+^N if their angular momentum (spin) has an integral value, and is H_-^N if their angular momentum has a half-integral value (Bohm 1986: 280).¹⁹

Thus, there is one law of composition for fermions (half-integral spin value) and one for bosons (integral spin value).

The law of composition for *electrons* is the same as for other fermions such as neutrons or protons. In the sense of Broad it is therefore a *general* law and two-electron-systems are thus non-emergent systems. The odd thing, however, with respect to Broad's conception is that the behaviour of *fermions* (in contrast to that of electrons) has to be counted as emergent because the law of composition is a fermion-specific law. The same is true for bosons as well. This is an artefact of Broad's explication of the specificity of laws. It is always possible to choose a class of physical systems such that whatever law you take, it is specific with respect to this class. By reclassifying a kind of system you can turn a non-emergent system into an example for a system with emergent behaviour. This problem with Broad's notion of specificity arises with respect to laws of interaction as well. Newton's law of gravity is specific with respect to physical systems that have mass. The desideratum here is a better criterion for the specificity of laws that excludes such cases.

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3.9. The case of quantum-entanglement²⁰

Quantum entanglement undermines micro-explanation. I will briefly discuss it and its implications. Let us suppose we are dealing with a compound quantum mechanical system consisting of two particles. To make things easy I confine myself to spin states of the compound system. What are the possible spin states of such a system? (Normalized) vectors in two-dimensional Hilbert spaces represent the spin states of the separate particles, say H_1 and H_2 . For the construction of a Hilbert-space for a compound system we need a law of composition. According to this law, the possible spin states of the compound system are all those states that can be represented as (normalized) vectors in the tensor product of H_1 and H_2 , $H_s = H_1 \otimes H_2$. H_s contains two kinds of states. Those that can be written as a tensor product of vectors of H_1 and H_2 respectively and vectors that cannot be expressed in such a way.

If we take as a basis for H_1 the eigenvectors in the spin z-direction $|\psi^{z-up}_1\rangle$ and $|\psi^{z-down}_1\rangle$ and as a basis for H_2 $|\psi^{z-up}_2\rangle$ and $|\psi^{z-down}_2\rangle$ we find all of the following among the possible states of the compound system (normalized):

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$$(i) \quad |\psi^{z-up}_1\rangle \otimes |\psi^{z-down}_2\rangle$$

$$(ii) \quad |\psi^{z-up}_1\rangle \otimes |\psi^{z-up}_2\rangle$$

$$(iii) \quad 1/\sqrt{2} |\psi^{z-up}_1\rangle \otimes |\psi^{z-down}_2\rangle - 1/\sqrt{2} |\psi^{z-down}_1\rangle \otimes |\psi^{z-up}_2\rangle$$

The essential point is that (iii) cannot be written as a simple tensor product of vectors of H_1 and H_2 . It can only be written as a superposition of such tensor-products. In terms of physics this amounts to the following. There are spin states of the compound system such as (iii) that do not allow the attribution of pure states to the parts of the compound. So the fact that the compound is in a determinate state cannot be explained in terms of determinate states the constituents occupy. Here we have an example of the failure of micro-explanation – or at least of one kind of micro-explanation, viz., micro-explanation of the *states* of compound systems.

This is the kind of emergence that Paul Humphreys discussed in a recent article. He starts with a notion he calls ‘fusion’ which he defines as follows:

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The key feature of [a fused system] is that it is a unified whole in the sense that its causal effects cannot be correctly represented in terms of the separate causal effects of [the components]. Moreover, within the [fused system] the original property instances [...] no longer exist as separate entities and they no longer have their [...] causal powers [...] (Humphreys 1997a: 10).

The essential feature of this example in terms of Humphreys is what he calls the failure of supervenience: The state of the compound cannot supervene on (let alone be explained in terms of) the states of the parts because there are no such states. Humphreys then suggests that the failure of supervenience implies emergence (Humphreys 1997a: 10).

I agree with Humphreys (and others) that quantum-entanglement is a case of emergence. What has to be kept in mind with respect to this failure, is that it concerns the *states* of parts and the *states* of wholes. Thus, it provides a counter-example to part whole micro-explanation of states – not, however, a counter-example to part whole micro-explanation of the dynamics of compound systems.

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Explaining the dynamics of a compound quantum mechanical system

As I mentioned in section 3.4. not much has changed while turning from classical mechanics to quantum mechanics – as long as we confine ourselves to the dynamics of compound systems, i.e. to micro-explanation(3). The laws that govern the temporal evolution of compound quantum mechanical systems can be explained in terms of those laws that would govern the isolated components plus the laws of composition (plus interaction laws).

Consider the example of the ideal crystal. In classical mechanics it is assumed that the mean equilibrium positions of the ions that constitute the crystal are the sites of a regular lattice. It is furthermore assumed that the oscillations of the ions around this equilibrium position are small compared to the interionic spacing, so that only interactions between nearest neighbours have to be taken into account. An additional idealisation is the supposition that the potential between nearest neighbours is harmonic (Ashcroft and Mermin 1976: 422). On the basis of these and further assumptions we can determine the classical Hamiltonfunction of the ideal crystal, i.e. the sum of the kinetic and potential energies

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$$H = \sum_i E_{\text{kin}}^i + U$$

$$H = \sum_i p_i^2/2m + (1/2) \sum_{ij} U_{ij} q_i q_j$$

with $U_{ij} = \partial^2/\partial q_i \partial q_j U(q_1 \dots q_{3N})$; ($\partial/\partial q_i$ stands for the partial derivative with respect to coordinate q_i).

The Hamilton-function allows us to calculate measurable thermodynamic properties such as the specific heat of a crystal.

$$c_v = - (1/V) (\partial/\partial T) (\partial/\partial \beta) \ln \int dq_1 \dots dq_{3N} \exp \{-\beta H\}$$

with $\beta = 1/k_B T$; (V stands for volume, T for temperature and k_B for the Boltzmann-constant).

According to classical (statistical) mechanics the specific heat of an ideal crystal is independent of its temperature (Law of Dulong and Petit).

This treatment of the crystal accords perfectly with our characterisation of micro-explanation(3): We analyse the compound system into contributions of subsystems: In a first step the complex physical system is split up conceptually into subsystems (ions). In a second step these subsystems are

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treated as if they were isolated; their lawful behaviour in isolation is determined (the kinetic energy terms). Finally the contributions of the subsystems as well as the interactions (the potential energy terms) are added up so as to determine the behaviour of the complex system.

Hardly anything changes with respect to the explanatory strategy when we go from classical to quantum mechanics. The point is that though the mathematical tools used to describe the systems and subsystems change, the analysis of the ideal crystal otherwise remains the same. The quantum-mechanical Hamilton-operator for the ideal crystal is determined on the basis of the kinetic energy terms for the ions and their interactions. The variables p and q are replaced by operators on Hilbert-space. This eventually leads to different empirical predictions (e.g. to a temperature dependence of the specific heat). However, there is no change with regard to the explanatory strategy that is involved.

The fact that the *states* of quantum mechanical systems cannot in general be explained in terms of the *states* of its constituents does not undermine micro-explanation in general. The explanation of the behaviour of a crystal is an example for the explanation of the *dynamics* of the system, i.e. it is an explanation of the *law* that describes its temporal evolution (micro-explanation(3)). The dynamics of a quantum mechanical systems is essen-

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tially determined by the Hamiltonian that goes into the Schrödinger-equation (or the partition-function). The Hamiltonian is built up by what we know about how the parts would evolve if they were separated and their interaction while constituting a compound; it is built up of the terms for the kinetic and potential energies. This information about the parts and their interaction is sufficient to explain the dynamics of the compound system.

The upshot is that the quantum mechanical explanation of the *dynamics* of compound quantum systems is just as good an example for micro-explanation(3) as its classical analogue.

An Objection

Kronz and Tiehen argue in a recent article that quantum entanglement (the non-separability of quantum *states*) is not the only feature of quantum mechanics that gives rise to emergence. The non-separability of Hamiltonians is said to lead to *dynamic emergence*.

The first point to note is that Kronz's and Tiehen's notion of emergence differs from the notion I have employed so far. They define emergence in terms of 'dependent characterization'. It gives rise to what they call 'dynamic emergence':

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Emergent wholes have contemporaneous parts, but these parts cannot be characterised independently from their respective wholes. Emergent wholes are produced by an essential, ongoing, interaction of its parts (Kronz and Tiehen 2002: 345).

The key notions in this definition are ‘characterization’ and ‘independence’ which are defined as follows:

A characterization is an exhaustive list of the properties that are instantiated by an entity. A characterization is independent if the elements of the list make no essential reference to some other entity (Kronz and Tiehen 2002: 344).

There are of course no strictures on definitions of emergence but it ought to be pointed out that the concept of *dynamic emergence* is very liberal. As soon as there are any non-intrinsic or relational properties among the parts, the whole turns out to be emergent because there is an essential reference to some other entity. This kind of emergence is, therefore, in no way characteristic of quantum mechanics (in contrast to what Kronz and Tiehen suggest). Our planetary system as described by Newtonian mechanics is an example for dynamic emergence. The temporal evolution of the earth, for instance, cannot be characterised independently of the whole system. The temporal evolution of the states of the earth invokes an essential reference e.g. to the sun. As this example indicates, ‘dynamic emergence’ is com-

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pletely *compatible* with the explanation of the dynamics of the compound in terms of those of the parts plus their interaction, i.e. the kind of micro-explanation we are interested in. The planetary system might be an example for dynamic emergence; its behaviour is nevertheless explainable on the basis of the laws for the isolated planets plus their interactions (and laws of composition).

However, the crucial question for us is whether – independent of their notion of emergence – what they call the ‘non-separability of Hamiltonians’ gives rise to emergence in *our* sense.

Let me start with their notion of ‘non-separability’.²¹ In the case of quantum *states* non-separability is equated with entanglement: A vector that can be written as tensor-product relative to a given basis is said to be separable. It is non-separable if it can only be written as a superposition of tensor-products as for example state (iii). In analogy, separability of Hamiltonians or evolution-operators is defined as the possibility of writing the relevant matrix as a tensor-product of the submatrices for the parts of the compound. The Hamiltonian or the evolution-operator is said to be non-separable if it can only be written as a superposition of tensor-products of the Hamiltonians or evolution-operators for the parts.

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Physically speaking a separable Hamiltonian leads to time evolutions of the parts of the compounds that are independent of one-another. A non-separable Hamiltonian, on the other hand, brings about interdependent temporal evolutions of the parts. Every Hamiltonian that contains an interaction term is non-separable, simply because the parts affect one another.

What are the effects of separable and non-separable Hamiltonians on separable and non-separable quantum-states? If we start with two separable quantum mechanical systems (no entanglement) and the dynamics of the two is described by a separable Hamiltonian there will be no interaction and the systems remain non-entangled. Entanglement is brought about by interaction. It requires a Hamiltonian that contains interaction terms – a non-separable Hamiltonian.

Kronz and Tiehen start with a non-separable, i.e. an entangled state and study its temporal evolution. If we start with an entangled quantum state a non-separable Hamiltonian might lead to quantum states that are more entangled than before (but it might also lead to disentangled quantum states – after all the Schrödinger-equation is time-symmetric). Kronz and Tiehen claim:

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The non-separability of the state of a composite system is one degree of inextricability, but it is not the most robust form to be found in quantum mechanics. A greater degree is to be found when the Hamiltonian of the compound is non-separable. In that case, the time evolution of the density operator that is associated with a part of a composite system cannot in general be characterised in a way that is independent of the time evolution of the whole. If the Hamiltonian is separable, then the time evolution of the density operator that is associated with a part can in general be characterised independently of the time evolution of the whole (Kronz and Tiehen 2002: 343/4).

Kronz and Tiehen substantiate their claim by calculating the density operator $\rho_1(t)$ of a part S_1 of a composite system S consisting of two parts (S_1 and S_2):

$$\rho_1(t) = \text{Tr}^{(2)} \rho(t)$$

where $\rho(t)$ is the density operator of the compound system S .

This partial trace is independent of U_2 if the temporal evolution U of the compound system S can be written as tensor product: $U = U_1 \otimes U_2$. That requires the Hamiltonian for the compound to be separable. If it fails to be

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separable the temporal evolution of $\rho_1(t)$ will depend on the temporal evolution of the whole (Kronz and Tiehen 2002: 344).

I agree with everything that has been said so far. However, the point is that quantum mechanics shares the feature described with its classical analogue. In the presence of interaction the temporal evolution of parts of compound classical systems depends on the temporal evolution of the whole. As I mentioned before, the temporal evolution of the earth cannot be characterised independently of the whole planetary system.

To conclude: The non-separability of *states* is something unknown in classical mechanics. In classical mechanics it is always possible to consider the state of a subsystem as something intrinsic. This is no longer the case when we go to quantum mechanics. However, there is no analogous difference between classical and quantum mechanics with respect to non-separable Hamiltonians. No additional non-classical feature is introduced by non-separable Hamiltonians. Both, in the classical as well as in the quantum mechanical case the presence of interaction terms leads to time-evolutions of the parts that depend on the compound. We may call this a case of ‘dynamic emergence’. What is essential, however, is that these cases do not undermine the micro-explanation of the dynamics of compound systems.

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Neither the classical nor the quantum case can serve as an example for emergence in the sense of Broad.

There is, therefore, no reading of quantum mechanics such that we ought to conclude ‘reductionism is dead’, as Tim Maudlin put it (Maudlin 1998: 54). Micro-explanation of the dynamics of compound systems has nothing to fear from quantum mechanical entanglement because it attempts to explain *laws* (the dynamics) rather than *states* of compound systems. There is therefore a clear sense in which the explanation of the properties of a crystal on the basis of quantum mechanics can be considered a successful micro-explanation. It is an example of micro-explanation(3): The dynamics of the compound is explained on the basis of the dynamics of the parts and their interaction.

3.10. A diagnosis

With respect to the concept of emergence we end up with the following result: Quantum entanglement provides an example for emergence that concerns the relation between the *states* of parts and those of compound systems. We did, however, not come across examples of emergence as the fail-

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ure of micro-explanation(3) – at least not in physics. It is worth asking why there are no such examples.

Brian McLaughlin has stressed the fact that the failure of the emergentists to come up with examples of uncontroversial evidence for emergent behaviour is not due to philosophical mistakes or contradictory claims they make. It is an empirical matter (McLaughlin 1992). I agree. It is, however, remarkable that there are no uncontroversial examples for emergence in the sense of Broad.

There are, I think, two reasons why it is rather unlikely that scientists will comfortably settle with examples of emergent behaviour. The first reason is a coherence requirement. We want our stories about parts and wholes to be coherent. They should yield the same predictions etc. Let us assume we are dealing with a compound system C. We measure C's specific heat and it turns out to be, say, $c_1(T)$ (T indicates its dependence on the temperature). Now assume that we have been set the task of explaining this phenomenon. On the basis of what we take to be the constituents of C and the interactions among them we calculate a diverging result, say, $c_2(T)$. How will we react? Well, surely something has gone wrong – either with the experiment or with the calculation. Presumably we will check whether there are further contri-

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butions to the specific heat that we have not yet taken account of in our explanation or whether there are interactions that we have neglected. Clearly, we are not allowed to postulate an unknown force, we have to rely on general laws. In short, we would consider every candidate for an emergent phenomenon as an anomaly. Along the lines of Kuhn it can be argued that we will have failed in our scientific aspirations unless we are able to bring into accordance the story about the whole ($c_1(T)$) and those about the parts ($c_2(T)$).

The second point is that this pressure would not have the effect in question if micro-explanation(3) were not to a certain degree a flexible research and explanatory strategy. This flexibility becomes apparent if one looks at how emergentists might conceive of certain episodes in the history of physics. There are at least two cases where they might have felt near victory. First case: gravitation. All attempts to micro-explain gravitational phenomena in terms of (roughly) Cartesian physics have failed. Gravitation, a case of emergence? Second case: electro-magnetism. All attempts to micro-explain electro-magnetic phenomena in terms of (roughly) Newtonian physics have failed. Electro-magnetism, a case of emergence? Ultimately physicists did not settle with these unsettling outcomes. Rather, in both cases they redefined the basis on which micro-explanation could rely. In the case of gravitation the constituents were now described as possessing mass, a disposition

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of particles to behave in accordance to a certain law, given the presence of other particles endowed with mass. The case of electro-magnetism is analogous. Charge was introduced as a new disposition that particles might be endowed with. On this redefined basis neither gravitational nor electromagnetic phenomena turn out to be emergent.

This looks like a rather frustrating game for the emergentists, one that they are bound to lose. Maybe that is the case. It should, however, be noted that there are also certain restrictions on micro-explanation – certainly not just any new kind of disposition/law of interaction will do. Introducing a soporific disposition to explain the effects of opium will not be considered to be an adequate move. Laws (or dispositions) should be general, not specific as Broad has put it. But generality and specificity are matters of degree.²² Given all this, *viz.*, the pressure for coherence and the flexibility of micro-explanation, we should not be completely surprised that we found no clear-cut examples of emergent behaviour (in the sense of Broad, i.e. in the sense of micro-explanation(3)) in physics.

These remarks should not be read as an a priori argument against the possibility of emergent phenomena in the sense of Broad. As I said, I agree with McLaughlin that this is ultimately an empirical matter. What I have argued is that micro-explanation is to some extent a flexible explanatory strategy,

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so as to turn alleged counterexamples, i.e. alleged examples of emergence, into phenomena that are micro-explainable after all. Thus, it is no good idea to rest one's argument against microphysicalism on the assumption that there are uncontroversial examples of emergence.

3.11. Other modes of explanation

It ought to be mentioned that micro-explanation is by no means the only kind of explanation that physicists make use of. Causal explanation, for instance, is a very different kind of explanation of why a system behaves the way it does. In contrast to micro-explanation which considers an isolated system and traces its behaviour to what the parts would do if they in turn were isolated (plus laws of composition and interactions among the parts) causal explanation takes into consideration the interaction with other, external systems. It is the behaviour of the other systems that does the explanatory work.

Similar remarks apply to further modes of explanation. Some explanations for instance appeal to mathematical structures. Many particle physics deals with systems that display critical phenomena. These systems can be represented in spaces with certain topological features – basins of attractions, for

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instance. The fact that a system is situated in such a basin may serve as an explanation for why, say the temperature dependence of the specific heat of the system near the critical point is of such and such a form. The fact that physicists use these and other kinds of explanation is quite compatible with a micro-explanation of the same system. Other modes of explanation might be more suitable to answer the questions physicists have. I have not claimed that micro-explanation is the most interesting kind of explanation.

3.12. Concluding remarks

In the first section of this chapter we have distinguished four kinds of micro-explanation. We have the explanation of the properties of a system in terms of other properties of the same system. Such an explanation may either concern the lawful behaviour of the system (micro-explanation(1)) or the states of the system (micro-explanation(2)). Furthermore we have part-whole micro-explanation. Again, it may either concern the explanation of the lawful behaviour of the compound system in terms of the lawful behaviour of the parts (micro-explanation(3)) or the explanation of the states of a compound system in terms of the states of its constituents (micro-explanation(4)).

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In the following sections I focused on micro-explanation(1) and on micro-explanation(3), both of which are explanations of laws and in terms of laws. The reason is that these kinds of explanation are not only more important in the sciences, micro-explanations of *laws* furthermore allow a link to discussions within philosophy of mind and other philosophical sub-disciplines that focus on *properties*. The reason for this connection between laws and properties can be explicated as follows. (I will confine myself on the part whole relation.) Let me first distinguish between determinable properties and determinate properties. Mass, temperature etc. are examples of determinable properties whereas a certain mass-value and a certain temperature-value are examples of determinate properties. The explanation of determinate properties of compound systems in terms of the determinate properties of its parts is a matter of the micro-explanation of *states*, i.e. of micro-explanation(4). Explaining *determinable* properties seems to be closely related to the micro-explanation of laws (micro-explanation(3)). Robert Cummins introduced a distinction between transition theories which are supposed to explain changes on the one hand and what he called ‘property-theories’ on the other (Cummins 1983: 1 – 27). The latter are meant to explain why a system has a certain *property*. Interestingly all the examples Cummins examines, such as Einstein’s photo-electric effect, are in fact cases of law-explanations. The reason seems to be that properties can best

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be understood in terms of the laws they figure in (their causal or functional role). Thus, I maintain that micro-explanation(3) captures what philosopher's in general and microphysicalists in particular have in mind when envisaging the explanation of properties of compound systems in terms of those of their parts.

The whole point of our analysis of micro-explanation is the physicalists' assumption that the success of micro-explanation implies the truth of (micro-)physicalism. One important result of our analysis is that what is usually taken to be micro-explanation simpliciter, does in fact contain two components that might be taken to support different versions of physicalism. The explanation of, say, the transparency of glass can be broken down into, first, an explanation of why glass is transparent in terms of a micro-based property of glass (micro-explanation(1)) and, second, an explanation of why glass possesses the micro-based property in terms of the constituents' properties (micro-explanation(3)). Micro-explanation(1) is an explanation of one property of a system in terms of another property of the same system and may thus be taken to be evidence for identity-physicalism. Micro-explanation(3) on the other hand concerns the relation of parts and wholes and is therefore, at least *prima facie*, evidence for microphysicalism.

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It was not the aim of this chapter to assess whether, on the basis of this alleged evidence, we may legitimately infer microphysicalism or identity-physicalism. That is what will be done in the following chapters. The point was rather an analysis of micro-explanation in the first place and an assessment of the physicalists' assumption that micro-explanation is a successful research strategy. If explanations fail to be successful (in principle) we are confronted with an emergent property. Our result with respect to micro-explanation(1) was that, given ordinary scientific standards, such explanations are to be had. Successful explanations do, however, presuppose that the property in question can be functionalized and that an appropriate micro-base property can be found. Whether that is indeed the case is an empirical matter and remains to be seen in every single case. If the standards are set unreasonably high, the situation is different. If micro-explanation(1) counts as successful only if certain metaphysical positions with respect to relation of the two properties in question are excluded, micro-explanations(1) is bound to fail.

With respect to micro-explanation(3) our conclusion is that microphysicalists are justified in their conviction that micro-explanation is a successful explanatory strategy – at least if we confine ourselves to physics. Micro-explanation(3) as an explanatory strategy is the explanation of the behaviour of compound systems on the basis of (1) general laws about how the

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constituents would behave if they were isolated, (2) general laws of combination and (3) general laws of interaction. Micro-explanation(3) is successful even in quantum mechanics. We did not come across any examples of emergence in the sense of micro-explanation(3). Quantum-entanglement is an example of emergence but it pertains to the explanation of *states* of compound systems in terms of *states* of constituents. I have argued that the failure of this kind of explanation (micro-explanation(4)) does nothing to undermine the success of micro-explanation(3).

Thus, the premise of the argument for microphysicalism that we set out to examine turns out to be warranted – at least with respect to physics. The microphysicalists may not have got all they wanted, for surely they were also envisaging the prospect of micro-explaining macro-*states* in terms of the states of the constituents. However, as a counter-example to micro-explanation *in general* its impact has been seriously overrated.

It of course remains to be seen whether *every* property of a non-micro-physical entity can be micro-explained. The question is whether we might legitimately induce that the success of micro-explanation(3) cannot only be extended to other natural sciences, but also to, say, the mental. Micro-explanation(3) of a mental property of a compound system only gets off the ground if the mental property can be conceived of as being in some sense

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micro-based. Whether or not this is the case is exactly the issue of identity-physicalism.

Be that as it may, microphysicalists are warranted in claiming that micro-explanation(3) is a successful explanatory strategy. For the remainder of the book I will concede that it is plausible to expect this strategy to be successful with respect to all of nature. Let us see what ontological conclusions we have to draw given this explanatory assumption.

¹ Parts of this chapter are revised versions of parts of a previous publication (Hüttemann and Terzidis 2000).

² The constants of a system are a special case depending on whether they are universal such as Planck's constant or – as is the case with mass – are constant only relative to a particular system. In the former case there is no micro-explanation, in the latter case the micro-explanation concerns either the question why a compound has a *determinate* mass value given the values of the parts or it concerns the question how the *determinable* property mass depends on the determinable properties of the parts. In the former case we have an instance of state-micro-explanation, in the latter an instance of law-micro-explanation.

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³ There is a problem here with the notion of ‘property’. In the philosophy of mind, concepts such as micro-determination and supervenience are often expressed in terms of ‘property’. In physics, however, it is more appropriate to talk about the behaviour of systems, i.e., its laws, states and constants. For the time being I will use the notions of ‘property’ and ‘behaviour’ interchangeably. Towards the end of this chapter I will discuss the question how micro-explanation of laws and states relates to micro-explanation of properties.

⁴ For this distinction see also (Stephan 1999).

⁵ To explain ferromagnetism, Pierre Weiss assumed that ferromagnetic substances contain small regions (Weiss-domains) in each of which the substance is magnetized locally to saturation in some direction. In the unmagnetized state these directions are distributed at random.

⁶ For a discussion of this point see (Menzies 1988: 554/5).

⁷ Broad uses ‘behaviour’ and ‘property’ most of the time interchangeably. Both are meant to refer to manifest properties of the system, i.e. latent and relational properties are usually not included.

⁸ Broad’s complete explanation of a unique or specific law requires: ‘(a) that it is not a special case which arises through substituting certain determinate values for determinable variables in a general law which connects the property of any chemical compound with those of its separate elements

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and with its structure. And (b) that it is not a special case which arises by combining two more general laws, one of which connects the properties of any silver-compound with those of elementary silver, whilst the other connects the properties of any chlorine-compound with those of elementary chlorine. So far as we know there are no such laws. It is (c) a law which could have been discovered only by studying samples of silver-chloride itself, and which can be extended inductively only to other samples of the same substance.’ (Broad 1925: 65).

⁹ For a discussion of the non-triviality of summing procedures see (Nagel 1961: 380 – 397).

¹⁰ For a similar analysis see (Beckermann 1999).

¹¹ The Hamilton-function or Hamiltonian describes the total energy of a system, i.e. its kinetic and potential energy (given certain conditions; e.g. the potential energy has to be independent of velocity). Knowing the Hamiltonian allows one to deduce the time evolution of the system both in Classical Mechanics (on the basis of the Hamilton equations) and in Quantum Mechanics (on the basis of the Schrödinger equation). The Hamilton-equations of Classical Mechanics are a generalization of Newton’s laws of motion.

¹² The degree of freedom of a system is the number of independent quantities necessary to express the values of all the variable properties of the sys-

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tem in question. A classical point particle has six degrees of freedom – three for position and three for momentum.

¹³ The converse is not true. The state of a compound system can only be explained in terms of the state of the constituents if a lawful connection between the latter and the former is presupposed (see next section).

¹⁴ J. B. Kennedy has called this prescription the ‘tensor product representation’ (Kennedy 1995). It comprises three components: The tensor product space $H = H_1 \otimes H_2$, the Restricted Action of Extension (for observables that pertain to one subsystem only) as in $A = A_1 \otimes I_2$, and the Combined Psi-Function (or Density Operator): $|\psi\rangle = \sum_{ij} c_{ij} |i\rangle \otimes |j\rangle$. He points out that the assumption that the relation between subsystems and compounds can be described in these terms goes beyond the usual axioms of quantum mechanics. Thus, he agrees that the law of composition is an independent assumption. Kennedy also points out that this assumption plays a major role in allowing no-signalling proofs and therefore has empirical import.

¹⁵ Paul Humphreys discusses the following criteria for emergent properties: novelty, the properties are qualitatively different from the properties from which they emerge, it could not be possessed at a lower level, different laws apply to it than to those from which it emerges, it results from an essential interaction between their constituent properties, it is holistic in the sense of

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being a property of an entire system rather than a local property of the constituents (Humphreys 1997b).

¹⁶ The non-availability is not meant to be due to epistemic limitations. See section 3.8. for a discussion.

¹⁷ Ansgar Beckermann has a more elaborated account of how this functionalization might work (Beckermann 1997: 310).

¹⁸ Another way of making the same point is to distinguish phase-transitions that involve singularities (what we have called *phase transitions in the mathematically rigorous sense* – they occur instantaneously) from phase transitions that do not involve singularities (what we have called *real phase transitions* – they take some time to occur). This is how Liu explains the same point, while simultaneously providing an explanation of why the need for the idealisation in terms of infinite systems arises. According to Liu ‘Actual systems are finite and phase transitions in them are never real singularities (due to *fluctuations*). Both TD [thermodynamics] and SM [statistical dynamics] with TL [the thermodynamic limit] idealize their systems, but they idealize them in opposite directions: in TD, systems remain finite but are idealized to be continuous, while in SM they remain discontinuous but are idealized to be infinite (because having an infinite number of particles in a finite volume is not an option). And the idealization in SM, which does not seem an approximation of any actual condition is required by the

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idealization in TD, which does not appear to be good approximation – in practical terms, a macro-system is dense with its parts. Therefore the need of TL is really the result of an artifact in TD. The dramatic claim that it is impossible in SM to have phase transitions in finite systems is in fact an exaggeration if not totally false. Finite systems do harbor phase transitions, only they are not singularities.’ (Liu 1999: S103). While I completely agree with this assessment as far as it stands, I disagree with Liu’s claim that phase-transitions provide examples of emergent phenomena. At least they are no examples of emergence in the sense of Broad. Liu takes phase-transitions to be examples of emergent phenomena because their thermodynamic description cannot be ‘reduced’ to their description in terms of statistical mechanics. But this does not amount to the kind of ontological claim we are interested in. It concerns the relation of two features of theories that are both known to be idealisations – as Liu points out himself.

¹⁹ The prescription for the composition of the Hamiltonians remain the same.

²⁰ I would like to thank Alexander Altland, Andreas Bartels and Claus Kiefer for helpful discussions of the issue dealt with in this section.

²¹ There is no consensus on how to employ the concept of ‘separability’ in the literature on the interpretation of quantum mechanics. For a recent dis-

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cussion see (Winsberg and Fine 2003). I will go along with Kronz and Tienhen.

²² Hoyningen-Huene presents a fictional conversation between a defender of reductionism and a defender of emergentism that suggests a similar conclusion (Hoyningen-Huene 1994).